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Diavik Waste Rock Project: Unsaturated Water Flow

Nathan Fretz

Dept. of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada

Steven Momeyer

Dept. of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada

Matthew Neuner

Golder Associates Ltd., Calgary, Canada

Leslie Smith

Dept. of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada

David Blowes

Dept. of Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada

Dave Sego

Dept. of Civil and Environmental Engineering, University of Alberta, Alberta, Canada

Richard Amos

Dept. of Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada

Abstract

A field study is on-going at the Diavik Diamond Mine, NT, Canada, to examine at several spatial scales the hydrologic, geochemical, microbiologic, gas transport, and heat transport mechanisms that control drainage water quality. Data sets on volumetric moisture content within a 15 m high waste rock pile (test pile), estimated using time domain reflectrometry (TDR), and discharge at the base of the test pile are presented to characterize the seasonal wetting of the test pile, freeze-thaw cycles within the test pile, and the discharge cycle at the base of an uncovered test pile. Differences in the dielectric properties of ice and water enable the propagation of freeze-thaw fronts to be recorded via TDR. A spatially uniform initial wetting of the matrix material throughout the test pile was recorded. Moisture contents following the initial wetting phase suggest that the matrix fraction has saturation values exceeding 0.8. Outflow from the test pile follows an annual cycle that is controlled by snowmelt infiltration on the batters, and the movement of thaw front into the core of the test pile.

Introduction

Flow Mechanisms in Waste Rock Piles

The heterogeneity of waste rock piles results from the grain size distribution of the material, and the proportion and spatial arrangement of matrix-supported and matrix-free zones (Smith and Beckie, 2003). This heterogeneity means that multiple flow mechanisms characterize the movement of water within the piles. Matrix flow occurs within the finer fraction of waste rock, where capillary forces enable water storage, and fluid flow can be described by conventional unsaturated fluid flow equations. The finer fraction is categorized by Yazdani (2000) as particles less than 5 mm, based on the observation that media with particles greater than 5 mm exhibit little capillarity. Preferential flow, such as through large macropore pathways or as non-capillary film flow, may occur in both the coarser waste rock fraction and open voids (matrix free zones). With little capillarity, this coarser fraction can result in rapid movement of water through waste rock piles, and is difficult to monitor in situ with current hydrological instruments.

The proportional contribution of each of these flow mechanisms, and interactions between them, control solute mobilization, solute transport within the piles, and subsequent drainage to the environment. Infiltration rates on the surface of a waste rock pile control the initiation of preferential flow; whereas the pile structure influences the residence time of water within the matrix and preferential flow paths and the temporal variation in solute loading (e.g. Smith and Beckie, 2003; Wagner et al., 2006). Stockwell et al. (2006) demonstrate the difficulty in characterizing fluid flow pathways within waste rock and then correlating the hydrologic properties of the waste rock with geochemistry.

Previous and concurrent field studies have examined flow mechanisms in unsaturated, heterogeneous waste rock; however, the Diavik Waste Rock Project is unique in that a large scale field experiment is being conducted on waste rock deposited in a permafrost setting, where water flow is disrupted by freeze-thaw cycles, and is restricted to an active zone that develops during the summer months.

Diavik Project Overview

The Diavik Diamond Mine is located approximately 300 km northeast of Yellowknife, NT, Canada, in the zone of continuous permafrost. Three 15 m high waste rock test piles were constructed and instrumented between 2005 and 2007 to monitor the hydrology, geochemistry, microbiology, gas transport and heat transport mechanisms that influence acid rock drainage. The hydrology component of the Diavik Waste Rock Project focuses on the examination of flow mechanisms, water balances and hydrological parameters of the waste rock observed at multiple scales including laboratory (tempe cell, lab permeameter), 2 m (lysimeter), and 15 m (test pile) scales. One objective of the Diavik project is to address scale-up issues in the prediction of fluid flow characteristics at the scale of the Diavik full-scale waste rock piles. An improved understanding of the mechanisms of water flow through waste rock in a permafrost setting can help advance mine closure strategies for waste rock piles in the Arctic.

15 m Test Piles

A summary of the aspects of test pile construction relevant to water flow is provided here. Additional details are provided in Smith et al. (2009b). Two of the test piles are distinguished by their sulfur content, whereas the third test pile is distinguished by its construction configuration. The Type I test pile has an average sulfur content of 0.035 wt. %S, and the Type III test pile has an average sulfur content of 0.053 wt. %S. The Covered test pile has a Type III core with an average sulfur content of 0.083 wt. %S that has been re-sloped and covered by 1.5 m of till and a further 3 m of Type I waste rock. Each test pile was constructed on top of its own basal drainage water collection system that consists of a basal drain composed of a high-density polyethylene (HDPE) impermeable liner, as well as multiple 2 m x 2 m and 4 m x 4 m basal collection lysimeters. The basal collection lysimeters are intended for the study of spatial variability in flow paths and aqueous geochemistry within the piles. Heat trace is used to facilitate routing of the drainage water to instrumentation huts. The Type I and Type III test piles have dimensions of approximately 50 m by 60 m at the base with slopes at the angle of repose of waste rock (38º or 1.3H:1V). The Covered test pile has dimensions of approximately 80 m by 125 m at the base with slopes recontoured to 18º or 3H:1V. Base dimensions of the piles were determined such that the crests of the piles would be a minimum of 20 m wide to accommodate equipment access. The test piles were constructed by both push-dumping and end-dumping techniques, in a series of tip faces with instrumentation installed along these faces. By constructing the piles in a series of tip faces, the waste rock can segregate as it falls down slope, resulting in the larger cobble and boulder fractions preferentially accumulating lower on the tip face and the finer fraction tending to remain higher on the tip face.

Hydrology Instrumentation

Flow in the basal drainage water collection system is recorded using a suite of tipping bucket flow gauges. Hydrology instrumentation interior to the test piles consists of:

- Custom-built Time Domain Reflectrometry (TDR) sensors, installed on the tipping faces of the test piles during construction, which measure moisture content of the matrix material at different vertical and horizontal locations.
- Commercial ECH_2O (Decagon Devices) capacitance sensors installed within the test piles measure moisture content of the matrix material, as well as electrical conductivity and temperature of the pore water in the matrix, at different vertical and horizontal locations.
- Tensiometers, installed within the upper 1.2 m of the test piles, measure near surface matric potential during thawed conditions.

These instruments facilitate the monitoring of wetting front migration. The TDR and ECH_2O permit monitoring of the propagation of freezing and thawing fronts within the test piles. All instruments have been placed within matrix-dominated zones, since they can only function within finer-grained material. This restriction of the instruments highlights the difficulty of monitoring fluid fluxes in matrix-free zones within waste rock piles. A series of thermistor strings were also placed within the pile (Pham et al., 2011).

Results

This paper presents a subset of the data collected for the Type III test pile, for the purpose of quantifying the wetting-up of the test pile, the freeze-thaw cycle within the test pile, and the discharge cycle at the base of an uncovered test pile at Diavik.

Precipitation

Precipitation typically occurs as rainfall between May and October. Mean annual precipitation is 280 mm, with approximately 40% occurring as rainfall (Environment Canada, 2008). Rainfall values, for the test piles area, are averaged from three rain gauge tipping buckets located on the crests of the test piles. Snow accumulation occurs primarily on the lee-ward batters of the piles, and is observed to be minimal on the crests of the piles due to wind scouring (Neuner, 2009). Obtaining measurements of snow depth remains a gap in the water balance of the test piles, and work is ongoing using alternative means to estimate the contribution of snowmelt on the batters to flow in the test piles. Table 1 reports the annual rainfall at the test piles.

Table 1: Average annual rainfall at the Type III test pile

Year	Total Rainfall (mm)
2007	153*
2008	152
2009	73
2010	95

* Natural rainfall was only 93 mm for 2007. Applied rainfall events to conduct a tracer test raised the total to 153 mm for the Type III pile.

Moisture Content | Wetting Fronts | Freeze-Thaw

Time domain reflectrometry (TDR) probes were built following the design of Nichol et al. (2002). The probes can be used to determine the dielectric permittivity of the matrix-fraction of the waste rock (Topp et al., 1980), which can be correlated to volumetric moisture content via the Topp et al. (1980) equation and lab calibrations. Neuner (2009) reports that the estimation error in moisture content measured by the probes for the Diavik waste rock, is ±0.03 cm^3/cm^3. Figure 1 displays the locations of the TDR probes within the Type III test pile.

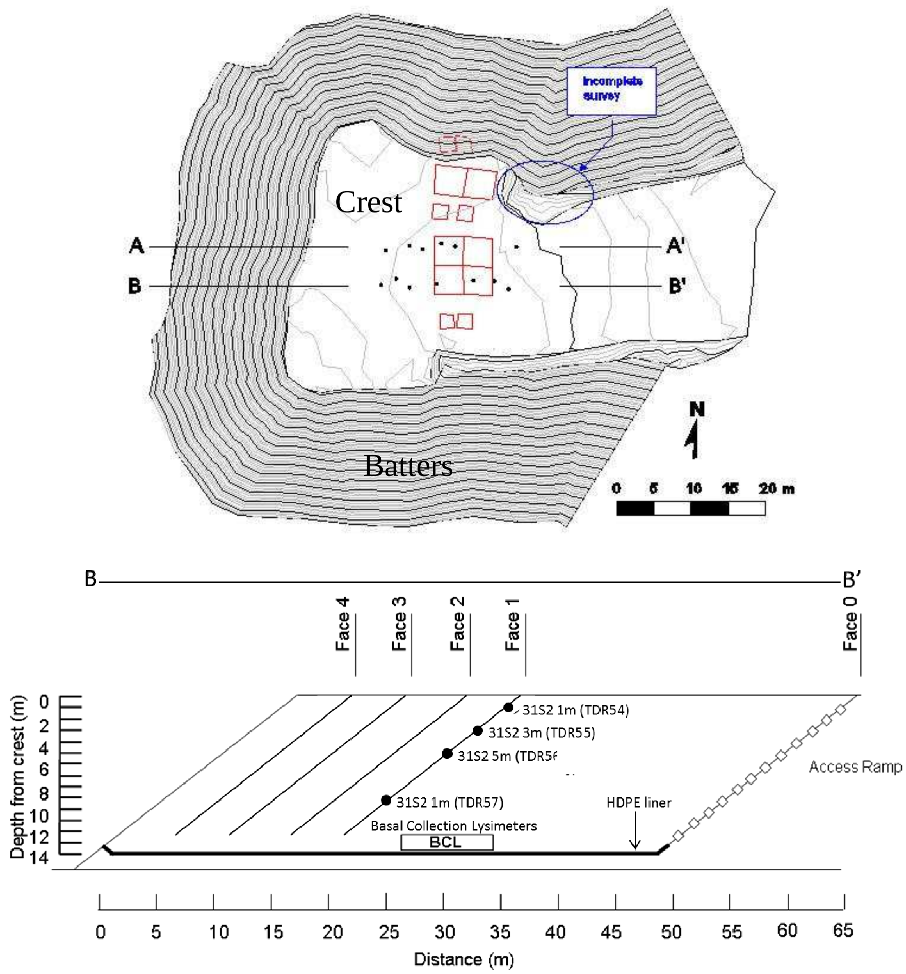

Figure 1: Plan and cross-sectional views of the TDR probe locations used in this paper. (Top figure from Neuner (2009). Bottom figure adapted from Smith (2009a))

Figure 2 presents the volumetric moisture content for the probe-locations along Face 1, the first instrumented tip face, 2 m south of the centre line of the crest (location 31S2). The annual oscillating response of the volumetric moisture content is due to the waste rock undergoing freezing and thawing cycles in response to the ambient seasonal air temperature. This freeze-thaw cycle is captured by the TDR probes due to differences in the dielectric permittivity of the different phases of water. A typical seasonal oscillation is described here using 2009 as an example. From January to June of 2009, frozen pile conditions yield TDR measurements that remain low (moisture content is not measured due to ice phase being present). A rapid rise in the measured moisture content begins in June, starting with the 1 m depth location, followed in order by the 3 m, 5 m and 9 m depth locations. This rapid rise corresponds to the pile thawing in response to increasing summer air temperatures. The TDR probes are positioned below the crest of the pile and are, therefore, not a representation of moisture content response in the batters of the pile where snow accumulates over the winter. As air temperatures drop below freezing again, the probes respond with a rapid decrease in measured moisture content corresponding to freezing conditions at the probe location. The onset of this freezing response can be seen starting in November and December. Figure 3 provides moisture content from the same locations as Figure 2 and compares these results to the temperature measured by thermistors installed within the test pile at corresponding depths. The nearest temperature measurements to the 31S2 location are at a location 3 m horizontally south, on the same tip face as the TDR probes (location 31S5). Despite the TDR probes being located 3 m closer towards the centre of the pile than the thermistor locations, there is a clear correlation between the onset of below 0 ºC temperatures and the rapid decrease in moisture content measured by the TDR probes (vice-versa for the onset of above 0 ºC conditions).

In addition to capturing the freeze-thaw response, the initial wetting-up of the matrix fraction of the pile was recorded by the TDR probes. The matrix portion of the waste rock was below or near residual saturation during the construction of the test pile (Neuner, 2009) and as a result, the pile had a measurable capacity to store water in the matrix portion of the waste rock. This resulted in water from early infiltration events going into storage and increasing the moisture content of the matrix pores before further downward infiltration could occur. Collection of TDR data began in September of 2006, and the evolution of the moisture contents at different depths from late 2006 to 2008 shows a clear wetting-up phase of the pile. Natural and applied rainfall events in 2006 and 2007 resulted in wetting fronts reaching at least a depth of 5 m in 2007 at the location shown in Figure 2. Two probes at 7 m depth within the test pile, not shown here, indicate the wetting front reached at least 7 m depth in 2007. At this location, wetting fronts did not reach a depth of 9 m until the test pile thawed in 2008. This initial wetting-up of the test pile, shown by the TDR probe data, suggests that a larger proportion of infiltration was retained as storage in 2007 and 2008 than in subsequent years. Moisture content of the matrix surrounding the probes after initial wet-up were approximately 25% (during thawed conditions), suggesting that the matrix fraction throughout the test pile has a saturation greater than 0.8. Additional probes at the same depths (but different horizontal locations) show very similar moisture content responses to the wetting-up of the test pile. The data from these additional probes are not presented in this paper; however, the similar responses of the probes highlight the degree of uniformity in matrix response under the crest of the Type III test pile.

In 2009 and 2010 (after the initial wet-up phase), moisture contents that are 2-5% higher at the onset of the thaw than at the end of the previous season (i.e., prior to freezing), and the increase in moisture contents at the 1 and 3 m depths beginning in October suggest that infiltration into the test pile occurs predominantly during those two time periods. The steady decline of moisture contents from July to October, and the absence of probe response to rainfall events, reflect a draindown condition and suggests that rainfall occurring during these months is lost to evaporation, with limited recharge.

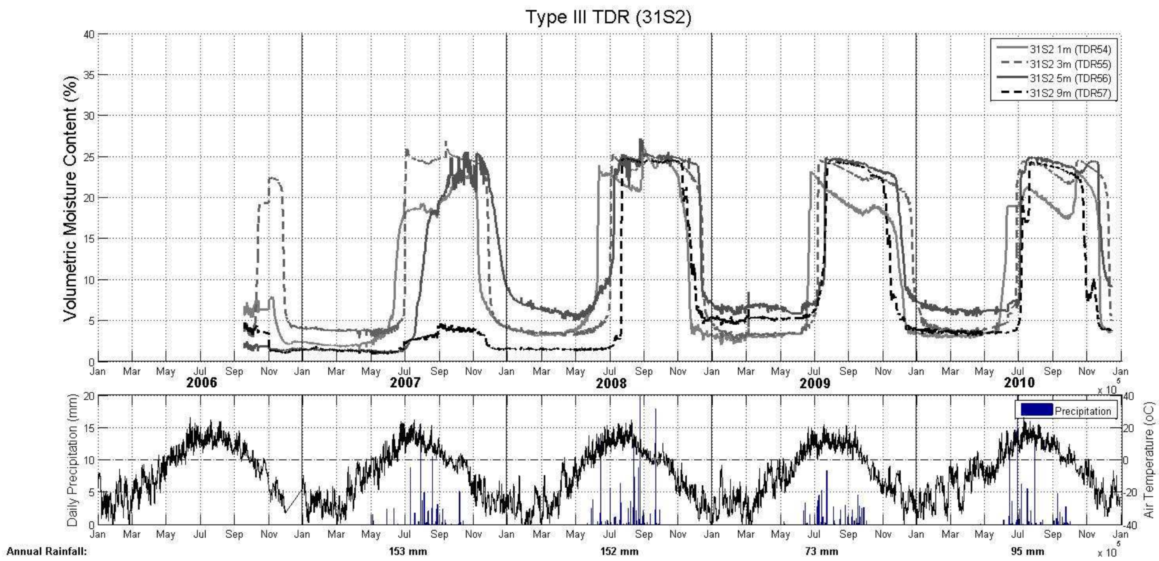

Figure 2: Type III test pile volumetric moisture content at 1, 3, 5, and 9 metre depths along tip face 1, 2 m south of the centre line of the crest

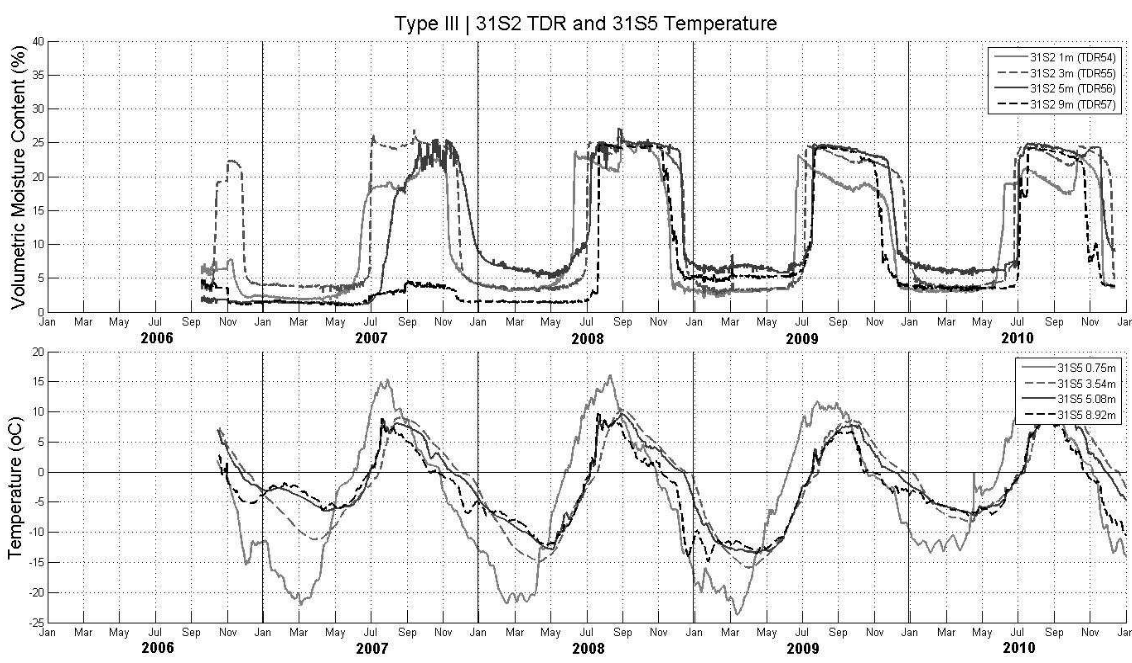

Figure 3: Comparison of TDR probe response and temperature in the Type III test pile along tip face 1

Pile Discharge

Water reaching the base of the Type III test pile flows across an impermeable HDPE liner that is graded to direct the water through a perforated drainpipe and finally to two tipping buckets for measurement of discharge volumes. Tipping buckets have been calibrated to determine the non-linear relationship between tip-time and flow rate, and the tipping bucket data has been processed to determine flow rates and volumetric discharge from the base of the test pile.

Figure 4 presents discharge recorded from the base of the Type III test pile for the period from construction completion to the end of 2010. Daily discharge (left axis) is presented in litres, while cumulative discharge for each calendar year (right axis) is presented in cubic metres. A subplot of precipitation (left axis) and air temperature (right axis) is also shown for comparison. The bar graph of daily discharge only corresponds to flow that was recorded by the tipping buckets. There have been instances of discharge not being automatically recorded throughout the project. Tipping bucket problems in 2007 for the Type III test pile resulted in data loss; however, manual measurements of discharge taken during that time allowed flow volumes to be interpolated. Total annual discharge has been annotated on Figure 4 and, given that this value may include interpolated volumes, should be viewed with this approximation in mind**.**

The Type III test pile flows in an annual cycle that corresponds to thawed conditions and when precipitation occurs as rainfall. As mentioned in the Precipitation section, thawed conditions and rainfall typically occur from May to October, which effectively limits the infiltration of water into, as well as discharge out of, the test pile to this time range. Snow that accumulates primarily on the batters of the test pile melts at the onset of thawing conditions. Neuner (2009) found that infiltration of snowmelt into the batters of the test pile has the potential to refreeze as it encounters waste rock that is still at sub-zero temperatures, and then remobilize as this area of the test pile continues to thaw. Work is currently ongoing to quantify the volume of discharge that is associated with early season infiltration of snowmelt.

By comparing test pile discharge, TDR response, and temperature, we can obtain a preliminary definition of the active zone within the Type III test pile, and how it may evolve throughout the season. The shorter flow paths of water moving from the batters to the test pile base (as opposed to the longer pathways from the crest to the base), combined with the earlier thaw (and larger accumulation of snowfall) of the batters, likely means that early season flow is a combination of direct snowmelt, remobilized water in the batters during thaw and early precipitation events infiltrating through the shorter pathways within the batters. This is confirmed by discharge that occurs before TDR and temperature measurements in the core of the test pile below the crest record above-zero temperature conditions. As the test piles thaw towards the core throughout the summer more of the waste rock is able to contribute to discharge, as frozen pore-water from the previous season is remobilized and can continue to infiltrate downwards. Work by Pham (in progress) shows that the Type III test pile thaws to a depth of at least 11 m in the summer. There are no thermistors located between a depth of 11 m and the thermistors located along the base of the test pile; however, sub-zero temperatures measured at the base of the test pile throughout the summer months suggest that some section of the core of the test pile below 11 m may remain frozen year long, while basal collection lysimeters that flow briefly in the summer months suggest that some section of the base of the test pile may thaw in the summer. Additional work is needed to evaluate this concept, and to determine which sections of the test pile contribute to the observed discharge.

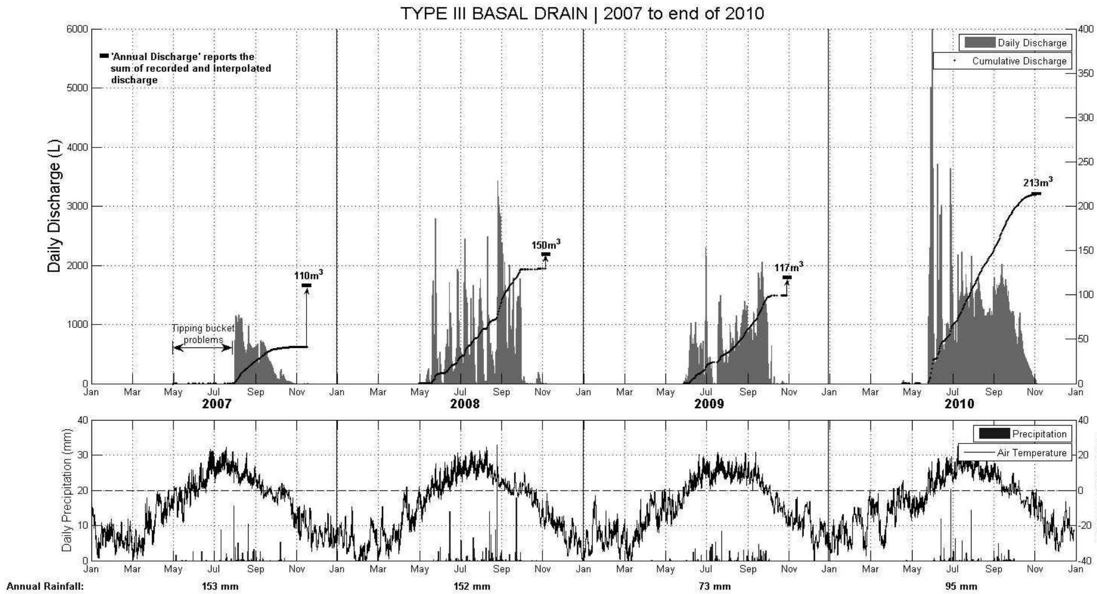

Figure 4: Type III test pile discharge

Conclusions

Diavik's location in a permafrost region means that flow through waste rock in an experimental waste rock test pile is restricted to an active zone that develops during the summer months as ambient air temperatures rise above freezing. The freeze-thaw cycle below the crest of an uncovered test pile, as it pertains to flow, is described by TDR measurements that are sensitive to the differences in dielectric properties of the different phases of water. The wetting-up of the test pile is also recorded by the arrival of wetting fronts at the matrix material surrounding the TDR probes. The similar response of the probes at the same depth in different locations within the test pile indicates the degree of uniformity in matrix response due to infiltration through the crest of the test pile. Post-wet-up-phase moisture contents that remain around 25% suggest that the matrix fraction throughout the test pile has saturation values exceeding 0.8. Outflow from the test pile follows an annual cycle that corresponds with thawed conditions. Work is on-going to determine the relative contribution of both rainfall and snowmelt, as well as the contribution of infiltration through the batters as compared to infiltration through the crest and core of the test pile, to the observed test pile discharge.

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References

Neuner, M., 2009. *Water flow through unsaturated mine waste rock in a region of permafrost*. Thesis (MSc). The University of British Columbia.

Nichol, C., Smith, L., Beckie, R., 2003. Time domain reflectometry measurements of water content in coarse waste rock. *Can. Geotech. J.*, 40, 137–148.

Pham, N., in progress. Thesis (PhD). University of Alberta.

Pham, N., Sego, D., Amos, R., Blowes, D., Smith, L., 2011. Diavik Waste Rock Project: Thermal Transport. *Submitted concurrently to:* Tailings and Mine Waste 2011, November 6-9, Vancouver Canada.

Smith, L.J.D., 2009a. *Building and characterizing low sulphide instrumented waste rock piles: Pile design and construction, particle size and sulfur characterization, and initial geochemical response.* Thesis (MSc). University of Waterloo.

Smith, L., Beckie, R., 2003. Hydrologic and geochemical transport processes in mine waste rock. *In*: Jambor, J.L., Blowes, D.W., Ritchie, A.I.M., ed. *Environmental Aspects of Mine Wastes.* Short Course Series, vol. 31. Mineral Assoc. Can. Ottawa, ON, 51-72.

Smith, L.J.D., Moore, M., Bailey, B.L., Neuner, M., Gupton, M., Blowes, D.W., Smith, L., Sego, D.C., 2009b. Diavik Waste Rock Project: From the Laboratory to the Canadian Arctic. *Proceedings of Securing the Future and 8th ICARD*, June 22-26, 2009, Skellefteå, Sweden.

Stockwell, J., Smith, L., Jambor, J.L., Beckie, R., 2006. The relationship between fluid flow and mineral weathering in heterogeneous unsaturated porous media: A physical and geochemical characterization of a waste-rock pile. *Applied Geochemistry*, 21, 1347–1361.

Wagner, K., Smith, L., Beckie, R., 2006. Hydrogeochemical characterization of effluent from mine waste rock, Cluff Lake, Saskatchewan. *In*: Proceedings of the 7^{th} International Conference on Acid Rock Drainage, St. Louis, MO, USA.

Yazdani, J., Barbour, L., Wilson, W., 2000. Soil water characteristic curve for mine waste rock containing course material. *6^{th} Environmental Engineering Specialty Conference of the CSCE & 2^{nd} Spring Conference of the Geoenvironmental Division of the Canadian Geotechnical Society*. 198-202