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Water balance modeling of preferential flow in waste rock materials

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ABSTRACT

For waste rock with a high percentage of gravel particles the spatial distribution of the gravel particles can create macropores and discontinuity in the pore-size distribution. Consequently, many studies have shown that preferential flow may dominate unsaturated flow conditions in waste rock in some cases and that two or more functions may be needed to describe the unsaturated flow in waste rock materials. Most unsaturated flow models use the Richards' equation to predict unsaturated flow behavior in soil matrix, and cannot simulate preferential flow through macropores. Alternatively, MACRO 5.1, a dual-permeability model, uses a kinematic wave equation to describe water flow in macropores, while the Richards' equation is used for water flow in micropores (soil matrix).

In order to simulate the potential for preferential flow, MACRO 5.1 was used to predict unsaturated flow behavior in a planned waste rock facility at a proposed mine in northwestern Pakistan. The site is extremely dry with a ratio of annual potential evaporation (3900 mm) to precipitation (32 mm) of 120. For this kind of climate region, if a model only involves matrix flow mechanism and neglects preferential flow, it would project unrealistic no deep percolation. The influence of waste rock dump geometry (area and thickness) on predicted percolation volumes exiting the base of the dump were also evaluated to predict wetting front arrival times and percolation rates.

The modeling results demonstrate that the large evaporative demand results in minimal deep percolation and a long delay from the time of waste rock dump placement to the beginning of outflow from the dump. For the higher dump, outflow from the dump is predicted to begin 204 years after dump placement and reach a maximum outflow rate 612 years after placement. Outflow from the lower dump is predicted to begin 82 years after dump placement and attain its maximum outflow rate 490 years after placement.

Keywords: Unsaturated flow, waste rock, macropore, dual-permeability model, kinematic wave equation

EXHIBIT

17

INTRODUCTION

For waste rock with a high percentage of gravel particles the spatial distribution of the gravel particles can create macropores and discontinuity in the pore-size distribution (Milczarek et al., 2006; Al-Yahyai et al., 2006; Poulsen, 2002). Therefore, the moisture retention characteristic relationship between water content and soil water pressure potential and relationship between unsaturated hydraulic conductivity and water content ($K(\theta)$) or soil water potential ($K(\psi)$) may require two or more functions to describe the unsaturated hydraulic properties for the entire pore-size distribution.

Most unsaturated flow models use the Richards' equation to predict unsaturated flow behavior, such as HYDRUS (Simunek et al., 1998), UNSAT-H (Fayer, 2000), SWIM (Verburg et al., 1996), and VADOSE/W (GEO-SLOPE International Limited, 2002). However, for gravelly materials the existence of macropores can lead to macropore flow (preferential flow), which cannot be simulated by the Richards' equation. For arid climates that experience periodic high intensity precipitation events, neglecting preferential flow may result in large under predictions of deep percolation. For porous media containing macropores, Larsbo et al. (2005) proposed a dual-permeability model (MACRO 5.1), where a kinematic wave equation (Germann, 1985) is employed to describe the water flow in macro-pores, while the Richards' equation is used for the water flow in micropores (soil matrix).

In order to account for macropore flow in a proposed waste rock facility in arid northwestern Pakistan, the one-dimensional dual-permeability model MACRO 5.1 was used to predict unsaturated flow behavior in the unvegetated waste material. The simulations predicted wetting front arrival and deep percolation rates under conditions which account for evaporation and surface run-off. The influence of waste rock dump geometry (area and thickness) on predicted percolation volumes exiting the base of the dump were evaluated using the MACRO 5.1 model predicted wetting front arrival times and percolation rates.

METHODOLOGY

Model

MACRO 5.1 is a dual-permeability model, separating the total porosity into two separate flow components, micropores and macropores. Each flow domain is characterized by a degree of saturation, conductivity, and water flow rate. The two domain model describing water flow requires modifications to the traditional van Genuchten (1980) moisture retention curve (MRC) function. The modified van Genuchten MRC function of the soil matrix (micropores) is described by (Larsbo et al., 2005):

$$S = \frac{\theta_{mi} - \theta_r}{\theta_s^* - \theta_r} = (1 + |\alpha_{vg}\psi|^{n_{vg}})^{-m_{vg}} \tag{1}$$

where S is the effective soil water saturation. This equation assumes a fictitious saturated water content (θ_s*), which is defined in place of the saturated water content (θ_s), where $\theta_s^* \leq \theta_s$. θ_{mi} is the micropore water content and the remaining parameters are the same as that in the standard van

Genuchten equation; θ_r is the residual water content and α_{vg}, n_{vg}, and m_{vg} are fitting parameters related to pore-size distribution of the material (where m_{vg} is set equal to 1 - 1/n_{vg}).

The modified van Genuchten-Mualem equation utilized in MACRO 5.1 is in the form (Larsbo et al., 2005):

$$K_{mi} = K_b \left(\frac{S}{S_{(\theta b)}}\right)^l \left\{ \frac{1-(1-S^{1/m_{vg}})^{m_{vg}}}{1-(1-S_{(\theta_b)}{}^{1/m_{vg}})^{m_{vg}}} \right\}^2 , \ \theta \le \theta_b \tag{2}$$

where K_{mi} is the unsaturated hydraulic conductivity in the soil matrix, l is the tortuosity factor (assumed to be equal to 0.5 (Mualem, 1976)), $S_{(\theta b)}$ is the effective water saturation at the break point between macro- and microporosity (θ_b), and K_b is the hydraulic conductivity at θ_b (K_b = saturated hydraulic conductivity for soil matrix). The other parameters are the same as in equation 1.

Larsbo et al. (2005) define the hydraulic conductivity function for the macropores (K_{ma}) as a simple power law of the macropore degree of saturation (S_{ma}):

$$K_{ma} = K_{s(ma)} S_{ma}{}^{n^*} = (K_s - K_b) S_{ma}{}^{n^*} , \ \theta > \theta_b \tag{3}$$

where $K_{s(ma)}$ is the saturated hydraulic conductivity of the macropores, n^* is a "kinematic" exponent reflecting macropore size distribution and tortuosity, and K_s is the total saturated hydraulic conductivity.

Model Domain

The total depth of the domain was 8 m, conservatively below the "zero flux plane", which is an imaginary plane above which water can move upward due to evaporation but below which water moves downward only. Node spacing near the surface was made smaller (e.g. 0.3 cm) to facilitate an accurate solution under conditions of large and rapid changes of soil water pressure potential in response to evaporation and precipitation. Node spacing at other depths were set to be progressively larger (e.g. 0.4 to 4 cm) to reduce model run time.

Hydraulic Properties

Average waste rock material hydraulic parameters were developed from a database of waste rock material saturated hydraulic conductivity and moisture retention data compiled by GeoSystems Analysis, Inc (GSA). The materials were chosen to represent coarse, high permeability material in order to provide a conservative estimate of percolation. Geometric mean K_s and van Genuchten (1980) hydraulic properties used for the simulation are provided in Table 1.

The soil water pressure potential at which macropores and the soil matrix partition (ψ_b) varies in the literature. Schaap (2005) suggested $0 > \psi_b \ge -4$ cm, while Jarvis (2007) reported the range $-6 \ge \psi_b \ge -10$ cm based on his literature review. At matric potentials above the partition point (less negative), K(θ) can increase by up to several orders of magnitude (e.g., Poulsen et al., 2002). To error on the side of greater macropore flow, a conservative ψ_b of -10 cm was assigned.

The hydraulic parameters needed to describe micro- and macropore flows as defined in equations 1 through 3 are presented in Table 1. K_b (soil matrix saturated hydraulic conductivity) applied in equation 2 and the kinematic exponent (n*) listed in equation 3 were established from previous work in which equations 1 through 3 were fit to moisture retention and unsaturated hydraulic conductivity measurements made on two waste rock samples (Keller et al., 2009). Based on the similarity of the fine earth fraction (<4.75 mm) for the Keller et al. (2009) sample and the database samples, K_b was assigned as the estimated unsaturated hydraulic conductivity of the Keller et al. (2009) sample at -10 cm (1.06×10^{-4} cm/sec) and n* was set equal to 2.4, the average of the Keller et al. (2009) measured values of 2.0 and 2.8. The modified van Genuchten soil water retention function and hydraulic conductivity function used in the simulations are presented on Figure 1.

Table 1 Waste rock material van Genuchten parameters

K_s (cm/sec)	α (cm^{-1})	n (-)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	Ψ_b (-cm)	θ_b (cm^3/cm^3)	K_b (cm/sec)	n* (-)
4.50×10^{-2}	0.131	1.911	0.048	0.315	10	0.215	1.06×10^{-4}	2.4

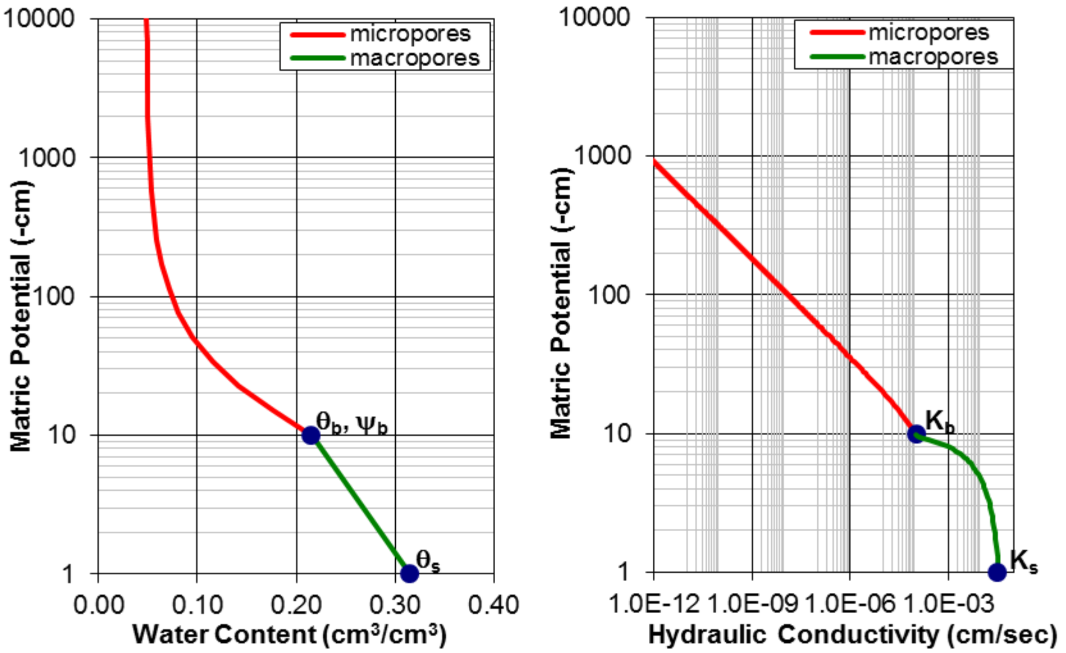

Figure 1 van Genuchten soil water retention function (left) and hydraulic conductivity function (right)

Climate Data

Synthetic daily 100-year precipitation data for the project site developed from historical climate records was used as the precipitation data input for the simulation. For the synthetic 100-year dataset, the maximum daily rainfall was 72 mm and the maximum annual rainfall was 192 mm. Hourly rainfall data was generated from daily rainfall data by assigning rainfall durations from one to twenty-four hours for each day and dividing the daily rainfall amount by the assigned rainfall duration. Rainfall durations were assigned using a random generator with the assumption of an even distribution of rainfall durations. Hourly rainfall intensities ranged from a high of 15 mm to less than 1 mm, with the majority of hourly rainfall intensities being less than 1 mm. This range of rainfall intensities is similar to measured rainfall intensities, which ranged from 29.3 mm/hr to 0.9

mm/hr for rainfall durations of 1 to 24 hours and reoccurrence intervals of 5 to 1000 years. The calculated hourly rainfall for each day was applied beginning at the first hour of the day and applied at each subsequent hour until the daily rainfall amount was satisfied.

Average daily temperature (maximum and minimum) and potential evapotranspiration (PET) required as model input were derived from a 3.25 year temperature and PET data record collected at the project site weather station. The applied sinusoidal annual temperature and PET relationships are shown on Figure 2.

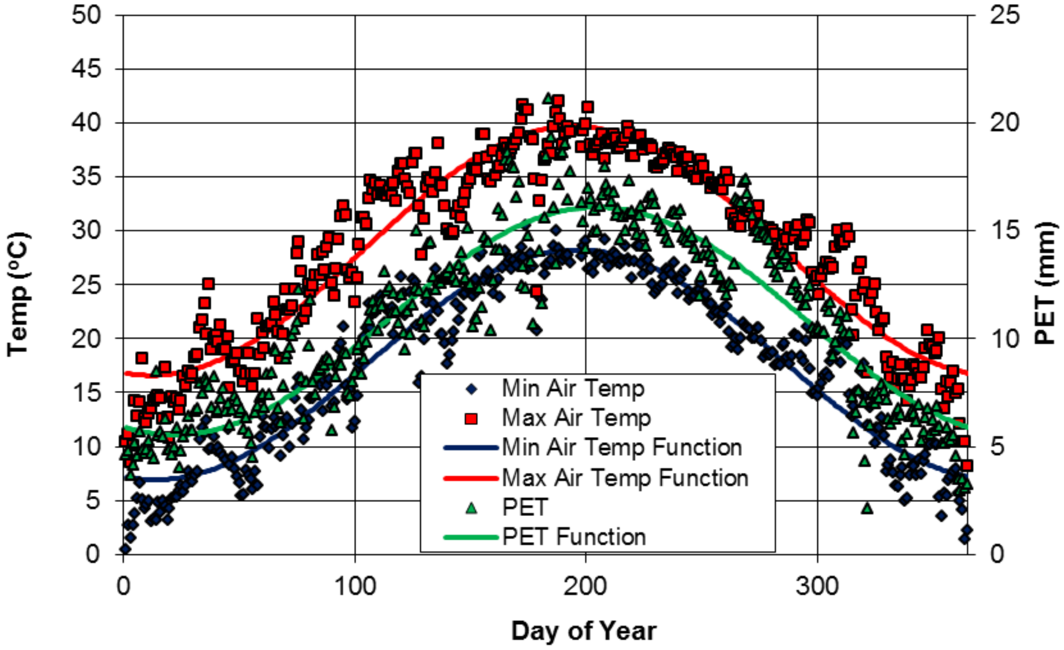

Figure 2 Measured average minimum and maximum air temperature and PET and sinusoidal functions applied in the model

Runoff Estimate

MACRO 5.1 does not model runoff but instead assumes all precipitation either evaporates or infiltrates into the soil micro- and macropores. Not considering runoff could potentially lead to a significant over prediction of deep percolation. As an alternative, the SCS runoff curve number method (USDA, 1986) was used to estimate runoff. The SCS runoff curve number method provides an estimate of runoff depth (*RO*) using the empirical relationship:

$$RO = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5}$$

where P is rainfall and S is equal to $1000/CN - 10$. CN is the curve number whose major factors are hydrologic soil group, cover type, and surface treatment. CN values obtained from USDA (1986) for newly graded, nonvegetated areas ranged from 77 for soils with high infiltration rates (hydrologic soil group A) to 91 for soils with low infiltration rates (hydrological soil group C). A CN value of 77 was assigned considering that the waste rock material will be relatively coarse. Estimated daily runoff was subtracted from the precipitation for that day and this modified precipitation amount (or net precipitation) was used as the daily precipitation input for the model.

Boundary and Initial Conditions

The upper boundary was set to allow evaporation while receiving hourly precipitation input. The lower boundary was set to allow free drainage (unit gradient flow). Given the arid conditions at the project site, it was assumed that the waste rock will be laid down at a very dry moisture content equivalent to a pressure head of -40,000 cm (approximating the permanent wilting point for desert plants), which is equivalent to a water content of 0.049 cm^3/cm^3. This initial water content was uniformly applied over the model domain.

Waste Rock Dump Geometry and Estimated Waste Rock Dump Outflow

The design of both dumps consists of three lifts. In order to estimate infiltration into, and outflow from the entire waste rock dump, each dump was mimicked by three columns. Each column represented the cumulative height (L) of the dump bench and the surface area (A) of the bench, as depicted on Figure 3. Column (i.e. bench) height and surface area and total dump waste rock volume are provided in Table 2. The column representation of the waste rock piles was relatively accurate, though slightly overestimated the design volume by 4 to 5 percent.

Table 2 Column (bench) height, surface area, and total dump waste rock volume

Dump	Column	Height (m)	Area (m^2)	Waste Rock Volume (m^3)
Higher	1	60	2,085,224	2,609,465,039
	2	120	1,833,968	
	3	180	12,579,308	
Lower	1	24	1,075,843	390,921,729
	2	84	1,048,152	
	3	144	1,924,005	

The model predicted average deep percolation rate and average water content increase at 8 m below ground surface (bgs) was then used to calculate the cumulative percolation volumes that exit the bottom of the dump. The percolation volume (Q) exiting the dump as a function of time was calculated and summed using:

$$Q(t) = \sum_{i=1}^{n+1} Q_i(t) = \sum_{i=1}^{n+1} \cdot q_i(t) \cdot A_i \qquad (6)$$

where t is time, q is the model predicted deep percolation rate at the bottom of column i, and A is the area of the dump with a thickness equal to column i.

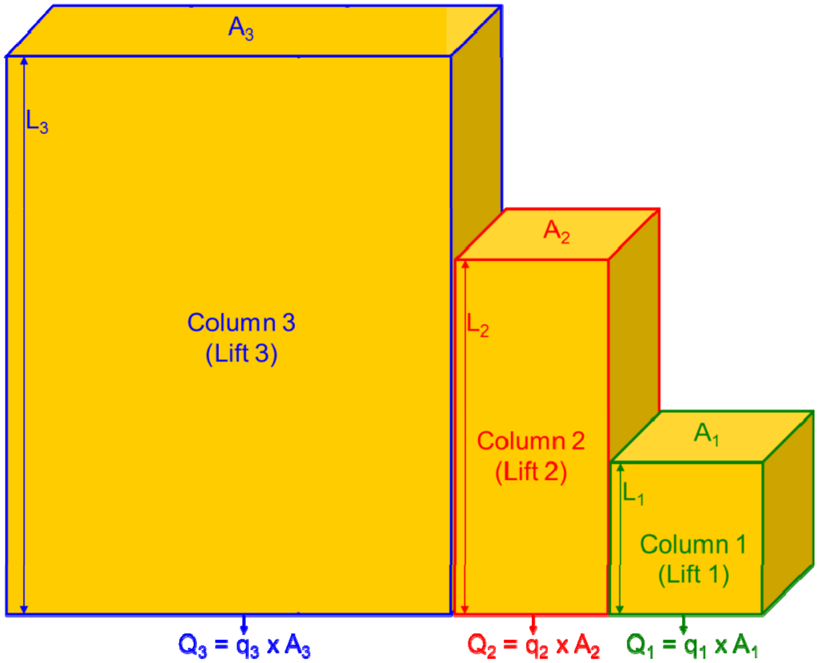

Figure 3 Hypothetical dump geometry consisting of three column heights

RESULTS AND DISCUSSION

Simulation of Waste Rock 100-Year Water Balance

The 100-year model predicted deep percolation, defined as the predicted percolation at 8 m bgs, and water content at 8 m bgs are presented on Figure 4. The simulated water balance is presented in Table 3. The large evaporative demand of the arid climate results in evaporation of the majority of precipitation (70%). Twenty percent of precipitation is predicted to become deep percolation with the remaining 10% of precipitation mass going to runoff or storage.

Arrival of the leading edge of the wetting front at 8 m bgs occurs at approximately 20 years as depicted by a sharp increase in water content (Figure 4). There is an approximate 4 year lag time before first arrival of the wetting front and the beginning of deep percolation, during which time the water content increases until reaching the water holding capacity of the waste rock material. After deep percolation begins, moisture content and percolation rate display moderate perturbations in response to arrival of water pulses stemming from larger precipitation years. From the onset of deep percolation to simulation year 100 the average deep percolation rate is 8.5 mm/yr (2.7×10^{-8} cm/s). The average water content during this same time period is 0.078 cm^3/cm^3, representing a 0.029 cm^3/cm^3 increase from initial water content conditions.

Table 3 Model predicted 100-year water mass balance at 8 m bgs

Total Precip (mm)	Total Runoff		Storage		Total Evaporation		Total Percolation	
	mm	% Precip	mm	% Precip	mm	% Precip	mm	% Precip
3191	117	4%	186	6%	2218	70%	654	20%

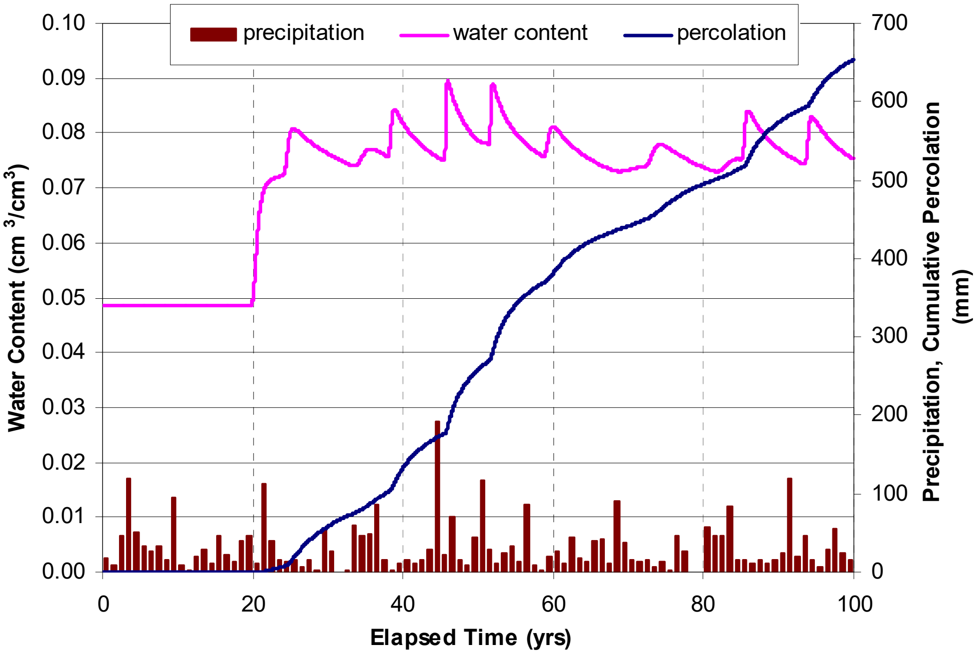

Figure 4 Precipitation and model predicted water content and percolation at 8 m bgs

Predicted Long-Term Outflow Volumes for the Waste Rock Dumps

Long-term percolation volumes from the base of the higher dump and lower dump waste rock columns were estimated from the model predicted average deep percolation and associated change in water content at 8 m bgs. Using a 60 m waste rock column as an example, to increase the waste rock water content by 0.029 cm^3/cm^3, such that deep percolation can occur, is equivalent to adding 1.74 m of water to the 60 m column. Based on an estimated average deep percolation rate of 8.5 mm/yr, the addition of 1.74 m of deep percolation would take 204 years, at the end of which the average percolation rate at 60 m bgs will be 8.5 mm/yr. This calculation was performed for each column and cumulative dump outflow calculated using the profile surface area and Equation 6. Like the model simulations, the calculation of long-term dump outflow assumes one-dimensional flow under homogeneous material conditions. The calculation also assumes that the 100-year synthetic climate record used in the simulation continues for subsequent centuries.

Figure 5 presents estimated cumulative dump outflow over a 750 year period, and dump outflow rates for the higher dump and lower dump. For the higher dump, outflow from the lowest 60 m lift at the average percolation rate is predicted to begin 204 years after placement of waste rock with outflow from the 120 m column 408 years after dump placement. Maximum drainage from the higher dump is predicted to begin 612 years after placement of the waste rock, at which time the dump outflow attains a predicted flow rate of 4.5 l/sec (71 gal/min). Outflow from the lower dump is predicted to begin 82 years after placement of waste rock from the lowest lift with a doubling of flow 286 years after dump placement in response to deep percolation from second lift. Maximum drainage from the lower dump is predicted to occur 490 years after dump placement, with the outflow rate reaching 1.1 l/sec (17 gal/min).

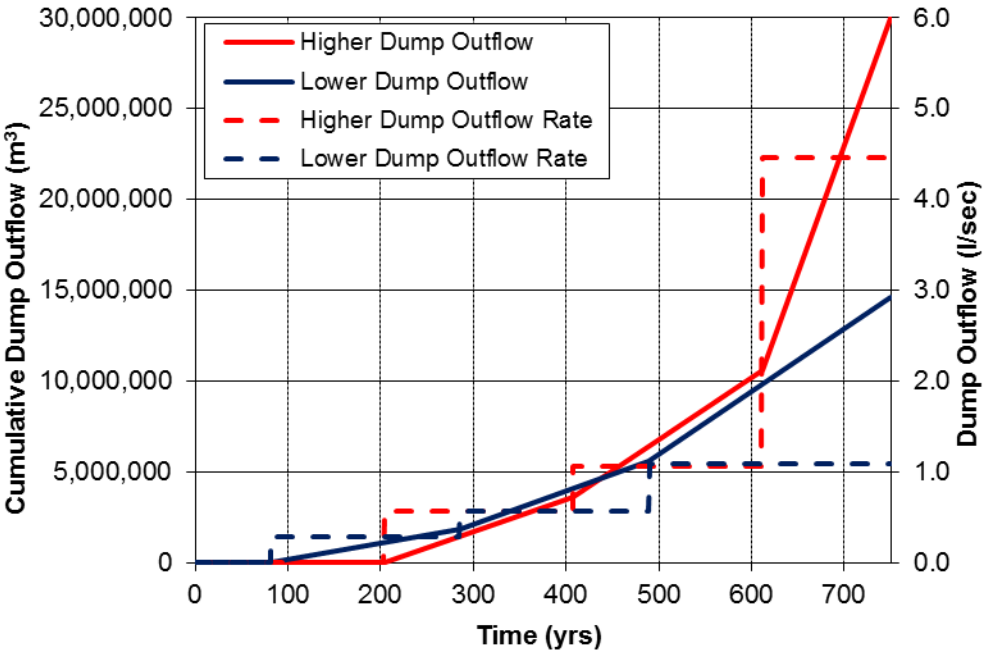

Figure 5 Predicted cumulative outflow and outflow rate.

CONCLUSION

The modeling results demonstrate that the large evaporative demand results in minimal deep percolation and a long delay from the time of waste rock dump placement to the beginning of outflow from the dump. An increase in water content from initial conditions (0.049 cm^3/cm^3) to 0.078 cm^3/cm^3 is predicted to occur before dump outflow begins. For the higher dump, outflow from the dump is predicted to begin 204 years after dump placement and reach a maximum outflow rate of 4.5 l/sec (71 gal/min) 612 years after placement. Outflow from the lower dump is predicted to begin 82 years after dump placement and attain its maximum outflow rate of 1.1 l/sec (17 gal/min) 490 years after placement.

The dump outflow predictions are conservative due to the hydraulic property assignment assuming homogeneous coarse, high permeability material. Finer grained waste rock material will reduce deep percolation due to greater moisture retention and evaporation and also increase total moisture retention. Furthermore, textural contrasts within waste rock can dominate flow processes by promoting lateral spreading, thereby increasing the time for deep percolation to occur at depth.

Other factors contributing to the predictions being conservative are:

- The analysis assigned a conservative value for the soil water pressure potential at which macropores and the soil matrix partition, resulting in greater macropore flow and less evaporation.
- Airflow within waste rock dumps can act to redistribute water and increase evaporative losses which would also decrease deep percolation.

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