Is the Water Balance of Your Waste Rock Pile Reliable? A framework for Improving Assessment of Water Inputs and Outputs for a Typical Storage Facility

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Abstract

Piles of waste rock placed during mining operations commonly increase from initial heights of several metres to more than 100 m during the life of a mine. Depending on geochemical properties of the waste rock, seepage emanating from the base of piles may require collection and treatment which necessitates adequate planning through development of reliable estimations of the waste rock pile water balance. Using a suite of numerical simulations of a synthetic waste rock pile, consideration of the pile's temporal development is shown to be an important factor on the distribution of water within the waste rock and the timing and magnitude of basal drainage from the pile for a range of climate regimes.

Keywords: Waste rock, numerical model, groundwater, seepage, HydroGeoSphere

Introduction

Waste rock is a ubiquitous mining waste often produced in large quantities as rock mass surrounding the orebody is extracted from the subsurface. The waste rock is frequently stored at the land surface in piles that may be more than 100 m in height and cover several square kilometres. These piles may be temporary features during active mining operations with the waste rock backfilled into open pits and underground workings at the cessation of mining; however, more often they become permanent fixtures in the landscape.

Mine development and closure require estimation of water quantities emanating from these waste rock piles, which, together with geochemical assessment of water-rock interactions within the waste, allow effective short- and long-term planning for water management. Hawley and Cunning (2017) provide generalized guidelines for application of numerical models to estimation of waste rock seepage. Nevertheless, Smith (2021) notes that current state-of-the-science numerical models are not widely applied in practice due to the inherent uncertainty in quantification of waste rock material properties resulting from the wide range in waste particle size (i.e., clay to large boulders) distributions. Moreover, where applied, the numerical models are generally limited to simulation of a static configuration of the piles that does not consider their transient development.

Here results are presented from one-dimensional numerical simulations for a synthetic waste rock pile that gradually increases in height throughout the mine life. One-dimensional simulations were conducted under the assumption that flow through the unsaturated waste rock is primarily vertical. The simulations were used to illustrate the influence of considering the temporal development of the waste rock pile on the pile's water balance.

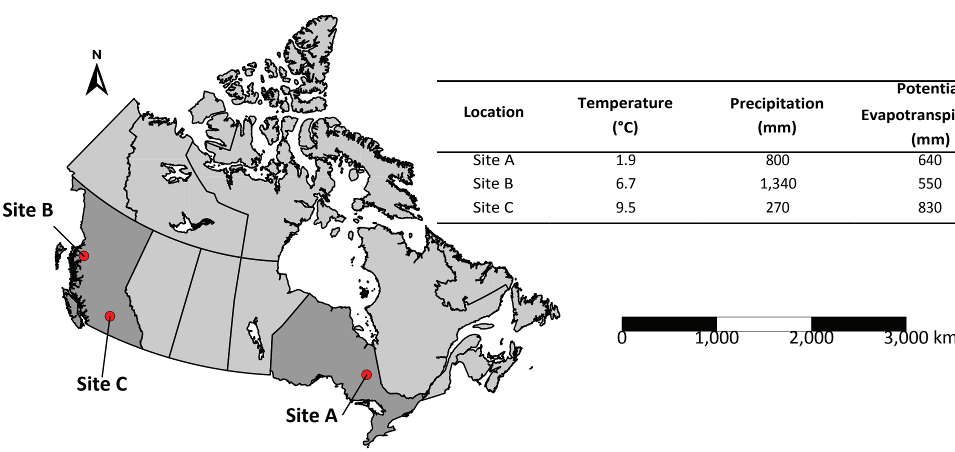
Methods

One-dimensional numerical simulations were conducted for a 100 m high waste rock pile using HydroGeoSphere (Aquanty 2024), a fully-integrated groundwater-surface water code. The simulations facilitated estimation of the partitioning of rain and snowmelt into infiltration, evapotranspiration, and overland flow at the land surface, changes in moisture storage within the subsurface, and drainage from the base of the waste rock using a physically-based approach. The numerical simulations were driven by daily atmospheric inputs of rain, snowmelt, and potential evapotranspiration derived from a range of climate regimes within Canada (Fig. 1) and marched forward in time using an adaptive time-stepping scheme that incorporated use of sub-daily timesteps as necessary.

The numerical simulations were conducted using 1 m^2 square column models extending vertically across the waste rock pile, and with a nominal ground surface slope of 1%. The vertical grid discretization ranged from 0.02 m at the top of the columns to 0.5 m at the base. Simulations were conducted for a period of 120 years (20 years active mining followed by 100 years closure) using either a static 100 m high column or a column that increased in height with 10 m of fresh (i.e., at low initial saturation) waste rock added every two years of active mining starting from an initial height of 10 m. At closure, a 1 m thick vegetated soil cover was placed at the surface.

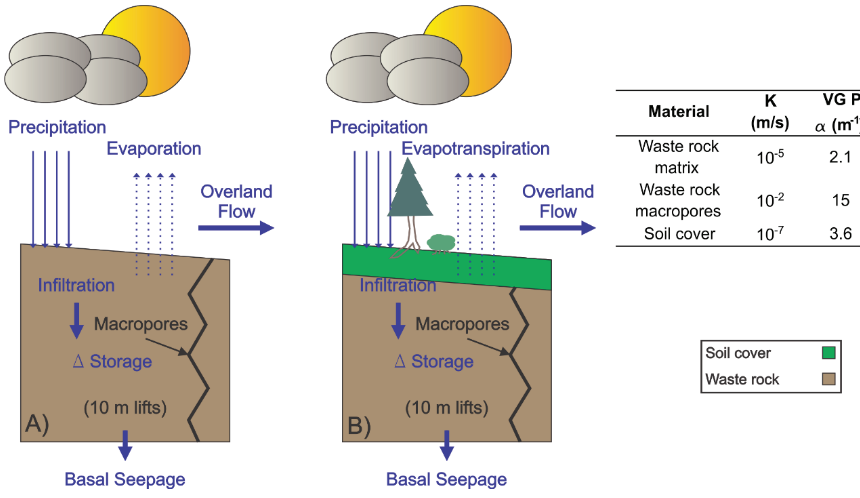
Simulations were conducted that considered the waste rock as both "soil-like" materials limited to matrix flow (e.g., commonly encountered in coal operations) or "rock-like" materials with matrix flow and macropore (i.e., dual domain) flow (e.g., characteristic of hard rock settings; Smith, 2021). Specified material properties (Fig. 2) for the simulations were specified based on values reported in the literature (e.g., Smith 2021; Broda *et al.* 2014; Carsel and Parrish 1988) and assumed to remain constant in time. A set of simulations was also conducted using the Site A climate dataset that assumed seasonal freezing due to sub-zero temperatures which may inhibit percolation of water through the waste rock (Langman *et al.* 2017) due to clogging of pores with ice. For these simulations, the hydraulic conductivity of near-surface materials (i.e., upper 1 m) was decreased by a factor of 10^4 from the base case values to represent ice formation with freezing and thawing specified to occur over a three-week period each year. However, changes in waste rock hydraulic conductivity due to freezing may be variable and dependent on a number of factors (e.g., climate, pore size and geometry, water content).

Boundary conditions applied to the surface of the model consisted of daily atmospheric conditions that included inflow from precipitation and snowmelt (calculated externally from the numerical model) and



Location	Temperature (°C)	Precipitation (mm)	Potential Evapotranspiration (mm)
Site A	1.9	800	640
Site B	6.7	1,340	550
Site C	9.5	270	830

***Figure 1** Map of Canada showing simulated locations and annual average (1990 – 2020) climate variables. Daily temperature and precipitation were obtained from Environment and Climate Change Canada datasets; potential evapotranspiration was estimated using ClimateNA (Wang* et al. *2023).*



Material	K (m/s)	VG Parameters α (m^{-1})	VG Parameters n (-)
Waste rock matrix	10^{-5}	2.1	1.5
Waste rock macropores	10^{-2}	15	1.4
Soil cover	10^{-7}	3.6	1.6

Figure 2 *Diagram showing simulated waste rock configuration for A) mining operations and B) closure along with model parameters (K is hydraulic conductivity, α and n are VG or van-Genuchten parameters).*

outflow from potential evapotranspiration and overland flow (Fig. 2). At the base of the model, seepage emanating from the waste rock was simulated using a free drainage boundary condition under the assumption that the water table in the native materials underlying the pile remains below the pile's base.

Results and Discussion

Fig. 3 provides an example of the simulated saturation within the waste rock at the end of the 20-year mining period. Above a depth of approximately 20 m, predicted saturations are relatively similar (i.e., within 0.05) for all scenarios reflecting recent climate forcings. Below 20 m depth, predicted saturations generally cluster into two groups defined by the temporal representation of the waste rock pile within the simulations. In the first group (Group A) that includes scenarios that represented the waste rock as a static pile at its full height, the predicted saturations are higher and more uniform with depth. In the second group (Group B) that considered the temporal development of the pile, the saturations are lower due to drainage reporting to the base of the pile earlier in the mine life (Table 1) and more variable with depth due to saturation disequilibrium between waste rock lifts.

Predicted water fluxes and saturation at the base of the waste rock using the Site A climate dataset are provided in Fig. 4 for the 120-year simulations, considering "soil-like" and "rock-like" waste rock, static and increasing pile height, and near-surface freezing. Predicted evapotranspiration and overland flow rates, controlled by recent near-surface conditions, are similar between scenarios. A wider range in water flux is predicted for basal drainage rates during mining operations and the initial years of closure, as the basal drainage is influenced by the cumulative evolution of the pile (e.g., volume of waste rock and available storage). For the climate prevalent in Site A, where precipitation is somewhat higher than potential evapotranspiration, consideration of the early stages of pile development where the

Table 1 *Predicted waste rock pile wet-up times.*

Climate Location	Predicted Wet-up Time (yr) Assuming Static Facility	Predicted Wet-up Time (yr) Assuming Transient Facility
Site A	15 to 19	2
Site B	9 to 10	<1
Site C	80 to >120	7 to 31

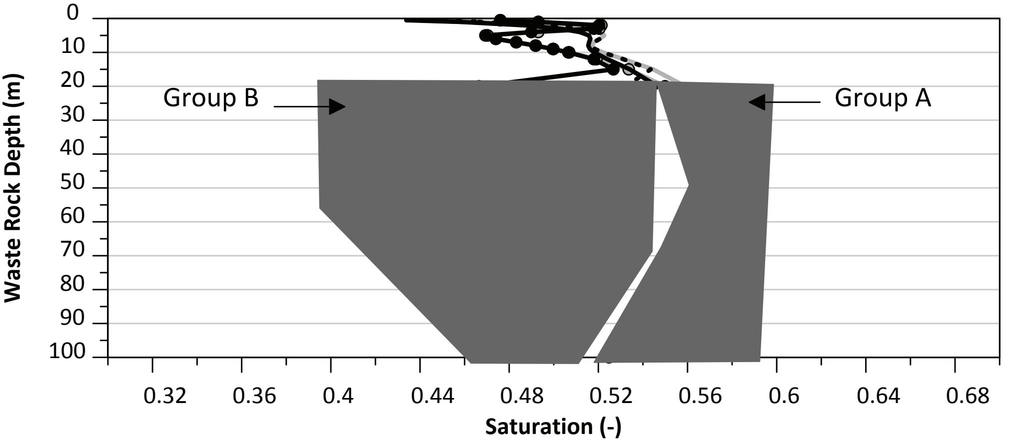


Figure 3 *Predicted saturation within the waste rock at the end of the 20-year mining period using the Site A climate data. Solid and dashed lines indicate respective "soil-like" and "rock-like" waste rock; grey and black lines indicate respective static height and increasing pile height, symbols indicate scenarios with seasonal near-surface freezing, and shaded areas are described in the text. Residual and initial saturation specified to be 0.08 and 0.18, respectively.*

waste rock is initially shorter with less available storage yields a wet-up time (i.e., time for drainage to start reporting at the base of the pile) of 2 years (Table 1). Representation of the waste rock pile with a static configuration (i.e., a more conventional analysis) results in longer predicted wet-up times of 15 to 19 years. For other climate regimes (Table 1), consideration of the pile's temporal development may alter predicted wet-up times on the order of years (e.g., wetter climate such as Site B) to decades (e.g., drier climates such as Site C).

Results of the simulations indicate that the temporal development of waste rock piles is an important factor that should be considered in waste rock seepage assessments where adequate information is available. The rate of pile development influences both the water distribution within the waste rock and the timing and magnitude of drainage rates at the base which may have important implications for mine developments due to costs associated with storage and treatment of waste rock effluent.

Mine planning and operations may require a large number of scenarios to be evaluated to address variants in mine development schedules and permitting requirements. Furthermore, extensive sensitivity analyses of predicted seepage quantities are commonly needed to adequately account for uncertainty in waste rock properties and climate variability. Nevertheless, the assessments are relatively efficient to conduct, particularly in a one-dimensional framework, with computational times on the order of two to five hours on a standard desktop computer.

Conclusions

The temporal development of waste rock piles is an important factor that should be considered in seepage assessments, as the rate of development influences the distribution of water within the waste rock and the timing and magnitude of drainage at the base. One-dimensional simulations conducted using HydroGeoSphere were used to derive predictions for a range of scenarios and climate conditions; however, the simulations could be extended to two- and three-dimensions based on project requirements and available data.

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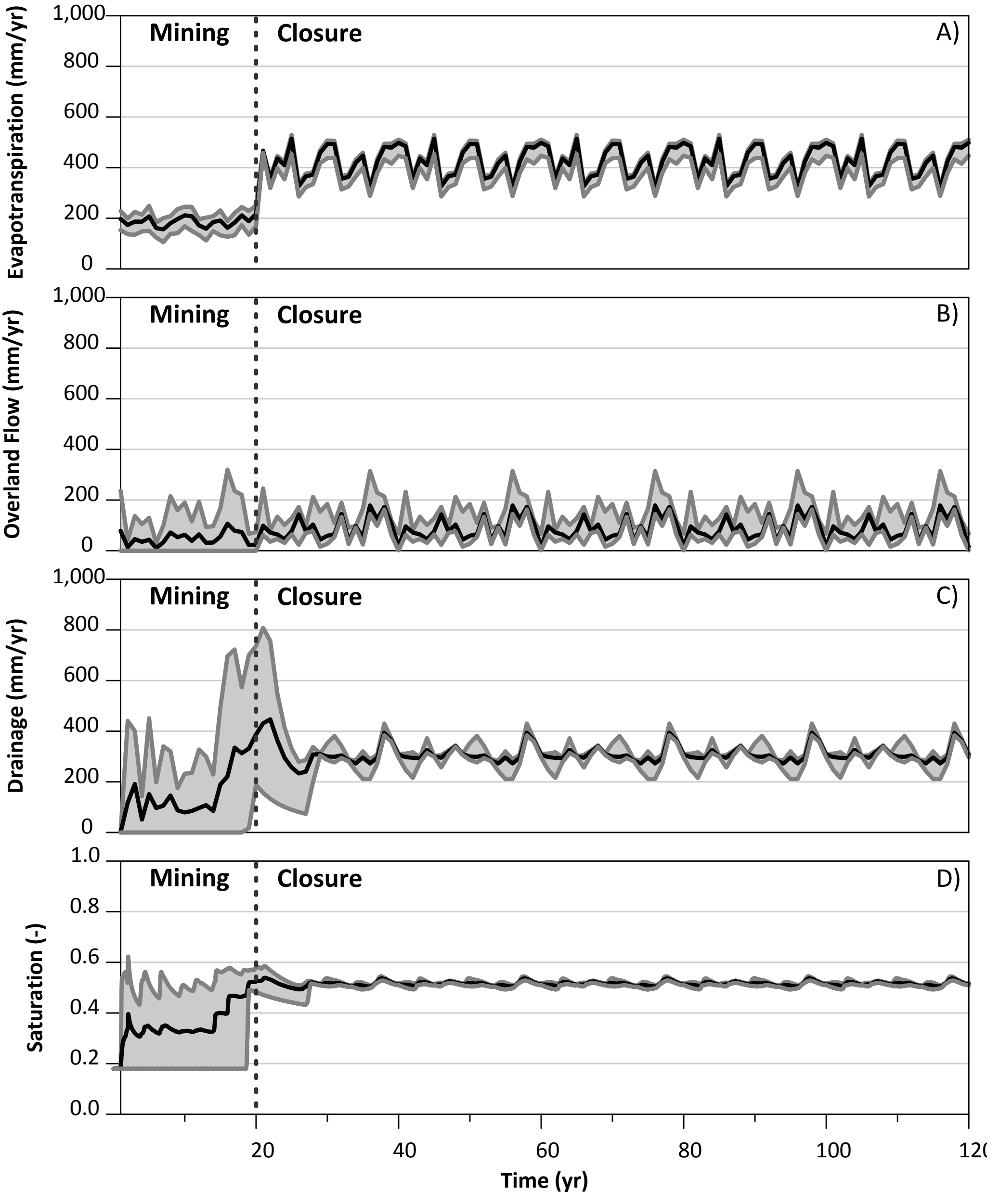

Figure 4 *Simulated range in A) annual evapotranspiration, B) annual overland flow, C) annual basal drainage, and D) daily saturation at the base of the waste rock pile using Site A climate data. Shaded area bounds minimum and maximum predictions, black line indicates average of predictions, and dashed line indicates transition from active mining to closure.*

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