Diavik Waste Rock Project: Preliminary Estimates of Multi-Year Net Infiltration

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Abstract
Estimates of evaporative flux and net infiltration at the crests of two uncovered experimental waste-rock piles are presented to highlight which periods and conditions are most important for infiltration of water into waste rock in a northern climate.Evaporation from the crests of the experimental piles has been estimated using the Food and Agricultural Organization of the United Nations Penman-Monteith formulation, in conjunction with a bare soil coefficient that limits evaporation based on water availability in the soil evaporation layer.Preliminary findings suggest that there is significant variability in annual net infiltration over a four year period. The net infiltration from relatively small rainfall events is restricted to periods early and late in the rain-season when decreased solar radiation, air temperatures and waste-rock temperatures minimize the evaporative energy at the ground surface. Net infiltration during June, July and August is predominantly restricted to relatively large rainfall events.Comparison of infiltration results with flux past tensiometer profiles, outflow from a lysimeter within the upper 2m of the surface of the experimental waste rock piles, and near-surface volumetric moisture content measurements provide quantitative and qualitative evaluation of the infiltration results.

Introduction

Infiltration into waste rock
Factors controlling infiltration through the surface of waste rock piles include rainfall intensity, infiltration capacity of the surface of the pile, surface texture and topography, evaporative energy at the ground surface, antecedent moisture conditions, and vegetative cover. This paper presents estimates of the evaporative flux and net infiltration at two experimental waste rockpiles(test piles) constructed at the Diavik Diamond Mine in northern Canada, using data collected from 2007 to 2010. Net infiltration is defined here as water that has moved past the zone of evaporative influence and is interchangeable with net or deep percolation.

Rainfall intensityand heterogeneity internal to a waste rock pile control the activation of different flow pathways through waste-rock. Matrix flow is the movement of water through fine grained material, where flow is controlled by gravity and capillarity.Preferential flow refers to the more rapid movement of water through connected, matrix-free voids between coarse grains (macropore flow) or film flow over the surfaces of large boulders. Larger infiltration rates may promote preferential flow. Flow mechanisms and pile structure influence the residence time of water in contact with waste-rock and, in turn, the temporal variation in solute loading to the environment(e.g. Smith and Beckie 2003, Wagner et al. 2006).

Diavik project overview
The Diavik Diamond Mine is located approximately 300 km northeast of Yellowknife, NT, Canada.Three 15 m high waste-rock test piles were constructed and instrumented between 2005 and 2007 to monitor the hydrologic, geochemical, microbiologic, gas-transport and heat-transport mechanisms that influence drainage water quality from waste rock. The hydrology component of the Diavik Waste Rock Project focuses on the examination of flow mechanisms, water balances and hydraulic parameters of waste rock observed at multiple scales including laboratory (tempe cell, lab permeameter), 2 m (lysimeter), and 15 m (test pile) scales.The estimation of infiltration into the test piles will lead to a better understanding of

water flow through thetest piles, highlight periods and conditions which are most important for the infiltration of water in a northern climate, andassist in closing a water balance for the test piles in order to understand controls on the temporal and spatial variations in solute loading.

Test piles

The Type I test pile is constructed of waste rock that is classified as non-acid generating; the Type III test pile is constructed of waste rock that is classifiedas potentially acid generating (Smith et al. 2011).These uncovered test piles measure 50m by 60m at the base, the batters are at the angle of repose (38^o), and the crests are approximately 30m wide.Eachtest pile is located on top of its own water collection system, which consists of a HDPE liner that is graded to direct water towards a perforated drain pipe and then to custom-built tipping buckets for flow measurement.Also located at the base of the test piles are multiple 2m x 2m and 4m x 4m basal collection lysimeters to quantify spatial variability in flow paths and aqueous geochemistry.Both test piles were constructed by push-dumping and end-dumping techniques. Construction progressed in a series of tip faces with instruments installed along these faces. Instrumentation for flow consists of custom-built Time Domain Reflectrometry (TDR) sensors, commercial ECH_2O (Decagon Devices) capacitance sensors, and tensiometers (Type III test pile only).The instrument leads were extended to the crests of the test piles. The leads were buried 0.5m beneath the surface to allow the haul trucks and dozers to continue constructing the test piles. Once constructed, an excavator was used to expose the buried leads, disrupting the traffic surface created by the heavy equipment. As a result, a traffic surface is only partially developed at the crests of the uncovered test piles.

Active zone lysimeters

Four Active Zone Lysimeters (AZLs) were constructed at the same crestelevation as the test piles, extending down 1.5 - 1.7 m in order to study water flow (and geochemistry) within the upper 2 m of the test piles. The AZLs were constructed by filling HDPE tanks with run-of-mine waste rock. Two of the AZLs consist of Type I waste rock, with $3.6m^2$ collection areas and drains at 1.45m depth. The remaining two AZLs consist of Type III waste rock, with $2.1m^2$ collection areas and drains at 1.7m depth.Drainage is directed through heat-traced PVC pipe to tipping bucket gauges. Since the upper surfaces of the AZLs are at the same elevation and in the same area as the crest of the test piles, they are exposed to the same climatic conditions.Due to construction methods, no traffic surface was formed at the AZLs.

Climate

The Diavik Diamond Mine is located in the Arctic Tundra biome. It is within the zone of continuous permafrost, with an active layer depth of approximately 4m. Mean annual temperature is -8.5^{o}C andmean annual precipitationis 281 mm, with approximately 60% of precipitation occurring as rainfall (Environment Canada2011).Rainfall recorded at the crest of the test piles averaged 103 mm/yr for 2007 through 2010. Rainfall typically occurs between May and October. Snow deposited onto the crests of the test piles is wind-scoured and deposited on the batters of the test piles, meaning that minimal snow is available at the crests for melt and infiltration. Visual observations during intense rain events show that local ponding can occur, but surface runoff does not occur fromthe crests of the test piles (Neuner 2009).

Methods

Evapotranspirationfrom the crests of the test piles is estimated using methods described by Allen et al. (1998) for estimating reference evapotranspiration and, subsequently, actual evapotranspiration. Estimation of actual evapotranspiration is separated into two steps. The first step is an estimate of the reference evapotranspiration using the FAO Penman-Monteith formulation (Allen et al. 1998, Chapter 4). The second step is an estimate of actual evapotranspiration by employing a dual crop coefficient for bare soil to limit evaporation based on water availability in the evaporation layer (Allen et al. 1998, Chapter 7).From this estimate of evapotranspiration, net infiltration into the test pile crests is estimated via a water balance (Equation 1).Net infiltration estimated this way is referred to here as the FAO-Model calculation of infiltration.

$$\text{Net Infiltration} = \text{Precipitation} - \text{Evapotranspiration} - \text{Runoff} \qquad (1)$$

Alternate methods for estimating actual evaporation from wasterock are documented in the literature. Carey et al. (2005) measured the evaporation and surface energy balance at a waste rock pile in northern Saskatchewan using the eddy covariance method, yielding a direct measurement of evaporative flux. This method cannot be applied at the test piles with current instrumentation.

Estimating reference evapotranspiration

Reference evapotranspiration (ET_o) describes the evapotranspiration rate from a surface (hypothetical grass reference crop with specific characteristics) that is not short of water (Allen et al 1998).Reference evapotranspiration is calculated on an hourly basis (Equation 2). An hourly time step was chosen rather than a daily time step due to:(1) Hourly time steps are more representative of reference evapotranspiration in areas where wind speed and cloud cover change substantially during a day, and (2) Diavik collects hourly meteorological data.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(37/(T_{hr} + 273))u_2(e^o(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

Where:

ET_o | standardized reference evapotranspiration [mm h^{-1}]
R_n | net radiation at the crop surface [MJ m^{-2} h^{-1}]
G | soil heat flux density [MJ m^{-2} h^{-1}]
T_{hr} | mean hourly air temperature [^oC]
Δ | saturation slope vapour pressure curve at T_{hr} [kPa$^oC^{-1}$]
γ | psychrometric constant [kPa$^oC^{-1}$]
$e^o(T_{hr})$ | saturation vapour pressure at air temperature T_{hr} [kPa]
e_a | average hourly actual vapour pressure [kPa]
u_2 | average hourly wind speed [m s^{-1}]

For brevity, equations for each variable in Equation 2 are not shown; however, the particular assumptions and approximations used in calculating ET_o at the test piles are outlined below.

Assumptions and approximations

- No hourly atmospheric pressure readings are taken at the Diavik meteorological station. As a result, atmospheric pressure has been estimated using Equation 7 in Allen et al. (1998).
- In calculating net longwave radiation (R_{nl}) an estimate of the incoming shortwave radiation that would reach the surface under cloudless conditions (R_{so}) is needed. In the absence of calibrated coefficients in the calculation of R_{so}, Equation 37 in Allen et al. (1998) is used to estimate R_{so}.
- A soil heat flux density (G) of 0.3Rn has been adopted from Carey et al. (2005).
- Negative values of hourly ET_o have been set to zero: Negative ET_o values can occur when longwave radiation from the surface is large during winter in northern latitudes. Theoretically, it can be argued that this suggests condensation couldoccur; however, following work by Choudhury (1997) these values have been set to zero.

Estimating actual evapotranspiration

In order to estimate actual evapotranspiration, crop coefficients are used to express the difference between $ET_o$and actual evapotranspiration. For the crests of the test piles, a dual crop coefficient method is used that splits the crop coefficient (K_c) into two coefficients: one for crop transpiration (K_{cb}) and one for soil evaporation (K_e). The formula for crop evapotranspiration is outlined in Equation 3.

$$ET_c = (K_{cb} + K_e)ET_o \qquad (3)$$

Where:
ET_c | crop evapotranspiration [mm d^{-1}]
K_{cb} | basal crop coefficient
K_e | soil evaporation coefficient
ET_o | reference evapotranspiration [mm d^{-1}]

Equation 3 is modified in order to represent the crest-characteristics of the uncovered test piles.

$$E = K_f K_e ET_o \qquad (4)$$

Where:
E | actual evaporation [mm d^{-1}]
K_f | frozen soil coefficient [0 or 1]

The absence of vegetation on the crests of the test piles allows$K_{cb}$to be set to zero to represent the waste rock as bare soil. Without vegetation to transpire, ET_c effectively becomes an estimate of evaporation (E). The frozen soil coefficient (K_f) has been adopted from Neuner (2009) to limit evaporation during frozen conditions. K_f is set to 0 during frozen surface conditions and set to 1 during above freezing surface conditions. Sublimation during this period is assumed to be negligible, since wind scours the snow from the test pile crests prior to thawing conditions.The soil evaporation coefficient (K_e) limits evaporation based on the availability of water in the evaporation layer near the soil surface. K_e requires an estimation of:(1) The depth of the surface soil layer that is subject to drying by way of evaporation (Z_e); this is also referred to as the topsoil.(2) The total evaporable water: the maximum depth of water that can be evaporated from the soil when the topsoil has been initially completely wetted (TEW), and (3) The readily evaporable water: the maximum depth of water that can be evaporated from the top soil layer without restriction (REW).

TEW is a function of the field capacity, wilting point, and Z_e of the soil. Field capacity of the matrix material was adopted from Tempe cell tests, on grain-sizes less than 5mm, conducted by Neuner (2009). Parametersof the matrix material have been used, since values for this grain-size fraction are readily available and because the crests of the test piles are matrix supported (see below).Even though the crests of the test piles are matrix supported, the exclusion of the effects of larger grain sizes may lead toerror in the FAO-Model.A $Z_e$of 0.1 m was adopted following Allen et al. (1998).A REW of 3mm was selected and corresponds to a typical value for a TEW of 7 mm(Allen et al. 2009, Table 19).

K_e is largest when the topsoil is wet following a rain event (energy-limiting stage) and decreases once the REW is depleted, reaching zero when TEW is depleted (falling-rate stage). The benefit of using K_e is that it allows evaporation to equal zero when water availability in the soil evaporation layer is zero. This is important during long periods of no rainfall (common at Diavik) to preserve the water balance in the evaporation layer (Allen et al. 1998). Table 1 is a summary of the parameters described above.

Table 1. Key parameters in the estimation of K_e

Parameter	

Field Capacity (m3/m3)	0.1
Wilting Point (m3/m3)	0.06
Ze (m)	0.1
TEW (mm)	7
REW (mm)	3

A key element of evaporation varying with the available water in the soil evaporation layer is the concept of deep percolation. Deep percolation refers to water that drains downwards from the soil evaporation layer following a rain event, and is calculated using Equation (5). Deep percolation occurs when the water content in the topsoil exceeds field capacity, allowing drainage of water from the topsoil.This water is then removed from the influence of evaporation.

$$DP_{e,i} = (P_i - RO_i) - D_{e,i-1} >= 0 \qquad (5)$$

Where:
$DP_{e,i}$| deep percolation loss from the topsoil on day i [mm]
$P_i - RO_i$ | precipitation minus runoff on day i [mm]
$D_{e,i-1}$ | cumulative depth of evaporation from the topsoil at the end of day i-1 [mm]

Additional assumptions and approximations used in calculating E are:

- K_e, and therefore the estimate of E, is only applicable to the test pile crests and not the batters.
- Runoff has been set to zero for each rain event, corresponding to visual observations at the crest of the Type III test pile (Neuner 2009).
- Rainfall values less than $0.2ET_o$ have been ignored, since they are typically fully evaporated (Allen et al. 1998).
- In the absence of moisture content measurements in the upper 0.1 m of the test piles, it is assumed that all evaporable water has been depleted from the top soil evaporation layerat the onset of thawed surface conditions.

Active zone lysimeter outflow

FAO-Model calculations of net infiltration for 2008 through 2010 are compared to outflow from the east-most Type I AZL (1UE).FAO-Model results for 2007 cannot be compared to any AZL outflow for two reasons: (1) No flow reported to the drains of the Type I AZL's in 2007 due to storage in the matrix during wet-up, and (2) Both Type III AZL's cannot be used for comparison due to applied rainfall events, not representative of conditions at the test piles, conducted in 2007.

As a result, 2007 FAO-Model results for the Type III test pile crest are compared to the estimated flux past two tensiometer profiles(Neuner 2009).This comparison cannot be made with the Type I test pile crest since there are no tensiometers in the Type I test pile.Without tensiometers,an independent calculation of net infiltration into the Type I test pile crest other than the FAO-Model cannot be made.

1UE is the only AZL used for comparison to the FAO-Model calculations. Multiple applied rainfall events conducted towet-up the Type III AZLs and to conduct a tracer test mean that the Type III AZL outflows cannot be used for comparative purposes.1UW outflow is excluded based on anomalous grain size characteristics of its surface.Figure 1 shows the surfaces of the Type I AZLs, and the Type I and III test pile crests. The bottom two photographs represent typical crest characteristics of the test piles. The grain size of the Type I and III test pile crests are more similar to 1UE than to 1UW.This visual comparison has been used to determine *only* which AZL has the most similar surface texture to the test pile crests and not to comment on the magnitude of the differences in grainsize. Since both thesurface of 1UE and the crests of the test pilesappear to be matrix-supported, and since a true traffic surface does not exist at the test pile crests, using 1UE outflow to examine net infiltration into the crests of the test piles isbest suited for comparative purposes. In addition, a surface that is matrix supported corresponds to the use of matrix properties in determining TEW.

1UE took slightly longer to wet up than1UW. 1UE was still wetting up during the first two major infiltration events in 2008, responding only partially to the second infiltration event.1UW shows no evidence of wetting up at the beginning of 2008, since outflow initiated at the same time and with approximately the same magnitude as the Type III AZLs, which had previously been artificially wetted-up in 2007. In order to derive an estimate of the outflow "lost" to wet-up during the initial infiltration events, a volume of water was added to the initial 1UE outflow, such that the percent difference between the outflow from 1UE and 1UWfrom the initial infiltration events was the same as the percent difference from infiltration events later in the season.

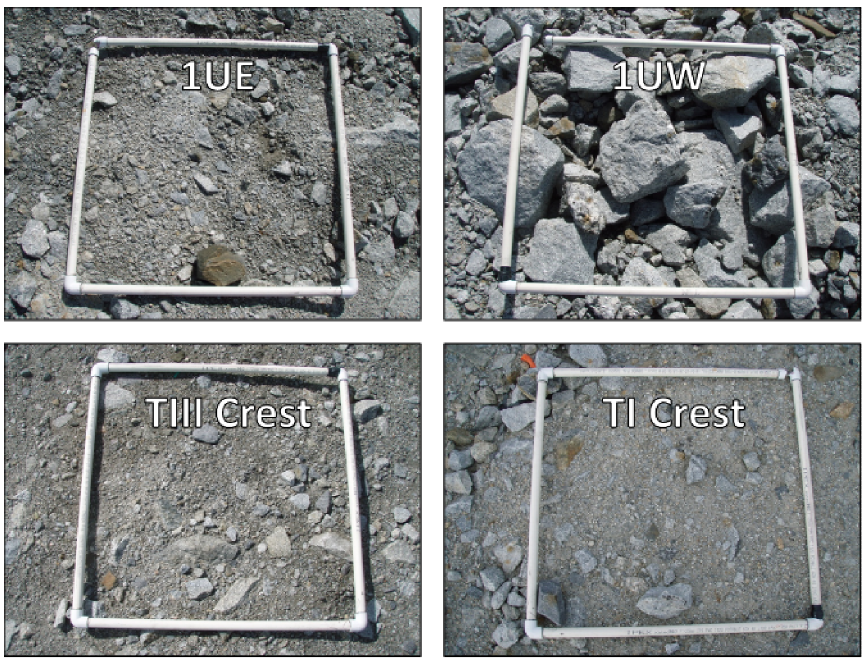

Figure 1. Visual comparison of the surfaces of 1UE, 1UW and the Type IIIand Type I test pile crests. Square is 1 m on a side.

Results and Discussion

2007

Several applied rainfall events were conducted on the crest of the Type III test pile in 2006 and 2007. As a result, separate estimates of actual evaporation and net infiltration have been made for the Type I and Type III test pile crests.In 2007 the Type I test pile crest received 91mm of rainfall, while the Type III test pile crest received151mm of rainfall (the reported rainfall values are cumulative rainfall of events greater than $0.2ET_o$).The applied rainfall events onto the Type III test pile crest were conducted in a series of three separate events: 16mm, 15mm, and 29mm.

Figure 2 and 3 present daily and cumulative rainfall, cumulative actual evaporation, and cumulative net infiltration for the Type I and III test piles, respectively.Rainfall data collected from three raingaugeslocated at the crests of the test piles is averaged daily. Cumulative actual evaporationis calculated as the annual summation of the daily actual evaporation (Equations 2 and 4). Cumulative net infiltration into the crests is calculated as the annual summation of daily net infiltration (Equation 1). Flux past two tensiometer profiles located on the Type III test pile crest are also plotted on Figure 3. Both profiles consist of a tensiometer installed at 60cm depth and a tensiometer installed at 120cm depth.Tensiometer data was collected from August 2nd to September 15th. As a result, 25mm of flux (the FAO-Model net infiltration as of August 2nd) was used as the pre-measurement flux to graphically compare flux past the tensiometers with the FAO-Model net infiltration estimate after August 2nd.

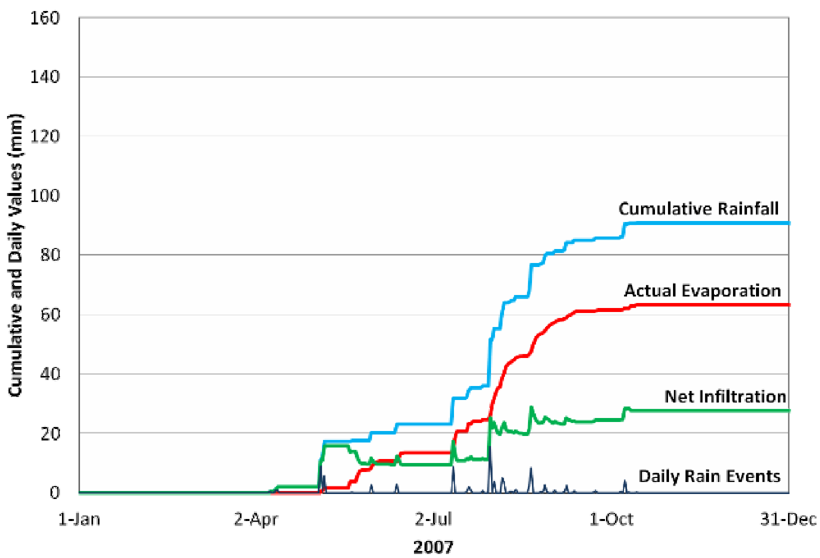

Figure 2. 2007 | Water balance for the Type I test pile crest.

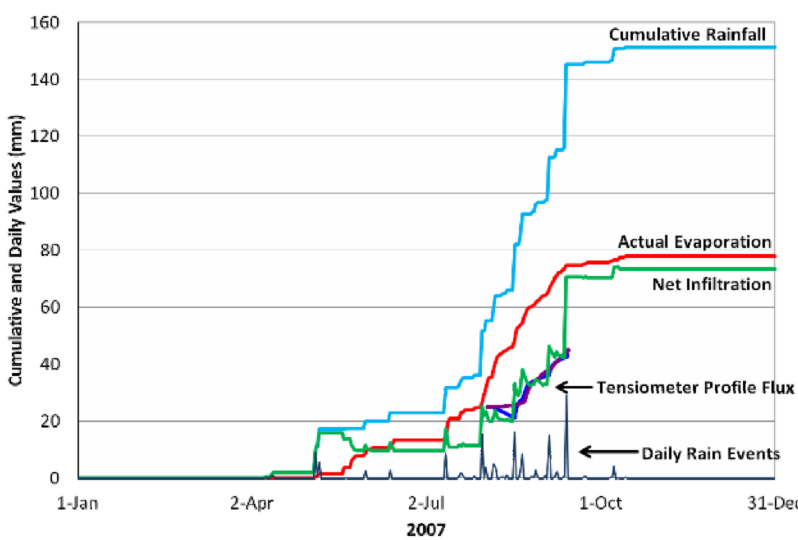

Figure 3. 2007 | Water balance for the Type III test pile crest and flux past tensiometer profiles.

Table 2. Summary of 2007 results for test pile crests

Year	ET_o (mm)	Rainfall > $0.2ET_o$ (mm)	Actual Evaporation (mm)	Net Infiltration (mm)	Fractional Net Infiltration
2007 (Type I)	342	91	63	28	0.31
2007 (Type III)	342	151	78	73	0.48

The good match between the independent estimates of net infiltration based on theflux passing the tensiometer profiles andthe FAO-Model supports the validity of the FAO-Model for the Type III test pile crest. Unfortunately, an independent estimate of net infiltration for the Type I test pile crest is not possible. Several important observations can be made regarding differences in net infiltration resulting from differences in rainfall. Table 2 summarizes the FAO-Model calculations for the Type I and III test pile crests.The last column in Table 2 presents fractional net infiltration: the ratio of annual net infiltration to annual rainfall.Although it is to be expected that a wetter year yields more total netinfiltration, the estimated fractional net infiltration into the Type III test pile crest is approximately1.5 times that into the Type I test pile crest. Fractional net infiltration is so dissimilar because evaporation (and hence infiltration) is strongly dependent on the timing and magnitude of rainfall events.The dependenceon timing of rainfall events is a function of : (1) the antecedent moisture content in the soil evaporation layer, which controls drainage of water past the zone of evaporative influence, 2) the magnitude of ET_o, which controls the energy available for evaporation, and(3) the state of the waste rock; whether the surface of the pile is frozen.The magnitude of a rainfallevent controlshow much and how quickly the water infiltrates past the soil evaporation layer. These dependencies are illustrated in Figures 2 and 3.It can be seen that the FAO-Model predicts that small rain events do not contribute to net infiltration in June, July and August (summer months) when ET_oat Diavik is the highest (see Figure 2). Instead, only the larger rainfall events contribute to net infiltration in the summer months. The infiltration of small rainfall events is restricted to periods early and late in the rainseason when decreased solar radiation, air temperatures, and waste rock temperatures minimize ET_o.The 29mm applied rainfall event conducted at the Type III crest on September 13th, 2007took place just before freezing conditions set in for a period of 8 days. As a result, this event is responsible for much of the observed difference in net infiltration between the Type I and III test piles, because minimal evaporation would have occurred.The timing of this event illustrates the significant contribution that large, late rain-season rainfall events can have to annual net infiltration in a northern climate.Because an independent estimate of net infiltration is only available from August 2nd to September 15thfor the Type III test pile, observations regarding net infiltration in 2007 are only supported during the time period of tensiometer data collection.Tensiometer flux has only been plotted to September 13th, since instrument removal on the 15th resulted in incomplete measurement of the September 13th infiltration event.

2008 / 2009 / 2010

Figures 4 to 6 present daily and cumulative rainfall, cumulative actual evaporation, and cumulative net infiltration for 2008, 2009, and 2010. Also plotted is cumulative annual outflow from 1UE for comparison tothe FAO-Model.1UE outflow response is delayed compared to FAO-Model calculations due to the 1.4m flow path that water takes from the surface to the drain of the lysimeter.1UE may have different characteristics than the test pile crests due to construction techniques, and due to reasons regarding scale and the representative elemental volume (REV) of the waste rock. The storage of water over the winter months due to freezing of pore-water in place may occur at 1UE, particularly in the case of late rain-season infiltration justprior to the onset of frozen AZL conditions. This should be considered when comparing FAO-model calculations of infiltration with 1UE outflow.

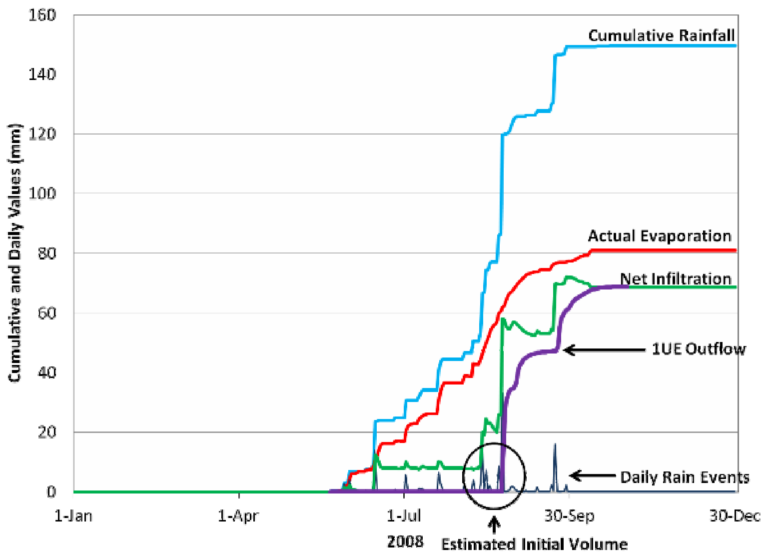

Figure 4.2008| Water balance for the uncovered test pile crests and 1UE outflow.

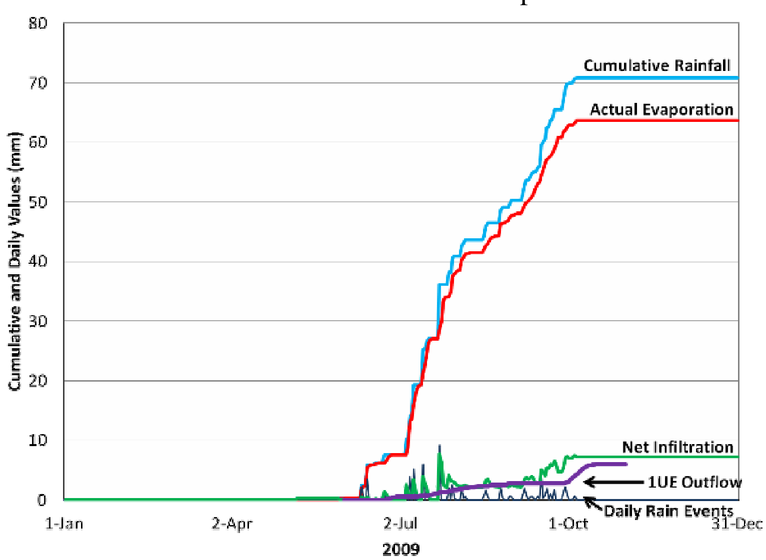

Figure 5. 2009 | Water balance for the uncovered test pile crests and 1UE outflow. (Vertical scale is different than other figures)

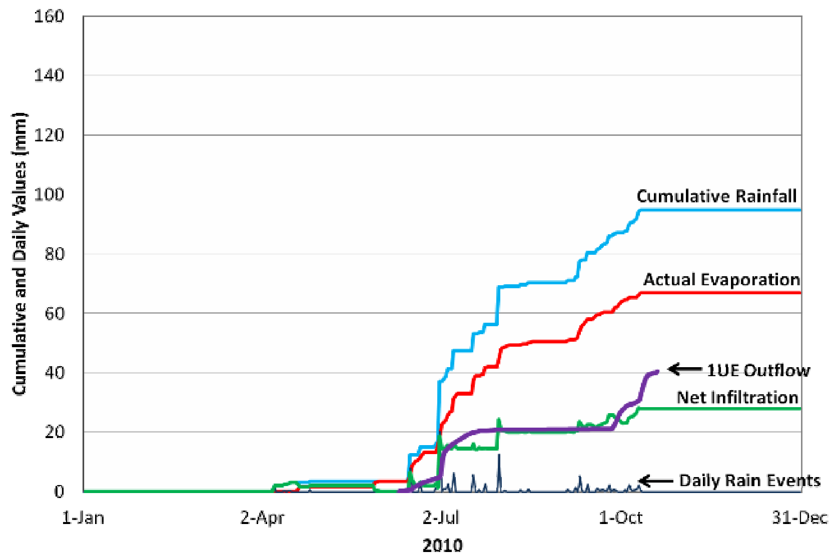

Figure 6. 2010 | Water balance for the uncovered test pile crests and 1UE outflow.

Table 3. Summary of 2008/2009/2010 results

Year	ET_o (mm)	Rainfall > $0.2ET_o$ (mm)	Evaporation (mm)	Net Infiltration (mm)	Fractional Infiltration
2008	320	150	81	69	0.46
2009	294	71	64	7	0.10
2010	357	95	67	28	0.29

Table 3 summarizes the FAO-Model calculations. Total rainfall in 2008 was similar to the total rainfall on the Type III test pile crest in 2007, and total rainfall in 2010 was similar to total rainfall on the Type I test pile crest in 2007. 2009 had the smallest amount of rainfall since the test piles became operational.Fractional net infiltration is vastly different between years, similar to what was observed in the calculations for 2007.As an illustration of two dissimilar years: rainfall in 2009 was 47% of rainfall in 2008; however, FAO-Model net infiltration in 2009 was only 10% of FAO-Model net infiltrationin 2008.This difference is explained by examining the timing and magnitude of the rainfall events. The majority of infiltration in 2008 resulted from 4 large rainfall events. In 2008 14mm, 13mm, and 33mm rainfall events on June 15th, August 13th, and August 24th, respectively,contributed to net infiltration during high ET_o periods. In addition, a 16mm rainfall event on September 22nd, 2008 occurred late in the rainseason, when ET_o was significantly less than in the summer months.The 2009 season however, consisted entirely of small rainfall events, all < 10mm, resulting in an estimated 10% of the rainfall contributing to net infiltration.

FAO-Model estimates of net infiltration and 1UE outflow correspond well; however, there is an exception in the 2010 rainseason, with an underestimation of net infiltration early in July after the 20.1 mm rainfall event on July 1st. This discrepancy is being investigated further. 1UE outflow supports the FAO-Model, due to there being a good match, ingeneral, each year without any changes to variables or processes in the FAO-Model.The good match also provides support to the observations made regarding the 2007 data.Large differences in fractional net infiltration (measured viaannual outflow) are recorded at 1UE for the different years. 1UE outflow in 2008 illustrates the significance of large rainfall events in the summer months. Disregarding the*applied* rainfall events in 2007, the large rainfall events in 2008 appear to be much less common than the smaller rainfall events of 2007, 2009, and 2010.This suggests that for years without large rainfall events in the summer months, the early andlate rain-season periods may be the most significant time for net infiltration into the test piles.

Volumetric moisture content response

Figure 7 compares the FAO-Model net infiltration with the near-surface volumetric moisture content response of the Type I and III test piles. TDR probes are used to measure the dielectric permittivity of the matrix-fraction of the waste rock in the test piles, which is then correlated to volumetric moisture content (Topp et al., 1980).A TDR probe 2m below the crest is used for the Type I test pilecomparison, while a TDR probe 1m below the crest is used for the Type III test pilecomparison.Volumetric moisture contents are plotted for the period from July to the end of October, corresponding to thawed conditions at the 1m and 2m probe locations. TDR probe measurements only correspond to volumetric moisture content during thawed conditions, due to the differences in the dielectric permittivity of the different phases of water.A complication can therefore arise during infiltration into the test piles while the matrix around the probes is still thawing. For example, the volumetric moisture content response at the beginning of July in 2010 shows a significant rise that corresponds with the predicted FAO-model net infiltration. However, the magnitude of the increase in moisture content due to the infiltration event is partially masked because the probe locationswere thawing (moisture contents increasing)as the wetting front reached them.No Type I test pile volumetric moisture content is shown for 2007, since the TDR probe was not recording data for the majority of the rain-season.

There is an excellent match between periods of predicted net infiltration and TDR probe response (Figure 7). Note that different vertical scales have been used in each year for volumetric moisture content in order to display the data. The downward trends in moisture content represent the downward drainage of water and correspond to periods when the FAO-Model predicts minimal net infiltration. Increases in moisture content represent the arrival of wetting fronts and correspond to periods when the FAO-Model predicts net infiltration. The match between TDR probe response and predicted net infiltration and lysimeter outflow is a qualitative indication that net infiltration is occurring into the crests of the Type I and III test piles.

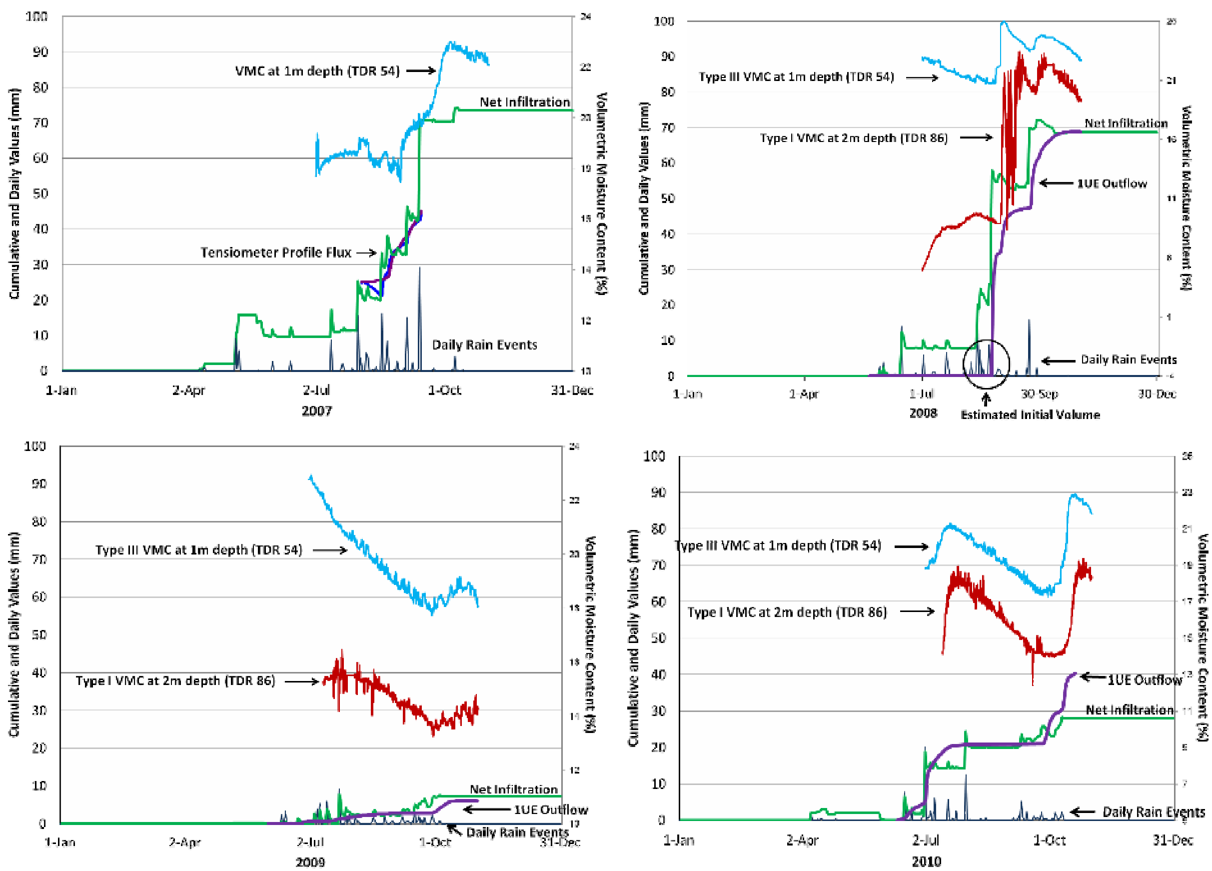

Figure 7. FAO-Model annual net infiltration and near-surface moisture content for the test piles.

Conclusions

1. There is significant variability in annual net infiltration to the uncovered experimental waste rock piles(Type I test pile and Type III test pile) over the four year period.
2. Evaporation and net infiltration into the crests of the test piles are largely dependent on the timing and magnitude of rainfall events.Net infiltration of small rainfall events is restricted to early and late in the rainseason.Net infiltration in June, July, and August is restricted to larger rain events.
3. Early and late rain-season may be the most significant period for net infiltration in years with no large rainfall events in the summer months (June, July, August).
4. FAO-Model calculations for the Type III test pile in 2007 match well with the flux calculated past two tensiometer profiles, suggesting the FAO-Model is applicable to the crest of the Type III test pile.
5. Outflow from the1.5 m active zone lysimeter 1UE and FAO-Model calculations match reasonably well for multiple years without any change to FAO-Model parameters.1UE may be suitable for comparison to the crests of the uncoveredtest piles when considering grain size similarities and the absence of fully developed traffic surfaces.
6. TDR measurements of volumetric moisture content near the surface of the test piles respond in concert with net infiltration predicted by the FAO-Model. This comparison is a qualitative indication that net infiltration is occurring into the crests of both the Type I and III test piles; the TDR probes show that downward drainage occurs during periods of no/low net infiltration, and show wetting front arrival during periods of predicted net infiltration.

It is necessary to come up with a model estimating infiltration into the test piles, due to the absence of AZL comparison in 2007 and due to differences in applied rainfall at the test pile crests and AZLs.It is; however, difficult to evaluate and compare the magnitude of net infiltration between the two uncovered test piles. Work is ongoing to explain the observed difference in outflow from the Type I and Type III test piles; the Type III test pile consistently discharges a larger volume of water per year than the Type I test pile and this difference cannot be explained by differences in applied rainfall events onto the crests. Differences in how discharge water is routed along the base of thetest piles and differences in permafrost conditions between the test piles may contribute to the observed difference in discharge.FAO-Model estimates of evaporation and net infiltration will aid in explaining this difference.

Only the net infiltration into the crests of the test piles has been explored in this paper and not the net infiltration into the batters.The surfaces of the batters have less fine-grained matrix material than the crests, suggesting that they likely have higher infiltration capacity and less ability to retain water in an evaporation layer. Also, snow accumulation on the batters of the test piles throughout the winter results in snowmelt infiltration during thaw. TDR response under the crests and outflow response from the base of the test piles suggests that batter flow is the dominant source of discharge.

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