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Evapotranspiration cover performance in a high desert environment, north waste rock disposal facility, Rain Mine, USA

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Abstract

Newmont Mining Corporation conducted a performance audit of an evapotranspiration (ET) cover constructed in 2002 at an acid generating waste rock disposal facility located at 2,000 m elevation. Based on technology available at that time, the monolithic ET cover design included approximately 0.9 m of local alluvium with native sagebrush steppe vegetation. The site receives an average of 540 mm of precipitation annually, 84% of which falls during October to April. The cover did not significantly reduce infiltration into the waste rock, as measured by a seepage collection system constructed beneath the waste rock facility. Average annual seepage following reclamation has ranged from 38,000 to 193,000 cu. m, or 13 to 44 % of annual precipitation for the 76 ha facility. Peak monthly average rates during the spring have been as much as 10 litres per second (L/s). Seepage chemistry is poor, with pH typically below 3, total dissolved solids concentration ranging from 5 to 30 g/L, and elevated metals concentrations.

Newmont proactively conducted studies of the reclamation cover including installation and monitoring of moisture sensor nests, laboratory testing, surface geophysics, monthly snow surveys, geochemical characterisation of the waste rock, and groundwater monitoring. A detailed assessment of the available design and construction data, site climate, and cover monitoring data was conducted in 2010 to assess cover performance. The study included precipitation gauge catch corrections, modelling of potential ET (PET) by aspect and slope, a direct method for computing infiltration from the moisture content sensor data, an analysis of seepage chemistry, and calibrated numerical modelling.

The assessment concluded that the compromised cover performance was due to the compounded effects from winter precipitation, snow drifting, slope and aspect influence on PET, available water holding capacity of the cover material, and cover construction unconformities. While the ET cover is able to fully reset the available water holding capacity of the cover each year, the cover profile is fully wetted each spring from snowmelt, resulting in significant infiltration into the waste rock. Newmont is using the results of this study together with an engineering analysis of alternative reclamation designs to identify a final reclamation strategy for the facility.

1 Introduction

The Rain Mine is located approximately seven miles southeast of Carlin in the Pinyon Mountain Range of northern Nevada. The site consists of the mine pit, tailings pond, heap leach, and the north waste rock disposal facility (NWRDF). The NWRDF received approximately 29 million m^3 (54 million tonnes) of waste rock from 1987 to 2002 and covers approximately 76 ha. The facility was constructed with limited waste segregation and no chemical amendments were applied during placement. Acid rock drainage (ARD) was first detected in 1990 and is collected by a piping system and a system of interception trenches at the northern perimeter. The non-impacted seepage from approximately 18 ha at the north-western end of the facility is not collected but monitored.

In 2001, Newmont USA Ltd (Newmont) commissioned the closure design for the NWRDF. The final cover configuration was selected by using results from the borrow source investigation, climate data collected from the on-site and nearby weather stations, and engineering predictions following the standard of practice and the available technology at the time. The design targeted an average annual precipitation 350 mm and calculated potential evaporation of 1,410 mm. Modelling based on the available climate data and materials properties predicted infiltration of less than 2% of the annual precipitation for a selected monolithic, mature evapotranspiration (ET) cover configuration. Hence, a single ET cover design was specified for the full dump surface consisting of a 0.9 m thick storage layer incorporating a well-graded compacted colluvium (or alternative mixture of colluvium and tailings materials) overlain by a 0.3 m thick growth medium. Specified vegetation species included grasses, forbs, and deep-rooted plants. The design directed operators to "regrade to drain" flat top areas (16% of dump area exhibits slopes less than 5%), with no re-sloping of steep areas (36% of dump area exhibits slopes greater than 33%, with slope lengths up to 150 m). Stormwater conveyance structures, such as benches on slopes and channels, were not included in the design.

Construction of the vegetative cover was finished in November 2002. Measured seepage reporting to the collection system decreased, but not to the degree predicted. Measured collection pipe outflows and the corresponding precipitation values, after applied wind and temperature corrections, are summarised in Table 1. Discharge from the collection system peaks in the spring during the snowmelt period, with measured peak monthly average discharges up to 10 litres per second (L/s). Consequently, questions arose about ET cover performance, and Newmont commissioned a series of investigations to assess cover performance and identify the root cause(s) of the apparent poor cover performance.

Table 1 Pipe outflows prior to and after cover construction

Period[1]	Avg. Precipitation[3] (mm/yr)	Avg. Pipe Flow (m^3/day)	Pipe Flow (% precipitation)
1996–2002[2]	590	272	29%
2002–2010	550	187	21%
2008–2010[4]	450	97	14%

Notes: [1] Duration in water years (WY), e.g. data for WY 1998 was collected from Oct 1997 to Sep 1998. [2] Period prior to cover placement. [3] Based on precipitation data after applying wind and temperature corrections. [4] Period with the well established vegetation.

This paper describes the final assessment of the ET cover performance at the NWRDF. The cover assessment included evaluation of local climate conditions, review of cover design and construction records, analysis of the available field moisture monitoring data, and comparison of the collected seepage outflows with the results from numerical models. In addition, the collected seepage chemistry data were used to confirm results from infiltration analyses.

2 Climate assessment

The assessment included a detailed analysis of the climate conditions at the site using available records. The assessment considered the accuracy of the precipitation measurements and microclimate effects.

2.1 Precipitation corrections

Precipitation at the site has been measured using a National Weather Service (NWS) 20.3 cm non-recording standard gauge. Measurements were taken once daily, and a wind shield was not used. It is well established that precipitation gauge errors affect measurements for a wide range of gauge types (Sevruk, 1985). Errors include:

- Wetting error, which refers to the rain or water from melted snow subject to evaporation from the surface of the inner walls of the precipitation gauge after a precipitation event and the water that remains in the gauge after emptying. Average wetting loss for the site gauge is 0.03 mm per observation for rainfall and as much as 0.15 mm per observation for snow and mixed precipitation (Yang et al., 1998).
- Evaporation loss, which is water lost by evaporation before the observation is made. This effect is greatest in environments where potential evaporation is high compared to the precipitation for certain periods, as with the Rain Mine.

- Wind induced or gauge catch error, which results from deviation of precipitation particle trajectories due to wind field deformation. Wind induced error can be on average 2 to 10% for rain (Nespor and Sevruk, 1999) and 0 to 75% for snow (Neff, 1997).

For unshielded surface gages, measurement errors during snow events accompanied with high winds can be much higher. Neff (1977) reports the 188 mm of precipitation measured by the mine pit gauge from 6–12 November 1966 at Reynolds Creek site in Idaho while the surface gauge at the same site collected only 17 mm.

Gauge catch errors are to be expected for the Rain Mine gauge, given the high measured wind speeds at the site (average daily wind speed is 2.4 m/s for precipitation days), high percentage of precipitation as snow or sleet (on average 73%), and the site instrumentation. Corrections for gauge catch errors due to wind and temperature for the Rain Mine site gauge were applied using a method developed by Yang et al. (1998). The wind corrections are regressions of the daily catch ratio as a function of average daily wind speed at gauge height. The equations for the unshielded gauge catch ratio are:

$$R = \begin{cases} Exp\left(4.606 - 1.57W^{1.28}\right) & \text{- snow} \\ 100.77 - 8.34W & \text{- mixed precipitation} \\ Exp\left(4.605 - 0.062W^{0.58}\right) & \text{- rain} \end{cases} \quad (1)$$

Where:

W stands for the wind speed measured at one meter above ground in metres per second. Correction factors applied to daily precipitation measurements are the inverse of the calculated gauge catch ratios. Classification of precipitation into rain, mixed rain/snow, and snow was based on the relative humidity (*RH*) required to keep the flake frozen at a given temperature. The melt line *RH* was computed using the following standard equation:

$$RH = 9.5\,Exp\left(\frac{-17.27\,T_c}{T_c + 238.3}\right)\left(10.5 - T_c\right)\ \% \quad (2)$$

Where:

T_c denotes the temperature in degree Celsius. Precipitation data prior and after calculated corrections a summarised on a monthly basis in Table 2. Note that the precipitation corrections are relatively minor for periods characterised by rain events. However, these corrections are relatively significant for snow events.

Table 2 Precipitation and air temperature – based on 2000 to 2009 on-site data

Month	Precip. (mm)	Corrected Precip. (mm)	T_{avg} (°C)	Month	Precip. (mm)	Corrected Precip. (mm)	T_{avg} (°C)
Jan	35	74	-4.6	Jul	8	8	22.7
Feb	37	80	-1.6	Aug	9	10	21.0
Mar	28	58	1.8	Sep	13	17	16.2
Apr	40	70	4.5	Oct	26	40	7.4
May	27	34	11.4	Nov	27	48	3.9
Jun	15	17	15.9	Dec	40	86	-4.3
				Total	304	542	7.9

Most of the precipitation at the Rain Mine falls during winter and early spring (October–April), averaging 84% of all precipitation and ranging from 77 to 95%. Snow surveys conducted for the site have measured high snowpack accumulation and snow water equivalence, with snow depths up to 2.44 m. The monthly snow water equivalent for March 2010 was 74 mm, which equates to approximately 78% of precipitation from October through March. Snowmelt is most evident based on the survey data in April and May, consistent with the average daily temperature rising above 0°C in late March.

2.2 Microclimate effects

Microclimate is important for this site and needs to be considered in the assessment of cover performance. It is well established that for sites with significant topographic variations, there can be large differences in the local microclimates. The elevations of the cover surface for the NWRDF range from approximately 6,455 ft amsl to 6,883 ft amsl, a difference of over 400 feet. The site has steeply sloped portions of the cover that make up a large fraction of the site area, thus climate data collected at a weather station may not be representative. In particular, the radiation exposure will be different for sloped surfaces with different orientation (aspect) towards the sun, despite them being located in the same general geographical area. Consequently, the evaporation potential may exhibit significant variation with changing topography (Weeks and Wilson, 2004, 2006).

Slope and aspect also affect wind and moisture distributions. Leeward slopes can experience less evaporation and greater snow pack accumulation due to drifting. Slopes can influence evaporation by affecting moisture distribution along the slope, as occurs when runoff from upslope areas reports to downslope areas increasing the potential for infiltration. This is particularly important for slopes with no interbenching or surface water conveyance structures, as with the NWRDF. The dominant wind frequency is from the southwest with the southwest winds also displaying the largest magnitudes. Consequently, the ET potential for the shielded NWRDF northeastern slopes will be reduced during this period. For the NWRDF, approximately 58% of the area is oriented between 0 and 90 degrees azimuth. These areas are also sloped at an average grade of steeper than 3(V):1(H), or 33%. Furthermore, the snow surveys have found that the greatest snowpack accumulation and persistence is along northeast facing slopes.

During initial design stages, potential evapotranspiration (PET) is often estimated based on the available climate maps and correlations with temperature data using Hargreaves and Samani (1982, 1985) methodology. For cases when a complete climate set is available, including cloud cover, solar radiation, humidity, wind speed, etc., the PET is typically evaluated based on the energy-balance and aerodynamic mass transfer relationships originally developed by Penman (1948) and subsequently improved by various authors (Allen et al., 1998; Walter et al., 2002). Ideally, PET would be estimated by measuring separate climate parameters for flat and south-facing areas, with additional measurements collected for the north-facing areas. Since the available radiation and temperature data were collected by a single set of probes located on a flat area, the approach of scaling radiation data proposed by Shapiro (1987) was adopted. The PET corrections resulting in values presented in Figure 1 were based on implementations adopted by Jordan (1991) and Flerchinger (2000).

Based on this analysis, approximately 59% of the NWRDF receives below average solar radiation with 39% of the NWRDF receiving approximately 70 to 90% of the average annual radiation recorded at the weather station (flat surface radiation). The areas receiving lower-than-average solar radiation are the steeper, leeward, northeast facing slopes, where snow drifting is more likely to occur.

2.3 Summary of climate assessment

The climate at this site presents challenges for the successful performance of an ET cover. First, the precipitation record used in the design did not consider gauge error, which resulted in an under-representation of average annual precipitation by 238 mm, or 44%. The error is critical for the winter months, during which precipitation falls as snow or mixed precipitation. On average 84% of average annual precipitation falls during October to April, and 78% on average falls as snow or mixed precipitation. The snowpack accumulation favours the north and northeast facing slopes due to the prevailing wind direction and the influence by slope and aspect on PET, which is lowest for the north and northeast facing slopes. Based on snow surveys and air temperature, snowmelt occurs in March and April, delivering significant stored water to the cover at time when vegetation is dormant or early in the growing season. For these climate conditions, the cover system must be able to store and subsequently release through ET potentially large quantities of precipitation to achieve the desired cover performance.

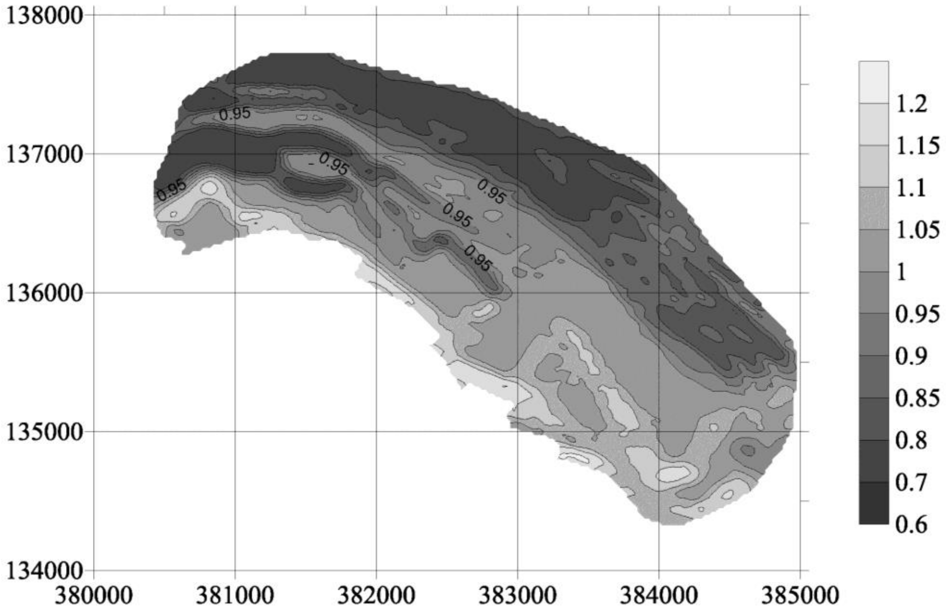

Figure 1 Calculated PET correction factor = actual PET/flat surface PET

3 Construction practices

The assessment included a detailed review of the borrow source characterisation studies and the Construction Quality Assessment (CQA) and Construction Quality Control (CQC) programs. Such programmes are necessary to ensure that construction activities and field decisions are consistent with design specifications or to alert the engineer to potential problems. The assessment of NWRDF CQA data as well as post-construction testing on test-pit samples found a number of discrepancies between the constructed NWRDF cover and the originally proposed design. For example, grain size analyses on collected samples of cover material indicate excessive amount of gravel material (up to 62% by weight) and fines contents well below the minimum design criterion. All tested cover material exhibited a fines content of less than 35% with approximately half of the samples containing less than 25% fines (defined as soil particles capable of passing the sieve opening of 0.075 mm).

Cover material was placed without compaction in order to facilitate the establishment of vegetation, despite a compaction specification in the design. Consequently, the average density of cover material is approximately 1,600 kg/m^3, or approximately 80% of the modified Proctor dry density. Laboratory permeability testing on cover materials prepared at their in situ densities resulted in an average permeability value of 2.2 x 10^{-6} m/sec, approximately three orders of magnitude higher than the average permeability of 3.3 x 10^{-9} m/sec determined for borrow samples during the design phase of the project. Subsequent in situ testing of the cover material yielded a mean permeability of approximately 4 x 10^{-6} m/sec, with measured values as high as 4.5 x 10^{-5} m/sec.

A test-pitting programme conducted after cover construction indicated high variability in both the vegetative layer and the cover material thickness. While the topsoil thickness ranged from 0.15 to 0.45 m (a minimum of 0.3 m was specified in the design), the thickness of cover material varied from 0.15 to 1.37 m with an average of 0.71 m (a minimum of 0.9 m was specified in the design). A prescribed cover thickness of 0.9 m or more was found in only 14% of the tested locations (in two of the fourteen tested locations).

Detailed regrading plans were not provided in the design; rather the design specified that all areas should be graded to drain at the discretion of the construction manager. As a result, isolated areas were not re-graded prior to cover placement resulting in flat slopes and closed basins capable of ponding water.

In addition, the applied seed mix included only deciduous species without subsequent establishment of evergreen deep-rooted vegetation. Consequently, the cover provides little or no transpiration potential during winter months and spring snowmelt periods, while more than 70% of precipitation is applied during those times (the original cover design specified the establishment of juniper trees).

The assessment of construction practices, stand of vegetation, cover geometry, and hydraulic properties of cover materials indicates potentially deficient ET cover performance due to compromised storage potential and the existence of conditions amenable to preferential flow, e.g. uncompacted covers are more likely to exhibit larger number of discrete flow conduits (fissures and fractures) than compacted materials placed in controlled lifts with a specified energy input.

4 Infiltration analysis

Cover performance can be inferred by the measured flow rates for the collection system. An infiltration analysis was conducted to determine if the measured soil moisture profiles, corrected climate inputs, and constructed cover properties are consistent with the outflow measurements from the collection system.

4.1 Analysis of soil moisture sensors

In climates with significant winter precipitation (Table 4), ET cover performance is often compromised as the amount of infiltration exceeds the cover storage capacity during periods when vegetation is dormant. In cold climates, snowpack accumulation and freezing ground conditions may inhibit infiltration during winter months with the majority of infiltration often occurring during the spring snowmelt period. Under these conditions, the ET cover performance may be estimated by applying the mass conservation principle, rather than utilising a more general approach based on Richard's equation.

The volume of water in a soil column element with the cross-sectional area, *A*, and the height, Δz, can be expressed as:

$$V_w = \int_0^{\Delta z} \theta(z)\,A\,dz \tag{3}$$

Where:

$\theta(z)$ is the volumetric moisture content as a function of depth. Denoting hydraulic head values at the top and the bottom of the column as h_1 and h_2, one can write the expression for the velocity through the soil column (note that the minus sign signifies that the flow of water is in the direction opposite of the increasing hydraulic gradient) as follows:

$$v_w = -k\,i = -k\,\frac{h_2 - h_1}{\Delta z} = -k\,\frac{h_{2e} + h_{2p} - h_{1e} - h_{1p}}{\Delta z} = -k\left(\frac{h_{2p} - h_{1p}}{\Delta z} - 1\right) \tag{4}$$

Where:

i	=	hydraulic gradient.
k	=	hydraulic conductivity.
h_{1e}	=	elevation head at the top of the column.
h_{1p}	=	pressure head at the top of the column.
h_{2e}	=	elevation head at the bottom of the column ($h_{2e} = h_{1e} - \Delta z$).
h_{2p}	=	pressure head at the bottom of the column.

Typically, the pressure head is negative for unsaturated flows through the ET cover. Hence, the expression for the Darcy's velocity through the unsaturated soil column is often expressed as:

$$v_w = -k(\theta_{avg})\left[\frac{-\left(h_{2c} - h_{1c}\right)}{\Delta z} - 1\right] = k(\theta_{avg})\left[\frac{h_{2c} - h_{1c}}{\Delta z} + 1\right] \tag{5}$$

Where:

h_{1c} = capillary head at the top of the column (h_{1c}= -h_{1p}).

h_{2c} = capillary head at the bottom of the column.

Assuming the wetting of the soil profile, one can compute the velocity as:

$$v_w = \frac{\Delta V_w}{A \Delta t} = \frac{V_{w2} - V_{w1}}{A(t_2 - t_1)} \tag{6}$$

Where:

V_{w1} and V_{w2} denote volume of water at times t_1 and t_2.

The Instantaneous Profile Method in this case effectively disregards the outflow velocity (Fredlund and Rahardjo, 1993), i.e. the method assumes that the outflow velocity is significantly smaller than the inflow velocity (outflow velocity is effectively equal to zero). For the vast majority of soils, this assumption is well justified as the unsaturated permeability often decreases by several orders of magnitude over a relatively small range of moisture contents.

Infiltration estimates presented in this study were based on the collected moisture profile readings at nine moisture monitoring stations (RMMS-1 to RMMS-9), each station containing five moisture monitoring sensors (EC-5 and EC-TM sensors manufactured by Decagon Devices, Inc.) at various depths. Note that calculations based on Equation (6) are an effective simplification of the Instantaneous Profile Method because the suction quantities are never introduced to calculate unsaturated hydraulic conductivities. Therefore, this Simplified Instantaneous Profile Method (SIPM) was utilised to determine NWRDF drainage for a subset of the potential winter/spring recharge periods, with an emphasis on the interval from 1 March to 30 April 2009. During this period, a large portion of the NWRDF surface was covered with snow and the vegetation was mostly dormant (germination of the native plants in 2009 likely started after 18 April 2009 based on the temperature records). Therefore, the loss of moisture within the soil profile was caused by deep drainage (deep percolation) rather than evaporation.

Calculation was performed in daily increments with the effective velocity calculated as (see Equation 6):

$$v_w = \frac{\left[(\theta_1 + \theta_2)_{t_2} - (\theta_1 + \theta_2)_{t_1}\right]\Delta z}{(t_2 - t_1)} \tag{7}$$

Where:

θ_1 = moisture content corresponding to the top of sensor interval.

θ_2 = moisture content corresponding to the bottom of the sensor interval.

The effective drainage/drying of the soil volume defined by sensors 1 (top) and 2 (bottom) was calculated as:

$$v_{eff,drainage} = \begin{cases} 0 & \text{for } v_w \geq 0 \\ -v_w & \text{for } v_w < 0 \end{cases} \tag{8}$$

Similarly, the effective wetting/infiltration of the soil column was calculated as:

$$v_{eff,wetting} = \begin{cases} v_w & \text{for } v_w \geq 0 \\ 0 & \text{for } v_w < 0 \end{cases} \tag{9}$$

Table 3 summarises drainage values based on the SIPM approach.

Table 3 SIPM drainage values from 1 March to 30 April 2009

Sensor ID	Infiltration Rate (m/sec)	Area (ha)	Flux (m^3/day)	Analysis Duration (day)	Effective Infiltration (mm)
1	5.4×10^{-9}	5	23	61	28
2	1.3×10^{-8}	1	8	61	70
3	1.9×10^{-9}	10	16	61	10
4	3.8×10^{-9}	7	23	61	20
5	5.2×10^{-9}	8	35	61	27
6	7.0×10^{-9}	8	47	61	37
7	9.8×10^{-9}	8	66	61	52
8	5.8×10^{-9}	14	68	61	30
9	5.0×10^{-9}	14	59	61	26
Total	5.5×10^{-9}	73	346	61	29

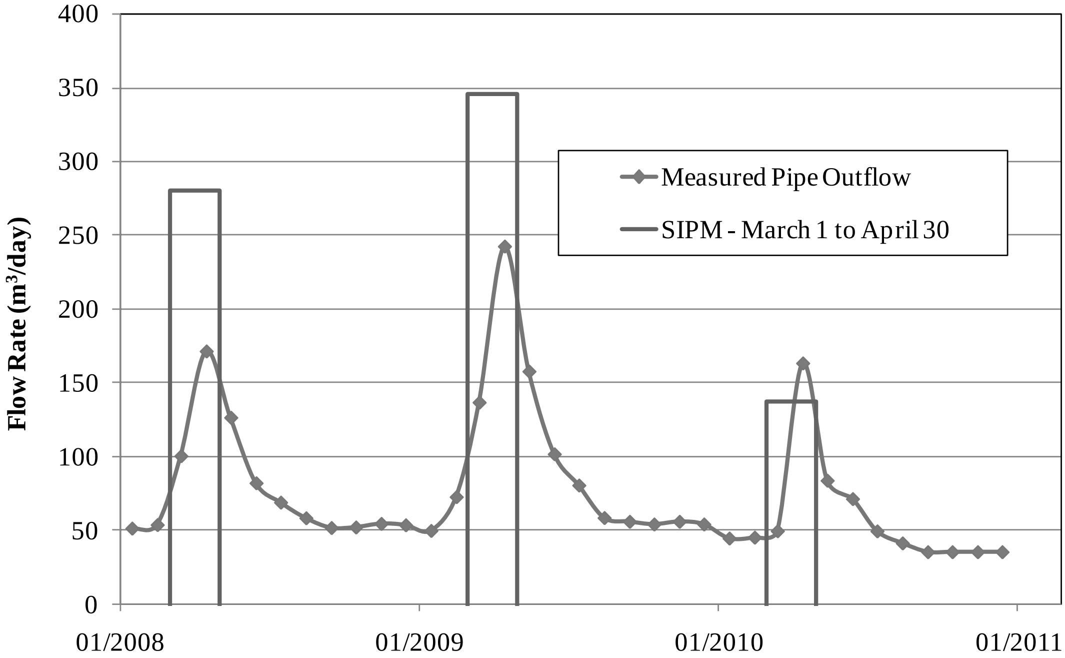

Figure 2 Measured outflows and peak seasonal infiltration predicted by SIPM

Results in Figure 2 demonstrate that the SIPM is capable of providing reasonable qualitative infiltration estimates, and the method may be used to estimate the magnitude of spring infiltration into waste rock during snowmelt and for other similar conditions during which the soil surface layer remains relatively wet and/or is covered with snow. In addition, the SIPM results confirm the assumption that seasonal seepage through the constructed ET cover is a major contributor to measured NWRDF outflows.

4.2 Numerical modelling

While the SIPM model provides a useful tool in predicting infiltration rates during peak periods (i.e. during the spring snowmelt), a model capable of predicting seepage flows throughout the year is required for additional design purposes, such as sizing for water treatment facilities. Two numerical models were developed to assess the NWRDF cover performance: 1) Lower Bound (LB) model estimating percolation rates during wet years, and 2) Upper Bound (UB) model estimating percolation rates during periods with lower than average and average precipitation. For a defined set of input parameters, it was noted that a single model was sufficient to provide a reasonable agreement with the estimated seepage rates for climate conditions characterised by lower precipitation and the corresponding lower seepage rates. This UB model, however, over-predicts the percolation during wet years. Similarly, the LB model provides favourable agreement with measured seepage rates (collected pipe outflows) for wet periods but under-predicts percolation rates for average and dry years. Results from the calibrated numerical models are compared with measured outflows in Figure 3.

Figure 3 demonstrates the ability of soil-atmosphere seepage models to bracket the range and capture the seasonal variations of the observed NWRDF outflows. Hence, the soil-atmosphere model results confirm that percolation through the constructed ET cover is a major contributor to NWRDF outflows.

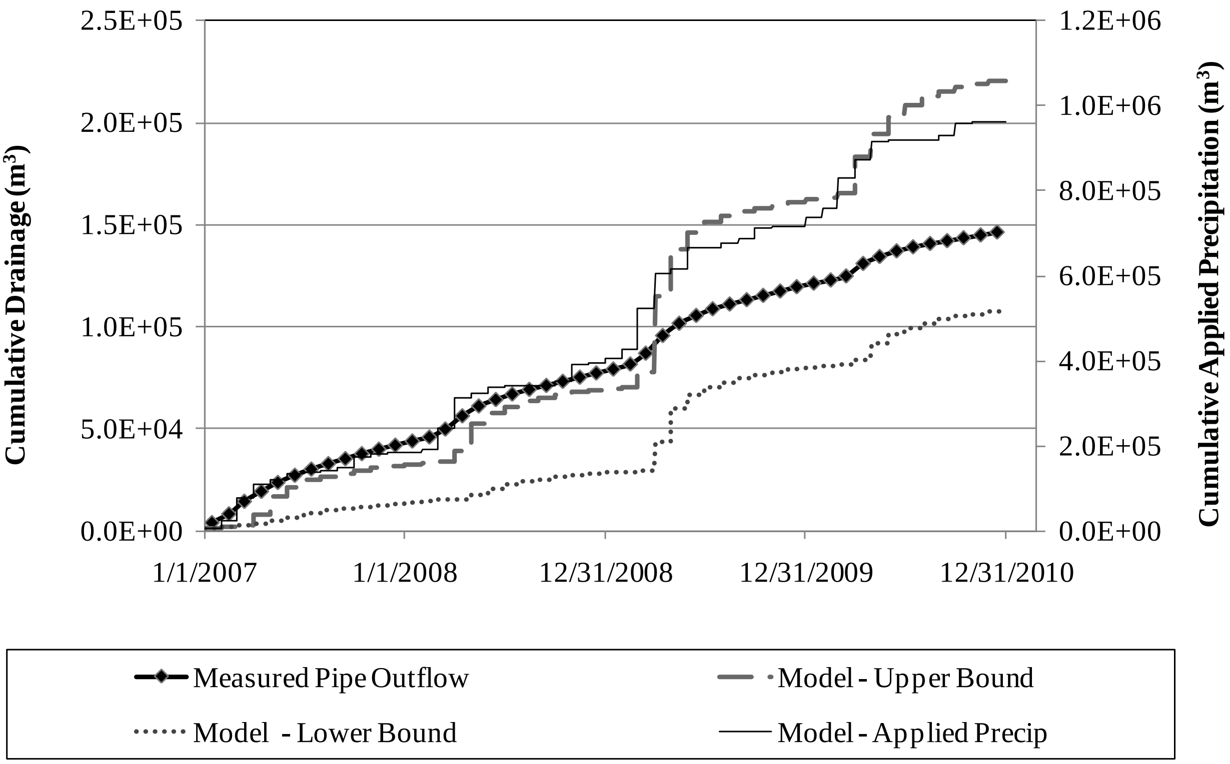

Figure 3 Measured pipe outflows and predicted cumulative infiltration

5 Conclusions

This paper presents an assessment of an ET cover in a high elevation, semi-desert environment in Nevada. Although the design evaluation determined that a monolithic ET cover was suitable, measured performance indicated the need for a more detailed evaluation of cover performance. The poor performance of the cover to control infiltration is a result of several issues, which upon study provide some key guidance for the design and performance prediction of similar cover systems in these environments.

Measured precipitation may not accurately represent actual precipitation. Measurement error needs to be identified and corrections applied to the extent practical. For the Rain Mine, the gauge errors were significant, with the largest errors for winter and spring precipitation, which accounts for 84% of the annual total. Failure to accurately consider the amount and seasonal distribution of precipitation in the design and prediction of cover performance – particularly ET cover systems – can lead to a failure of the cover to meet infiltration performance objectives.

The NWRDF provides an important lesson in the potential role of microclimates on cover performance. Reduced PET occurs along the predominantly of north and north-east facing slopes, resulting in below average solar radiation for 59% of the NWRDF. These areas are also more prone to snowpack accumulation due to the prevailing wind direction and the large percentage of precipitation that falls as snow. When combined with the long slope lengths from the design, the potential for infiltration through the cover is greatest along these slopes. Therefore, a single cover design may not be appropriate for the entire facility.

The NWRDF case study underscores the importance of the CQA programme to ensure that construction activities and field decisions are consistent with design specifications or to alert the engineer to potential problems. The program implemented at the NWRDF failed to accomplish this objective resulting in critical differences between the constructed cover and the original designs, including cover thickness, borrow material characteristics, compaction, and vegetation community.

Soil moisture sensor data can be interpreted based on the mass conservations principle adopted in the instantaneous profile method. The SIPM analysis can be used in periods of low PET to directly compute infiltration through an ET cover. The SIPM relies solely on the soil moisture sensor data, thereby avoiding sources of error in laboratory testing and the need for numerical soil-atmosphere modelling. The method is applied to actual data from a high elevation desert environment in northern Nevada using installed moisture monitoring probes. The results compare favourably with the measured outflows from the drainage collection system and from more advanced predictions using numerical modelling.

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