

# A Simplified Water Balance Model with Macro-pore Flow for Mine Waste Facilities

**Robert Hull**, GeoSystems Analysis, Inc., United States

**Mike Milczarek**, GeoSystems Analysis, Inc., United States

**Jaime Banuelos**, GeoSystems Analysis, Inc., United States

**Guosheng Zhan**, Barrick Gold, United States

**Jason Keller**, GeoSystems Analysis, Inc., United States

## Abstract

Predicting seepage rates and water quality from waste rock and heap leach facilities is critical for mine operations and closure management. Flow rates and the chemical composition of seepage from mine waste facilities (MWFs) are controlled by unsaturated solution and air flow dynamics and mineral dissolution / reaction rates. Although spatially-distributed reactive unsaturated flow and transport models can be used to simulate physical and chemical interactions between the porous media, solution, and gas, they suffer from practical issues related to computational expense and lack of data to validate parameter choices in the highly heterogenous and large-scale novel flow systems that exist in MWFs.

We introduce MWF MACRO, an Excel-based tool designed for practitioners to model the water balance within large catchment-scale variably saturated mine waste facilities. MWF MACRO simplifies computationally intensive physics into key processes relevant to the dump water balance while retaining physical interpretability. The application of the methodology to simulate MWF seepage under operations and a closure scenario is explored. The application demonstrates the model's predictive capacity to simulate high-resolution (i.e. daily) seepage responses and provide reasonable estimates of unobserved variables such as the effects of flow through less- and more-mobile (i.e. macro-) pore flow domains.

## Introduction

Understanding the water balance within waste rock dumps and heap leach facilities (Mine waste facilities (MWFs)), is essential for predicting drainage (seepage) from the MWF (Vriens et al., 2020). Seepage can potentially carry elevated concentrations of dissolved metals, sulfate, and acidity, requiring capture, treatment, or controlled discharge. Effective drainage management is fundamental to the performance of mine waste facilities, as it directly influences environmental risk mitigation, regulatory compliance, and the

development of sustainable closure strategies (Milczarek et al., 2023).

Solution movement through MWF occurs as a function of complex unsaturated flow dynamics (Blackmore et al., 2018; Milczarek et al., 2023; Schofield et al., 2024; St-Arnault et al., 2020; Vriens et al., 2020; Waples and Wickham, 2024). Fully distributed multi-physical reactive transport models (RTMs) providing detailed representations of physical and chemical interactions have been used in prediction of drainage quantity and quality from mine waste (Demers et al., 2013; Lahmira and Lefebvre, 2015; Lahmira et al., 2016; Molson et al., 2005; Munjruzzman et al., 2018; Pabst et al., 2017) using a diverse set of commercial and research codes. Despite being powerful investigative tools, high-fidelity numerical RTMs can be computationally demanding and require extensive parameterization, with challenges including equifinality (Cranmer et al., 2020), computational constraints (Bierkens et al., 2015), and difficulties in obtaining adequate field data for reliable calibration (Vriens et al., 2020). The application of such models to represent MWF processes represents a significant investment of time and energy that may not produce realistic and interpretable predictions of key water balance quantities, and often at substantial cost.

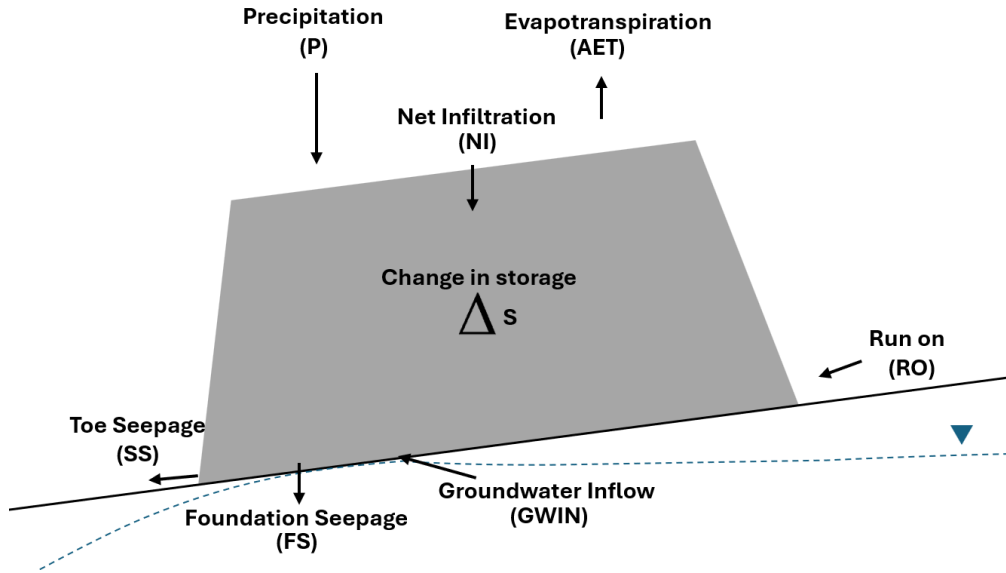
Lumped-parameter phenomenological and data-driven models may be applied more readily to simulate MWF water balances. Francoeur-Leblond and Hossain (2024) assess solute transport in coal waste rock spoils using a simplified ‘reservoir’-style unsaturated waste rock hydrogeochemical module to generate drainage predictions. Zhang et al. (2023) applied a machine learning framework, combining decision tree classification with a recurrent neural network to predict mine waste drainage responses to climatic variables, demonstrating that empirical models can effectively capture primary hydrological dynamics despite their lack of mechanistic representation. However, relying solely on lumped-parameter or data-driven models sacrifices physical realism, making it difficult to evaluate flow pathways and interactions between them, which are critical to interpretability and robust decision making.

MWF MACRO is a novel excel-based platform that addresses this gap by offering a simplified yet physically interpretable water balance model designed specifically for large waste rock and heap leach facilities. This manuscript provides the conceptual model underlying MWF MACRO, details on its technical implementation, and an application to an active waste rock facility. The application demonstrates that MWF MACRO can be used to: 1) Accurately predict seepage responses on monthly and daily timescales; 2) Identify critical process(es) driving seepage responses; and 3) Evaluate how closure may affect long-term seepage trends.

## **Hydrologic Conceptual Model (HCM) of Solution Flow through Waste Rock**

A high-level conceptual diagram of the primary inflows, outflows, and storage terms in an unlined waste rock facility (WRF) is provided in Figure 1. This HCM focuses on details relevant to coarse-textured WRFs and heap leach facilities (HLFs), however MWF MACRO can also be applied to finer-textured mine waste

such as tailings.



**Figure 1: High-level conceptual diagram of waste rock facility (WRF) water balance**

### Inflows

Precipitation (P) is the primary inflow, converting to net infiltration (NI) after evapotranspiration (AET). Zhan et al. (2019) showed that for HLFs in high-precipitation environments, large seasonal and wet/dry outflow cycles are observed, with significant NI occurring during rainy periods. In colder regions, snow accumulation leads to a significant spring freshet, where infiltration magnitude is affected by the rapid melting of accumulated snow. Zhang et al. (2023) noted that in a British Columbia, Canada WRF, freshet-driven NI pulses coincide with peak seasonal precipitation, intensifying seepage responses and driving sharp increases in drainage outflows. Groundwater inflows (GWIN) from pre-development springs can also add significant moisture to the dump, particularly if the springs persist beneath or within waste deposits, providing a continuous source of recharge. Surface water run-on (RO) from upslope areas may move laterally into the base of a MWF, or in the case of “valley fill” dumps redistribute across the waste surface, influencing NI by locally focusing solution flow (Schofield et al., 2024).

### Outflows

Drainage from MWFs occurs by surface seepage (SS) and foundation seepage (FS) if the MWF is unlined. In WRF, SS occurs out of the ‘toe’ of the dump. SS represents the dominant drainage mechanism in lined dumps and in settings where the underlying geology has limited permeability. In high-precipitation regions, MWFs can exhibit SS rates exceeding 40% of annual precipitation input (Vriens et al., 2020). Face seepage can occur where solution emerges from upper exposed surfaces of a MWF; generally, it is assumed to move downslope and re-infiltrate back into the MWF. FS occurs when water moves from the base of the facility

and enters the underlying groundwater system. Unlike SS, which is typically managed at surface discharge points, FS typically bypasses collection and is unobserved. The relative proportion of SS to FS depends on the construction of the MWF, underlying material permeability, and climate.

### Storage

From a water balance perspective, WRFs undergo three distinct phases:

- **Wet up:** Following the initial depositional period, water infiltrates and is stored via capillary forces in the pore spaces of the waste rock, gradually increasing moisture content to the so-called “field capacity”.
- **Steady state:** Moisture stored in the facility reaches a dynamic equilibrium, in which the drainage rates approximately equal NI.
- **Drain down:** Cover systems installed after mine closure are typically engineered to either limit oxygen ingress or reduce water infiltration. The reduction in NI creates a transient state of 'drain-down', in which stored moisture will continue to flow from the dump until the drainage rates approximate the new, lower NI rates through the cover system.

For the case of a HLF, the wet up occurs during operations and drain-down step occurs immediately after cessation of heap leaching.

### Matrix vs Preferential Flow

The heterogenous mixture of coarse- and fine-grained waste materials creates distinct porosity and flow regimes within a MWF (Milczarek et al., 2023). Mine waste with a high percentage of gravel particles can create macropores and discontinuities in the hydraulic property distributions that can significantly affect flow and transport behavior of both solution and air within these materials. Additionally, as MWFs evolve, their physical structure changes due to ongoing deposition and consolidation; mineral dissolution and chemical decrepitation of particles may also occur in acidic HLFs or WRFs with active sulfide oxidation. Facility geometry changes over time result in new drainage pathways and may alter the rate of moisture uptake (Francoeur-Leblond and Hossain, 2024).

Under low NI rates, water flow can be expected to occur through pores created by fine-grained (<4.75 mm) material layers (matrix flow). Matrix flow occurs through a continuum of pore size diameters; under the unsaturated conditions typical of MWF the flow of water is determined by material-specific moisture retention and unsaturated hydraulic conductivity properties. At higher (i.e. more negative) matric potentials, the majority of flow may occur through smaller pores (Lahmira, 2016; Newman et al., 1997). Hydraulically stagnant zones can also occur; these “immobile” regions can serve as a source or sink of solutes and reaction products (e.g., Waples and Wickham, 2024).

At intermediate to high infiltration rates (i.e. high precipitation periods and heap leaching) preferential flow can occur through macropores or higher conductivity material layers that are sufficiently wet. Jarvis (2007) has suggested that pore diameters larger than approximately 300  $\mu\text{m}$  allow rapid non-equilibrium flow under gravity, whereas Beven and Germann (2013), suggest that preferential flow is caused by infiltration nonequilibrium that results in pressure induced solution displacement into a range of pore sizes with typical film thicknesses in the approximate range of 3 to 100  $\mu\text{m}$ . In this latter model, the rapid infiltration of solution results in a wetting front that behaves like a kinematic wave in addition to flow in macropores, until the infiltration event ceases. Consequently, if NI rates exceed the pore space associated with the fine earth fraction, or if solution content is already high (i.e. during HLF draindown) macropore/preferential flow should be expected. Unstable wetting in the vadose zone can create ‘fingers’ that preferentially and rapidly transport moisture vertically, even in relatively homogenous porous media (e.g. Glass et al., 1988).

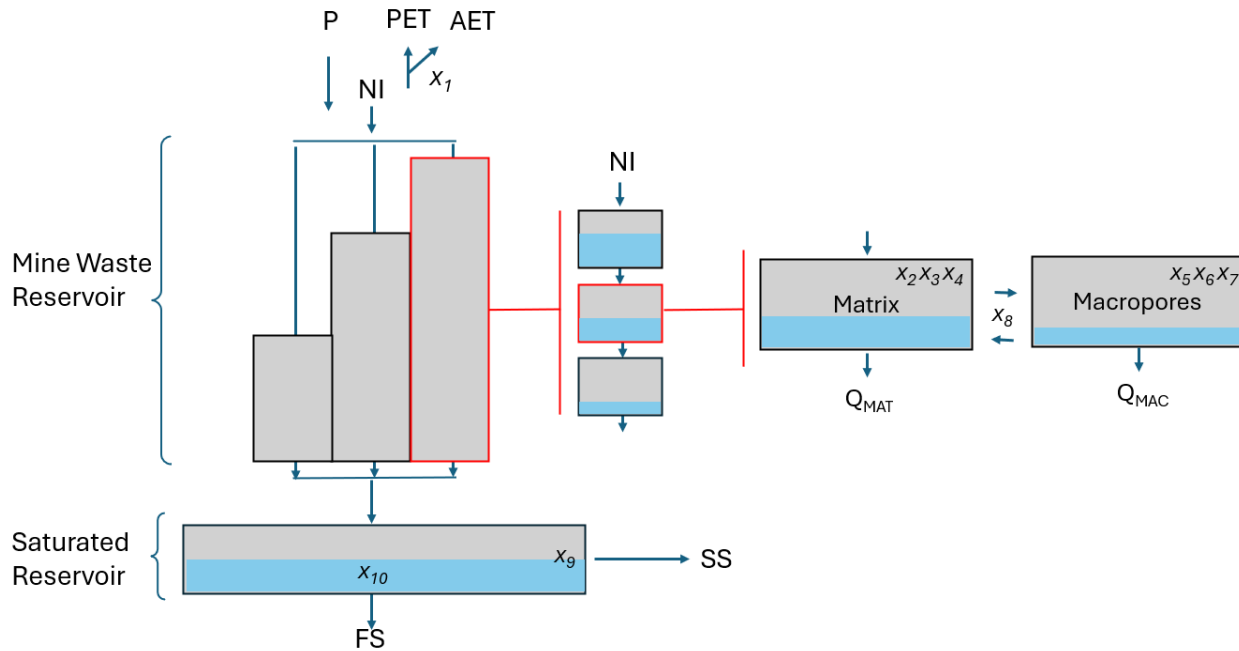
Macropore and preferential flow have been observed in numerous mine waste studies and is dependent on the climate, material type and waste properties. While matrix flow occurs gradually over years in large dumps, preferential pathways can cause NI pulses to reach drainage collection points within days or weeks (Milczarek et al., 2023; Vriens et al., 2020). Observed preferential flow velocities and wetting front arrivals three to four orders of magnitude faster than median and average pore water velocities have been reported in several waste rock studies (Smith et al., 1995; Nichol et al., 2005; Neuner et al., 2013; Peterson, 2014). Li (2000) and Eriksson et al. (1997) separately estimated that between 55% to 70% of the solution in their waste rock studies flowed preferentially.

Thus, prediction of the hydraulic response of seepage from MWF requires consideration of interactions between matrix and macro-pore flow. Wilson et al. (2018) was able to adequately predict flow and solution geochemistry from the matrix flow dominated Diavik Waste Rock pile described by Neuner et al. (2013). Blackmore et al. (2018) attempted to model two of the Antamina waste rock piles described by Peterson (2014) using a mobile-immobile flow model but concluded that a third preferential domain was needed. Eriksson et al. (1997) concluded that models should represent waste rock as a continuum of interacting flow pathways. Smith et al. (1995) and Lopez et al. (2005) successfully applied a kinematic wave approach to simulate flow in toe drains at the Island Copper mine.

## **MWF MACRO Model Structure and Computational Approach**

A detailed system diagram of key MWF MACRO flows, reservoirs, and parameters is provided in Figure 2. The waste reservoir is discretized into elements to represent mine waste geometry. Each element represents a “block” of waste of uniform thickness, which can be distributed spatially across the facility at a rate dictated by depositional history. Waste material is added vertically starting from the bottom to match

the historical record. This allows for the temporal and spatial evolution of each MWF to be accounted for, as is critical for matching water balance and water quality trends (Huang et al., 2021).



**Figure 2. Detailed system diagram of MWF MACRO model**

P and potential evapotranspiration (PET) as calculated from the Penman-Monteith equation (Allen et al., 1998) are the primary meteorological inputs. AET is computed following Xu and Vandewiele (1995) from these meteorological inputs based on moisture stored in the top-most ‘blocks’ of the WRF and the calibration parameter  $x_1$ ; NI into the WRF is the residual of P and AET. An optional snowmelt module based on a degree-day factor approach (Bergstrom, 1992; Bednář and Marton, 2024) is under development. Surface runoff is not explicitly represented, as water that does not evaporate will percolate into the MWF.

Percolation through the MWF matrix ( $Q_{MAT}$ ) occurs as a linear function of the unsaturated hydraulic conductivity ( $x_2$ ) and the dynamic moisture storage relative to field capacity ( $x_3$ ) and the volumetric water content of fresh waste rock ( $x_4$ ); plausible values can be constrained by hydraulic property testing. Macropore flow ( $Q_{MAC}$ ) occurs kinematically as downward moving and receding waves after Germann (1985) as a function of macropore hydraulic conductivity ( $x_5$ ), kinematic exponent ( $x_6$ ), and total macropore porosity ( $x_7$ ). The exchange ( $x_8$ ) between these two domains follows a dual-permeability approach adapted from Larsbo et al. (2005), allowing redistribution of solution from the matrix to macropores under high moisture conditions and vice versa for dry soils. Because the heterogeneity of an MWF is in practice difficult to characterize, the same material properties are applied to each model element.

Percolation to the base of the MWF enters a reservoir representing saturated conditions, where it is stored before being routed to the surface as SS. Drainage is mediated by the attenuation parameter  $x_9$ . Optionally, in the case of an unlined WRF, a portion of the moisture may drain as FS to points downgradient mediated by a separate attenuation parameter  $x_{10}$ . Additional moisture inputs in some use-cases may include RO from upslope areas and GWIN from upgradient recharge zones and/or springs.

The water balance is solved at daily time steps over a duration defined by the user. A simple interface to set up the model, define parameters, input data, and observations, can be accessed in Excel. Calibration is implemented automatically in Solver and includes the ability to add custom weights or omit individual observations. A number of model metrics to evaluate goodness of fit are provided. Run time is less than a second for typical MWF and results are reported by a dashboard tool built using Visual Basic integrated directly into the spreadsheet-based software.

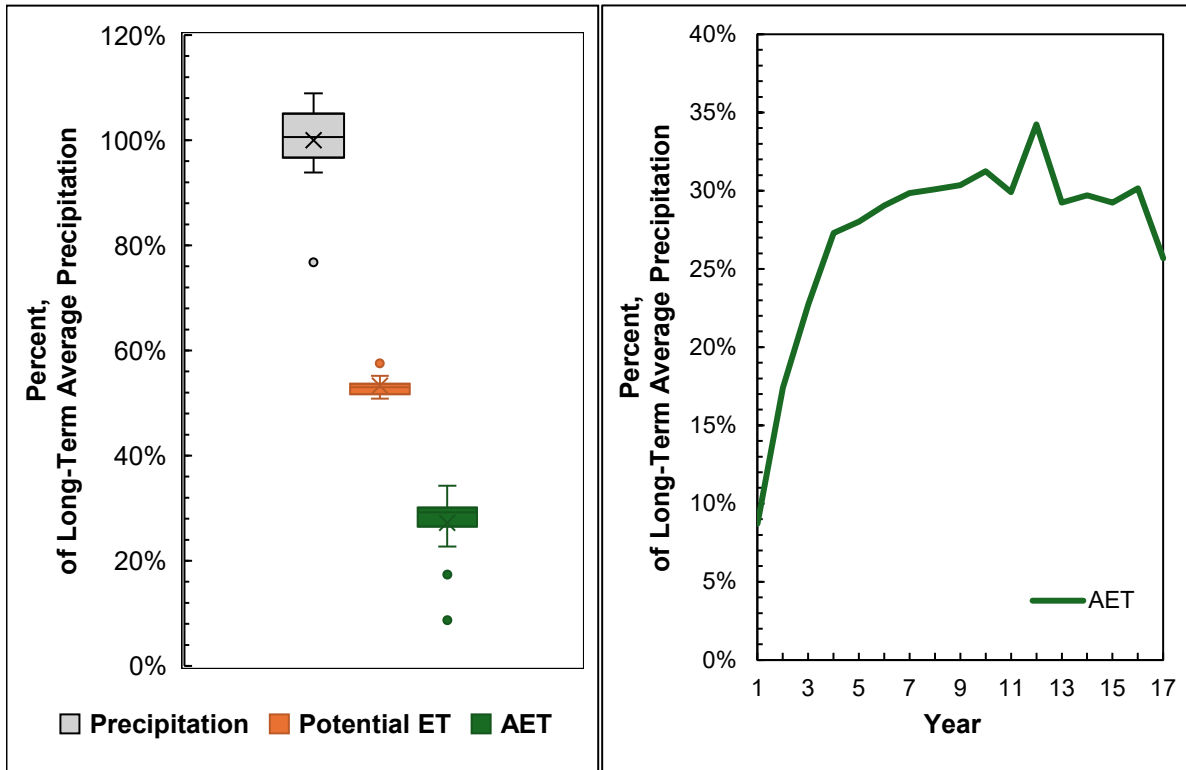
## Model Application

MWF MACRO is applied to a large, valley-fill WRF with an areal footprint of approximately 130 ha. The WRF is constructed of a mix of acid and non-acid forming run-of-mine (ROM) material deposited in 10 m lifts over a period of approximately 5 years, to a maximum height of 330 m and total volume of 200 million cubic meters. The ROM material contains a high-proportion of gravel (greater than 4.75 mm diameter) particles, and thus a high proportion of clast-supported pore space. Underlying the dump is low-permeability bedrock through which rates of deep percolation into the groundwater system are assumed negligible. Engineering controls over upgradient surfaces limit the occurrence of RO, and no pre-development springs that could contribute groundwater inflows were identified prior to dumping.

SS was first observed within a year of WRF construction, and measurements were collected semi-regularly over a period of 10 years before continuous (i.e. daily) monitoring began. To leverage all of the data collected, the entire observational record of SS over 17 years ( $n=1210$ ) was used to calibrate MWF MACRO. The goodness of fit between daily simulated and observed SS by the Kling Gupta Efficiency metric was 0.857, which is considered very good (Gupta and Kling, 2011). Only three degrees of freedom ( $x_8$ ,  $x_6$ ,  $x_9$ ) were permitted for model calibration; estimates of the remaining parameters were developed a priori based on site understanding. To maintain client privilege, all simulation results are expressed as a percent of the long-term average precipitation rate.

Annual climate variables are provided in Figure 3. Seasonally-variable rainfall ranges between 20 and 230 mm / month, with the rainiest time of year occurring between January and March; temperature is typically between 5 and 10 degrees year-round. Annual precipitation exceeds evaporative demand (PET) by roughly a factor of 2. Simulated rates of actual evapotranspiration (AET) were consistent with independent site-specific estimates of AET over uncovered waste rock. Model-predicted AET also varied

as a function moisture changes through time, as initially fresh deposits of material retained moisture to meet evaporative demand.



**Figure 3. At left, Box and whisker plots of annual average precipitation (P), potential evapotranspiration (PET), and model-calculated actual evapotranspiration (AET). At right, annual rates of AET over 17 year observational period**

Figure 4 compares daily 10th, 50th (median), and 90th percentile observed and the simulated SS summarized by month. SS peaks during the rainy months (Dec to Apr) and decreases over the dry months (Jun to Oct) as stored moisture ‘drains down’ and exits the MWF. In general, the seasonal variability and central tendency of SS is well-represented by the model.

Figure 5 provides model-derived daily SS in response to precipitation over the final four years in the observational period. Although daily seepage predictions are generally accurate, two non-behavioural model responses are noted. First, the model slightly underestimates variability during the rainy months. High-magnitude SS flows in response to high-intensity rainfall events are under-predicted, which may have engineering implications (i.e. in design and operation of seepage capture). Second, SS is generally underpredicted before the onset of rainy conditions in October. Stored moisture continues to drain from the MWF during dry periods, which occurs more rapidly in the model than in the real system. Modeled seepage may thus be more responsive than expected after a cover system is installed at closure (i.e. the model predicts drain down too rapidly).

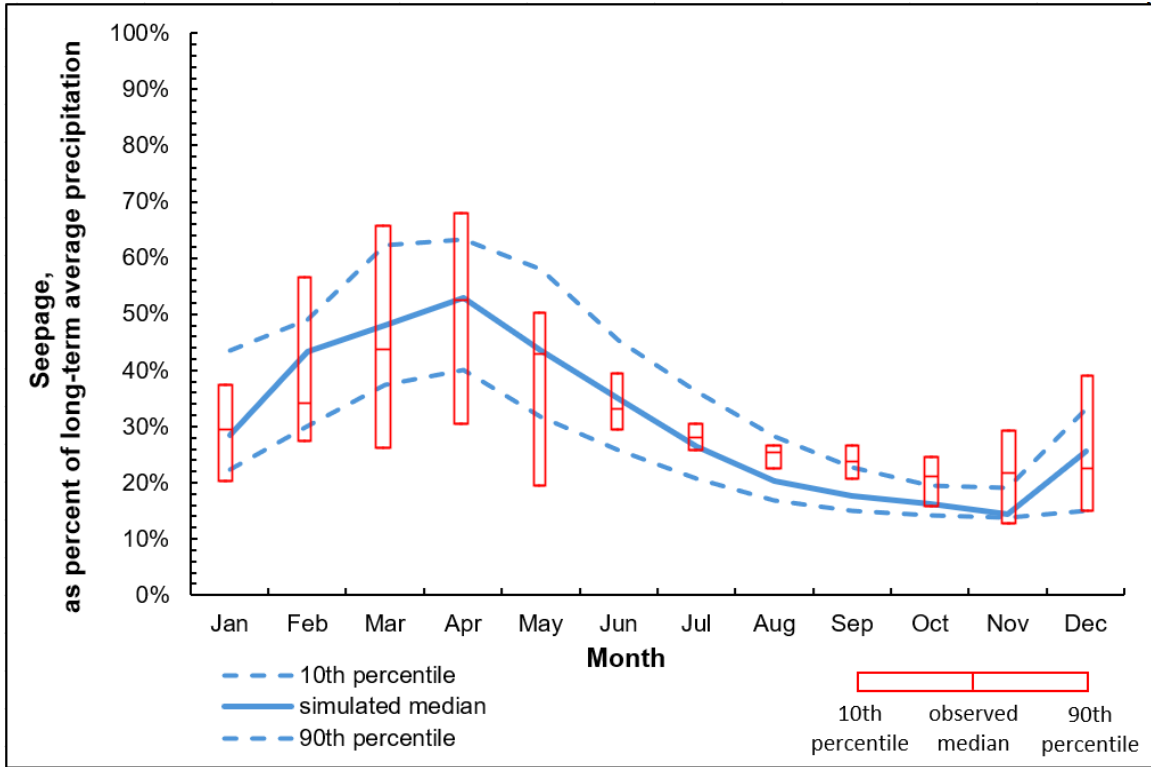


Figure 4. Simulated and observed daily surface seepage (SS) summarized by month

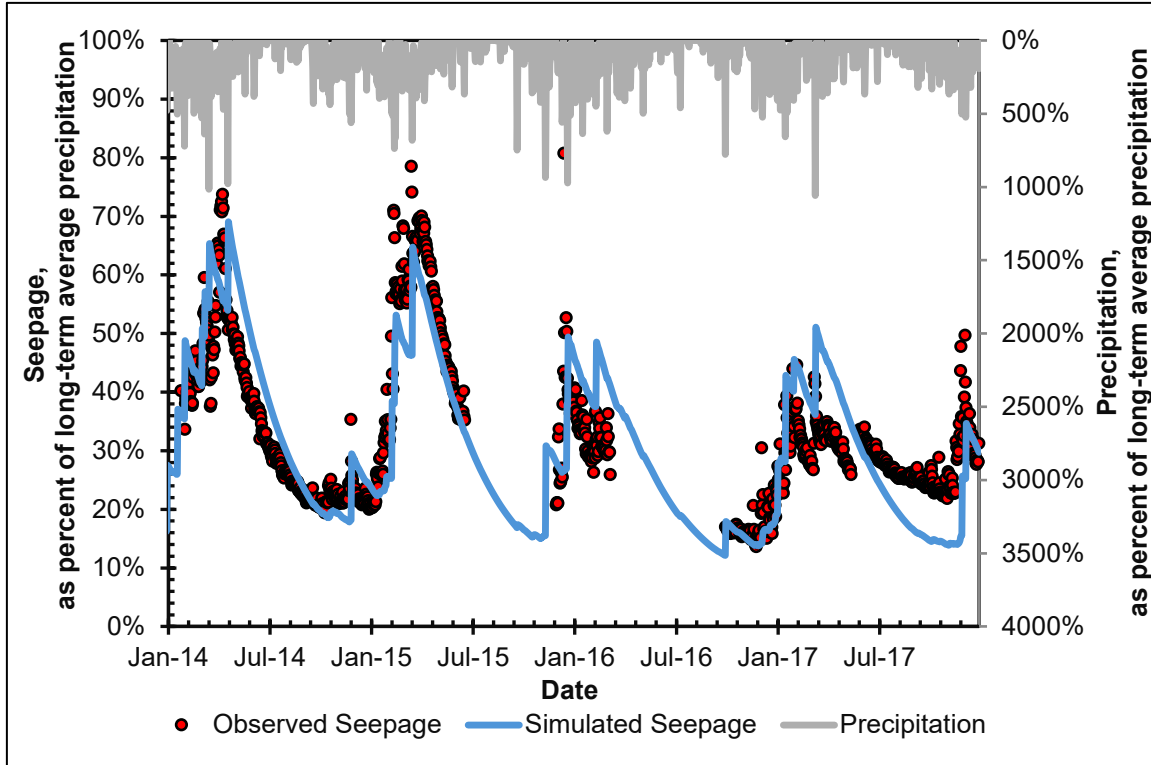


Figure 5. Simulated and observed daily surface seepage (SS) and Precipitation (P) time series

Figure 6 shows the simulated annual water balance components within the WRF. NI partitions between storage and SS, which occurs by matrix- and macropore-dominant pathways. The rate of NI reflects annual climate variability after the initial depositional period. Most NI is retained in the MWF, causing a positive change in moisture storage. The proportion of NI added to storage decreases over time as the MWF wets up. Over the 17-year calibration period, steady state (i.e. when net change in storage is zero) is not achieved; this is generally consistent with expectation that satisfying the moisture uptake of dry waste rock in large facilities can take decades or even centuries (Milczarek et al., 2023). SS breaks through within the first year, and generally increases in magnitude over the simulation period. Macropore flow initially composes nearly all of SS; the proportion of SS from the matrix increases as the MWF wets up over the simulation period. During low-NI years 12 and 16, approximately 70% of SS drains from the MWF by way of the macropores, which is generally consistent with results from Eriksson et al. (1997).

MWF MACRO was also used to evaluate trade-offs associated with MWF closure scenarios. Compared to the uncovered ‘baseline’ scenario, the ‘cover system’ scenario reduces the NI to approximately 12% of long-term average precipitation after year 25. Figure 7 compares daily 10th, 50th (median), and 90th percentile SS summarized by year over a longer predictive period. The baseline SS increases in magnitude and variability as the MWF continues to wet-up. Conversely, the cover system is associated with drain down and re-equilibration of SS rates to be roughly consistent with NI, with very little intra-annual variability. The Figure 7 inset provides daily simulated SS before and after cover system installation; drain down to net infiltration rates occurs within one year (~11 months) after the cover system installation.

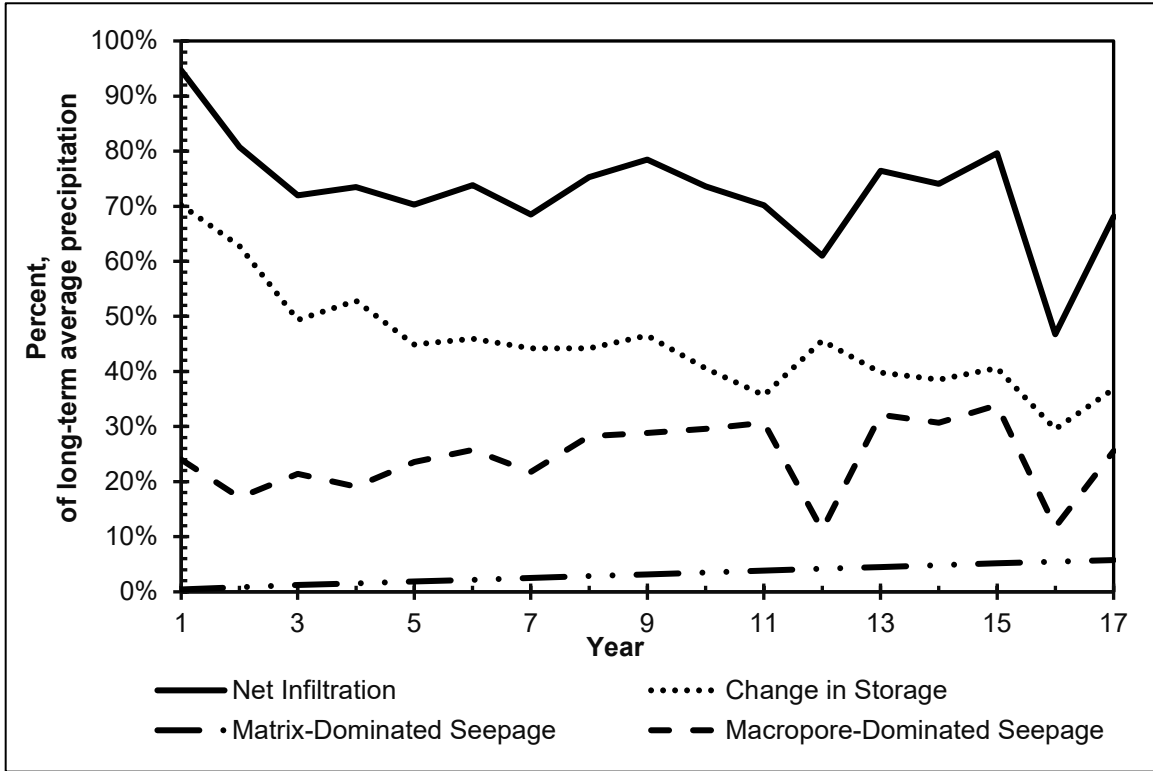


Figure 6. Simulated water balance components over the observational period

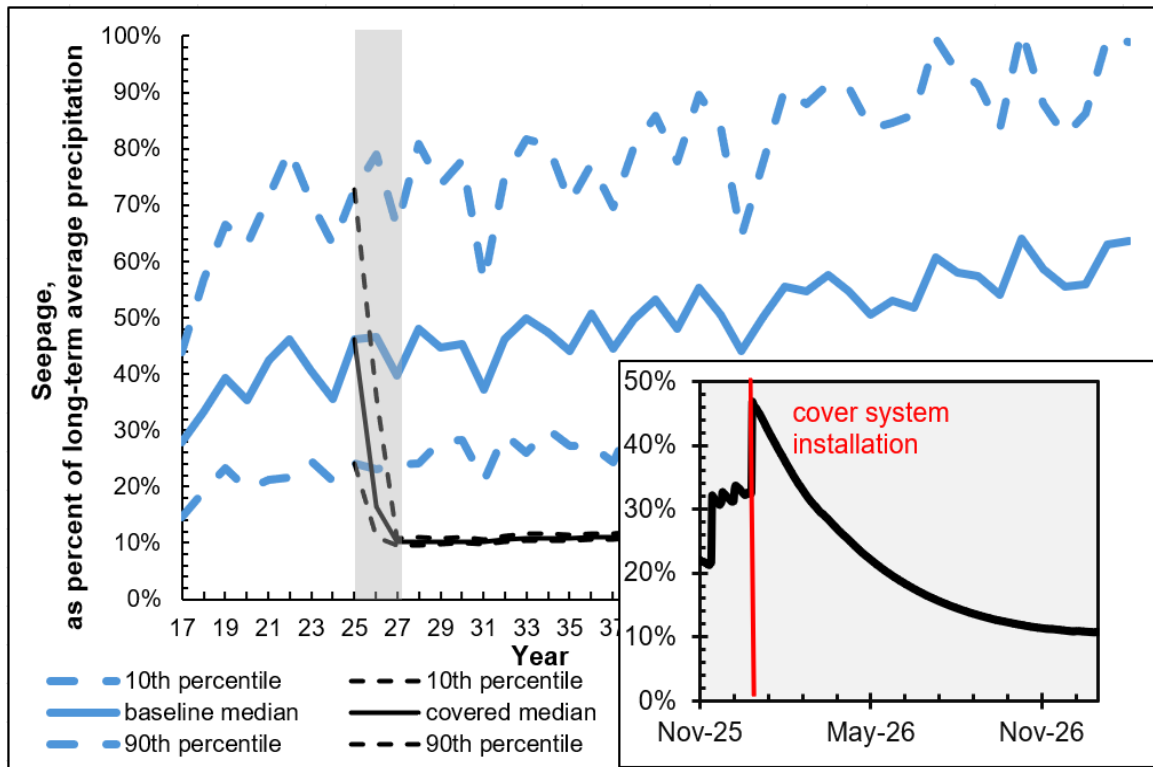


Figure 7. Surface seepage (SS) under baseline and cover system scenarios. Inset: Drain down.

## Discussion and Conclusions

This manuscript has introduced MWF MACRO, a water balance model for catchment-scale variably saturated mine waste facilities based on a limited set of physical assumptions. MWF MACRO was applied to a large (130 ha) WRF located in a seasonally-variable high-precipitation environment with a high-proportion of gravel (i.e. greater than 4.75 mm diameter) particles and thus a high proportion of clast-supported pore space. The purpose of the MWF MACRO application was to accurately predict seepage rates from the toe of the WRF, as is critical for mine operations and closure management. The model reproduced rapid (i.e. within one year) breakthrough of seepage, and simulated daily and seasonal trends in seepage consistent with observations during the wet-up phase of the facility. The model was also used to predict long-term seepage response to cover system installation (i.e. drain down), as demonstration of its utility as planning tool.

The simplified water balance approach is effective partly because it represents separate matrix and macro-porosity components within the WRF. This structure allows for preferential flow in response to moderate- and high-intensity infiltration events and subsequent seepage. We are certainly not the first to have simulated field scale seepage responses via a fast- and slow-component model that approximates macropore and matrix flow domains. Trinchero et al. (2011) adequately simulated preferential and matrix flow observed at the Cluff Lake test piles (Nichol et al., 2005). Zhan et al. (2019) use a fast/slow component model to accurately simulate the long-term net percolation and drainage behavior at two closed HLFs. However, our implementation is novel in that it solves the water balance within discretized model elements, each retaining a fast- and slow- mechanism; this allows for the consideration of differential wet-up across the facility in relation to its geometry and expansion over time, which as others have noted is a critical to matching observed seepage trends (Huang et al., 2021).

We developed MWF MACRO to meet specific project objectives and its refinement as a general purpose model is continuous. One immediate need is to further refine representations of critical internal processes, which are linear approximations of partial differential equations (PDEs) (i.e. Richards, 1931; Germann, 1985). PDEs solved numerically in RTMs have longer solve times, require a greater number of explicit assumptions, and may be less flexible for application to dynamic MWFs. Linear representations have the advantage of being faster and easier to solve, perhaps at the expense of some physical realism. Two non-behavioural responses in the context of the case study were noted and should be further evaluated. 1) Under-representation of seepage variability in response to the highest-magnitude infiltration events may be explained by improper parameterization of the macropore function (i.e. by over-estimating the degree to which macropore dominated flow exchanges back into the matrix). 2) The drain down response to reduced infiltration is more rapid than expected given the observed data; this could be due to unrealistically low retention in the matrix at low water contents, as matrix flow is parameterized as a linear function of

hydraulic conductivity and soil moisture. As we continue to develop the model and its conceptual underpinnings, subsequent publications will benchmark MWF MACRO to a greater number of environments and facility types.

Future model improvements will also include the development of a coupled geochemical module to simulate the effect of hydraulic response and retention time on hydrogeochemistry. Two approaches will be evaluated: A) embedding geochemical source terms and solute release equations and; B) a machine learning (ML) approach. Francoeur-Leblond and Hossain (2024) showed that drainage geochemistry for mine spoils could be accurately simulated using a limited set of zero-, first-, and second-order solution release curves defined for a focused set of water quality parameters; such an approach is simplified compared to the reactive transport approach described by Vriens et al. (2020) but has advantages in data sparse settings. Ma et al. (2021) demonstrated accurate ML predictions based only on the observed drainage geochemistry. The advantage of ML is that it does not require definition of internal variables (e.g., sulfide weathering reactions, mineral precipitation, and other processes as described above) to generate reasonable predictions of the drainage composition, potentially making model development less time- and data-intensive. We plan to trial a constrained ML approach that uses process-informed water balance estimates from MWF MACRO in conjunction with a long short-term memory (LSTM) model to predict water quality seepage fluxes. The two approaches to simulating the geochemistry will be compared across a range of facilities with differing geochemical source terms.

To manage potential impacts from MWF drainage, effective long-term wastewater quantity and quality predictions are critical. Given the size and variability of most MWF, it is not possible to consider fully characterizing mine waste materials at the facility scale. Moreover, the data and computational requirements to develop a predictive RTM may not always be practical. Alternatively, parsimonious prediction frameworks, such as we have introduced, can be used to generate accurate and reasonable long-term predictions of seepage dynamics to support facility decision making. The MWF MACRO simplified water balance model requires only mine waste characterization of the hydraulic properties of the major rock types, and uses these data with climatic and operational data to estimate the amount of time needed for MWF wet up, partitioning of matrix and preferential flow, and hence solution residence and hydraulic response times and the long-term potential drainage rates integrated across the facility.

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