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A novel modeling approach coupling post-closure tailings storage facilities draindown and water balance simulations

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Abstract

Traditional methods of tailings management involve spigotting or cycloning tailings slurry into large tailings storage facilities (TSF). The draindown of entrained TSF water at closure can take decades to centuries and requires careful management. As a result, knowledge of the evolution of the TSF draindown rate in time and duration of active management in closure and post-closure is an important cost consideration for mine closure optimization.

Predicting TSF draindown typically employs a numerical or an analytical approach based on unsaturated flow principles. The complexities of tailings solution flow dynamics may be more rigorously predicted by a numerical model compared to an analytical model. However, incorporating solution management alternatives, such as recirculation to the surface of the TSF, is not feasible in the numerical modelling codes commonly used today. A well-calibrated analytical model, even with simplified water flow dynamics, may still be able to reproduce draindown as accurately as a numerical model, but also allows unlimited flexibility in evaluating water management methods.

We propose using a combination of numerical modelling and analytical modelling to predict the time required to achieve passive water management. Variability in tailings properties, TSF geometry, and the time dimension are considered in the numerical model, which is coupled to an analytical model that allows feedback of typical water management methods. The analytical TSF water balance model includes the calibrated flux curve and incorporates water management elements such as seepage recirculation, passive and forced evaporation, effect of the shrinking pond surface, and effect of the closure cover construction.

An example of the method applied to the Nevada Gold Mine's Gold Quarry mine in Nevada is described in this paper, detailing the assumptions that were made with respect to the closure water balance and the functional parameters used for modelling the final draindown of the TSF.

Keywords: tailings, closure, water management, draindown

1 Introduction

The deposition of tailings as wet slurry in mining operations poses significant water management challenges in closure and the post-closure phase. As part of the closure process, it is crucial to manage surface water effectively to ensure environmental sustainability and regulatory compliance. This paper presents an integrated modelling approach that combines finite element modelling (FEM) of unsaturated flow with an analytical surface water balance model to evaluate TSF water management methods in closure and post-closure.

Draindown is defined here as the period of time during which the seepage rate is gradually reduced from the operational level, i.e. active tailings deposition, to the residual steady-state value. Draindown is highly non-linear, with an initial quick reduction in flow rates followed by a gradual slowing down.

Unsaturated flow refers to the movement of water in porous media, where hydraulic conductivity and water content vary with saturation level. Understanding unsaturated flow is crucial for predicting water movement within the tailings mass and seepage behaviour.

Finite element modelling (FEM) has emerged as a powerful tool for simulating unsaturated flow dynamics in complex geological settings. By discretising the domain into finite elements, FEM provides a robust framework for solving the governing equations of fluid flow in porous media. This approach considers various parameters such as hydraulic conductivity, water retention, and boundary conditions to accurately predict water movement in unsaturated zones.

However, to comprehensively address the water management challenges associated with tailings deposition and closure, it is necessary to consider the broader surface water balance. The surface water balance model incorporates various surface water management methods, including recirculation, forced evaporation, and passive evaporation from E-cells.

By integrating the outputs of unsaturated flow modelling into the surface water balance model, the combined approach allows for a more holistic understanding of the TSF water management issues and designing appropriate closure and remediation strategies.

In subsequent sections of this paper, we will discuss the theoretical foundations, computational implementation, and case study applications of the integrated modelling approach. The results and implications of the model simulations will be presented, showcasing the effectiveness of surface water management methods such as recirculation, forced evaporation, and passive evaporation from E-cells.

1.1 Problem definition

The need for this method arose from the need to determine the cost to run the water management system in post-closure period. Water management is generically divided into two periods: active management phase and passive management phase respectively. As a result, knowledge of the evolution of the TSF draindown rate in time and duration of active management in closure and post-closure is an important cost consideration for mine closure optimization. Besides the unit costs associated with the water management system, the quantities of water to be managed as well as timing and duration of the active and passive phases are required to estimate the costs. In other words, how much water needs to be managed during the active water management period, and when is it possible to transition to the passive management phase?

Predicting TSF draindown, with the associated closure management needs, typically employs a numerical or an analytical modelling approach. The complexities of tailings pore water flow dynamics can be more rigorously and accurately predicted using FEM numerical methods compared to analytical methods. However, incorporating solution management alternatives, such as recirculation to the surface of the TSF, is not feasible in the numerical modelling codes commonly used today because of internal logic feedback issues yet to be resolved.

An analytical model may, on the other hand, over-simplify water flow within the TSF leading to unacceptable error in draindown prediction. It will however allow unlimited flexibility in evaluating water management methods.

The first part of the question can only be answered if one can predict the TSF draindown curve equation constants. These curves are highly non-linear, with very steep decline in flux in the beginning, and reduce gradually as the tailings desaturate and inventory is diminished. Taking it separately, as a zero-input system, the draindown curve of a TSF can be accurately predicted using FEM (Rykaart, ME, Fredlund, D.G, Wilson, WG 2002). It is best if laboratory determinations of the tailings hydraulic properties are available, together with measured outflow flux data suitable to be used as calibration for the FEM (Whitman 2016). An accurate representation of the TSF shape and geometric configuration is also important.

Over the long term, the net percolation remains constant, but its proportion relative to the seepage flux changes. Initially, during the active water management phase, net percolation from cover surface infiltration constitutes only a small fraction of the seepage flux, negligible in some cases. However, as the system reaches drained long-term steady-state conditions, the net percolation becomes the dominant component of the overall flow, making up the majority of the seepage flux. The draindown of entrained TSF water at closure can take decades to centuries and requires careful management.

2 Methodology

2.1 Conceptual model of TSF hydrologic conditions

Hydraulic deposition of slurry tailings results in the segregation of tailings material types by particle size, which in turn controls vertical flux through the facility. A conceptual schematic of TSF tailings type distributions is shown in Figure 1.

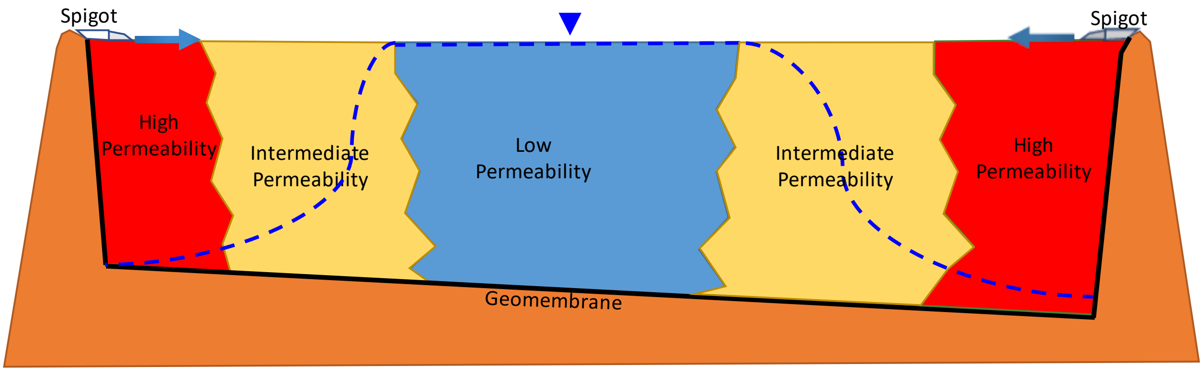


Figure 1 Conceptual tailings storage facility material type distribution cross-section. Dotted blue line indicates water level

The deposition of tailings is akin to the fluvial sedimentation process that results in temporal and spatially variable tailings deposition patterns as deposition source (i.e., spigot) locations are changed over time. Consequently, TSFs usually contain a highly heterogeneous array of sandy, silty, and even clay layers of varying thickness that relate to the distance from the tailing spigots. In general, tailings grain-size and permeability decrease with distance from tailings spigots leading from high permeability to intermediate permeability and then to low permeability tailings (slimes area). Coarse-grained tailings settle near the spigots and form the beach area which is composed of higher permeability tailings. Intermediate permeability tailings represent the transition from coarser to finer texture tailings as the tailings flow moves from the spigot towards the decant pond where the finest, and lowest permeability tailings settle.

Thus, as shown in Figure 1, tailings can be generally classified into:

- a beach area which has relatively high permeability and rapidly draining moisture retention characteristics (MRC)
- an intermediate permeability zone which contains moderate K_{sat} values and higher retention MRC properties, and
- the slimes area which has the lowest permeability and the highest retention MRC

The relative distribution of these general material types therefore defines the tailings drainage rate and volumes during closure.

2.2 Determining the suitable TSF draindown curves

Simulations using FEM at various degrees of complexity can be used to generate the draindown curves appropriate for the TSF considered (Silver 2013). 1D, 2D, and even 3D FEM simulations can be completed, to suit the level of understanding of the TSF configuration, as follows:

1D method would produce separate draindown curves for each of the tailings domains, and then extrapolate those curves to the surface area corresponding to those tailings properties. As many curves must be generated as the number distinct tailings hydraulic domains identified in the TSF. Segregation of properties both in horizontal domains (high permeability to low permeability) as well as vertical domains (decreasing permeability with depth) is desirable, as shown in Figure 2. The more curves are generated, the more accurate the prediction is likely to be. The total seepage flux is then obtained by integrating the predicted flux values with the representative surface area and depth, and reassembling the computed values into a single curve as a weighted average.

2D method uses a representative cross section through the TSF, which collapses all tailings properties domains into one single curve. The tailings properties zones still need to be determined, but there is a single draindown curve. The extrapolation to the 3D volume of the TSF, illustrated in Figure 3, is done purely on a geometric method by abstracting the TSF as an extruded shape of the 2D cross section, which is equivalent to the total volume of the TSF.

3D method is self-explanatory, as it uses the complete TSF as the model domain. It encompasses all identified tailings hydraulic properties domains and the entire volume is modelled. This method is computationally expensive and it is often difficult to complete for older TSFs which do not have good as-built records and therefore the 3D shape of the TSF is not known accurately. For newer TSFs this should not be an issue and it is fully expected that 3D models will become dominant in the future.

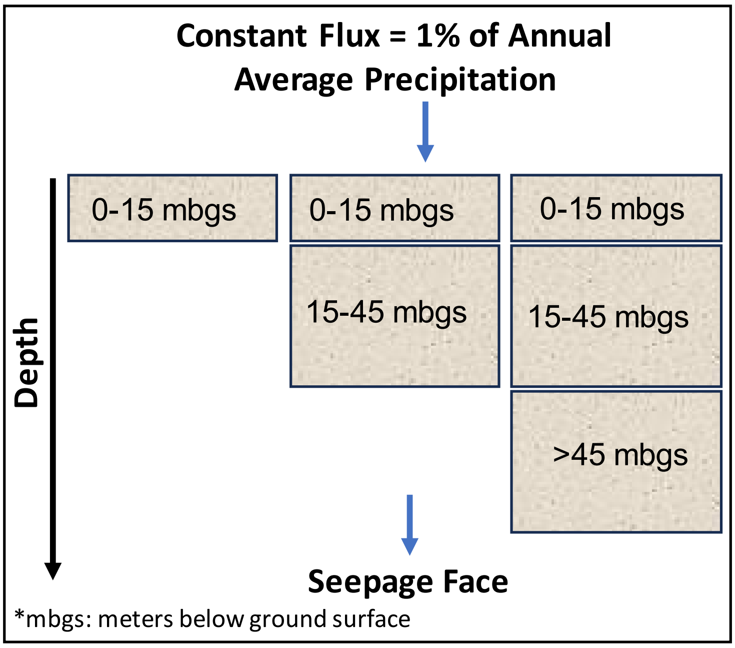


Figure 2 **Example one-dimensional tailings type draindown model domains for 15 m, 45 m, and greater than 45 m tailings thickness**

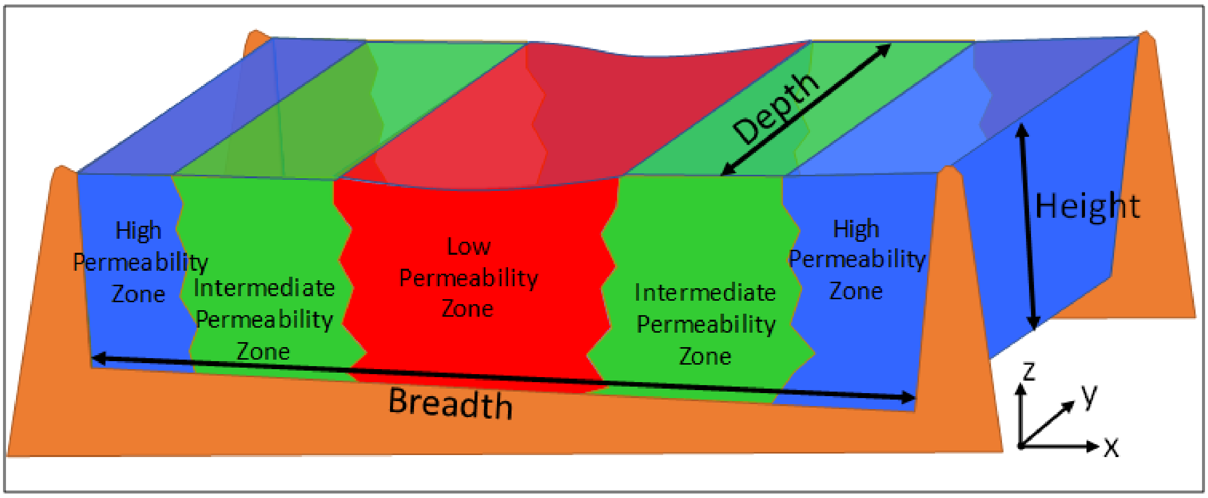


Figure 3 **Extrapolation of 2D representative FEM domain to 3D volume**

The draindown curves predicted using the FEM are simulating the TSF seepage behaviour in absence of the feedback mechanism of water recirculation into the TSF reclaim pond. Including the variable recirculation flux which is dependent on the predicted seepage flux is not feasible in the numerical modelling codes commonly used today and is akin to the circular references in spreadsheet models. Accounting for recirculation and simulating other water management practices is done in the analytical model described in the next section.

2.3 Surface water balance model

A schematic of the conceptual water balance is shown in Figure 4.

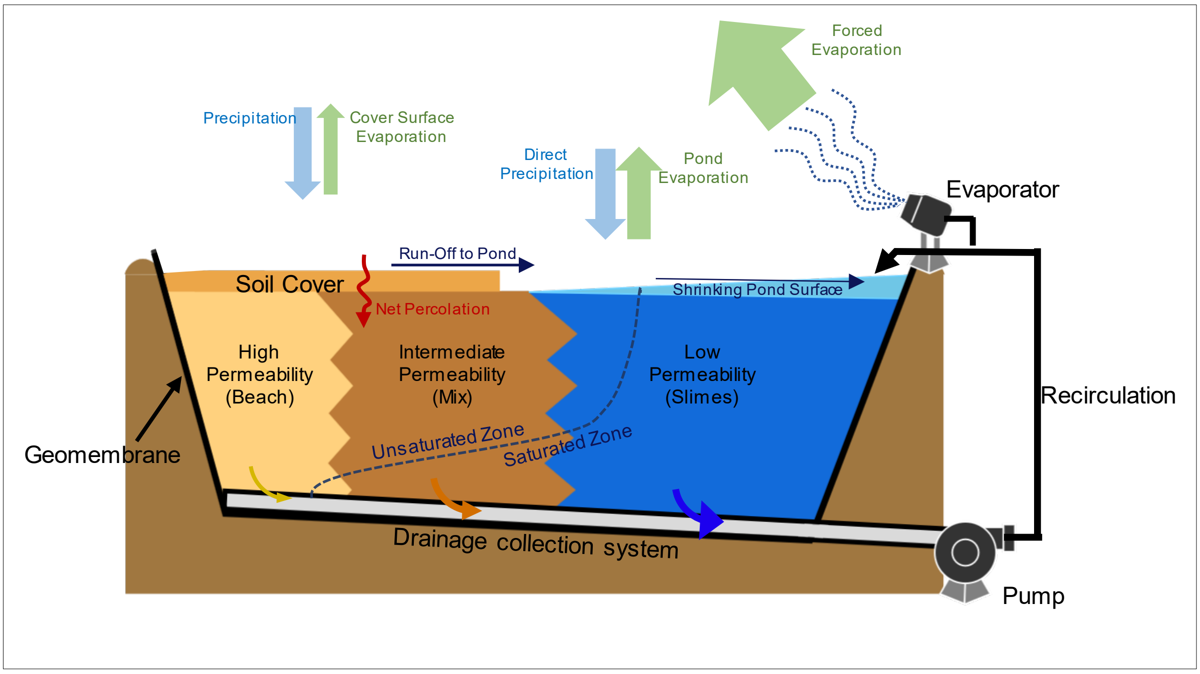


Figure 4 **Conceptual TSF water balance during active recirculation. Dotted blue line indicates water level**

Once the draindown curves are produced, the next step is to determine how the water management scheme will affect the draindown as well as the influence of the natural and forced evaporation on the evolution of TSF water inventory (Madariaga P, Wells C, Robertson A, 2004). This is achieved in the analytical model which can integrate the complex dynamics between any number of system elements such as seasonally variable precipitation and evaporation, run-off from covered areas, variable reclaim pond footprint and volume, installed pumping capacity for recirculation and forced evaporation, reclaim of water for processing use, etc.

Geochemical changes and the associated water quality evolution are integral to this system. However, these are beyond the scope of this paper and not discussed further.

During the active water management period seepage is recirculated to the reclaim pond. Recirculation acts to balance the water inventory in two ways ,it

1. provides a means to store most of the water inside the tailings pore space (as opposed to the ponds), and
2. maximizes evaporation by inclusion of a large wet surface area (beside open water evaporation) thus gradually diminishing the water inventory.

In theory, recirculation is no longer required when the daily drainage volume from the TSF becomes less than what can be passively evaporated from evaporation cells (E-cells) or the water management pond. At this point the water inventory in the pond will start diminishing at a rate equal to the difference between the daily evaporation and the daily inflow. In reality, the storage capacity of the ponds plays an important role, and passive water management can be achieved earlier (i.e., inflow rates still exceed pond evaporation rate) if there is sufficient excess storage capacity to make up the temporary shortfall in evaporation. At this point only E-cell evaporation can be accounted for, as terminating recirculation also eliminates wet surface evaporation and the reclaim pond eventually dries up completely.

The model is time-dependent, computed in a monthly time step. Time zero of the model, or initial condition, is the first day after tailings deposition is complete. At this point the water inventory is at its maximum and losses to the inventory are assumed to occur only through evaporation. The single intended output is the seepage flow, calculated as a daily rate on the first day of each month and applied for the total number of the days in that month.

The water balance model is coded into an analytical model (Microsoft Excel is a convenient platform) which then allows the feedback of recirculation to be quantified and the TSF draindown curve to be reshaped. The new curve will then provide an indication of how the seepage flux will evolve in time. Recirculation becomes an important input into the system, causing the draindown curve to become less steep while recirculation is occurring and there is influx from the pond. At some point the pond area will become smaller asd the influx from the pond decreases, i.e., the recirculation flux will become smaller, while the forced evaporation may be maintained at a constant rate. At the end of recirculation, the draindown curve will retake the steep decline, until such time that the pond disappears and enhanced evaporation becomes impractical. This is the time when transition to passive water management is most desirable, and depending on the seepage flux at this time sending the entire seepage to E-cells should start.

This transition should be coupled with other closure measures, such as final soil covers installed such that clean run-off can be diverted and discharged to the environment as opposed to being captured by the seepage collection system and having to manage it.

3 Case study

3.1 Site description

In support of Nevada Gold Mines' tailing storage facility closures at the Gold Quarry Mine in Nevada, USA, GeoSystems Analysis, Inc. (GSA) has completed a study to predict long term post-closure TSF draindown seepage rates for the Mill 5/6 West TSF. Estimated draindown seepage rates from the TSF was used to develop process fluid stabilization cost estimates. In addition, seepage estimates will be input into a surface water balance model being prepared separately to evaluate surface water management alternatives.

To achieve this, the following tasks were completed:

- field characterization to evaluate the physical property characteristics of the TSF
- laboratory testing to measure physical and hydraulic properties of the different tailings material types, and as a function of tailings depth
- development of conceptual hydrologic models of the areal extent of tailings types based on the field and laboratory based physical and hydraulic property data
- development of numerical and analytical surface water balance models to predict TSF seepage rates during 100-years of post-closure draindown

3.2 Tailings physical and hydraulic properties

Field characterization tasks consisted of hand augering to depths of 2.5 meters feet at transect locations across dry areas of the tailing impoundments or tailings impoundment proxies to log tailings physical attributes and evaluate tailings layering and segregation. A total of 112 tailings depth intervals were logged for physical properties and selected samples were tested for laboratory hydraulic properties, including saturated hydraulic conductivity and moisture retention characteristics.

3.2.1 Tailings permeability units

High, Intermediate, and Low Permeability tailings types were delineated using ArcGIS (ESRI, 2023). Figure 5 shows the estimated tailings permeability types for the TSF.

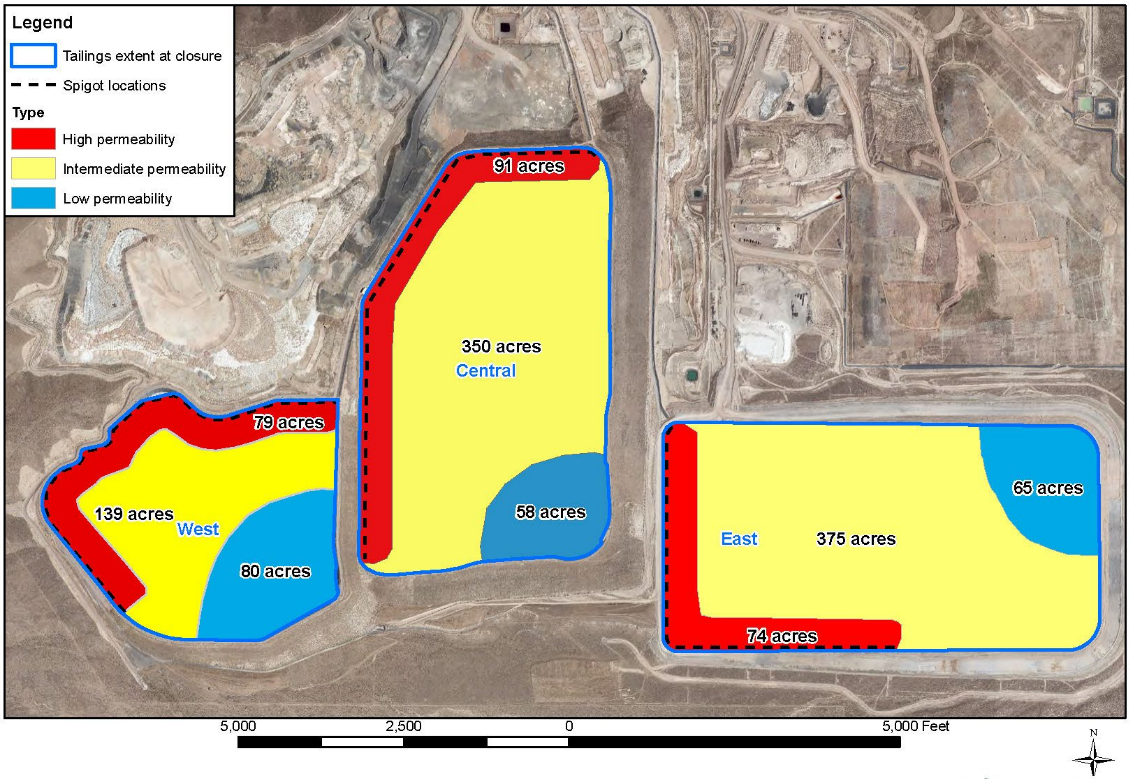


Figure 5 Areal extents of tailings types at Gold Quarry Mill 5/6 West, Central, and East TSFs

The High Permeability areas were defined as extending 150 m beyond the spigot location located along the edge of the TSFs. The 150 m distance was based on observations of predominantly <50% fines tailings being encountered at auger points within 150 m of the TSF. The decant pond areas are predominantly comprised of finer textured tailings (>80% fines), representing Low Permeability tailings. Low Permeability areas were delineated using ponded area extents (i.e., decant pond areas) shown in 2020 orthoimagery. Intermediate Permeability areas were defined as the areas between the High and Low Permeability areas. This assignment of Low Permeability tailings resulted in a transition from Intermediate to Low Permeability tailings at a distance ranging from approximately 600 m to 1,200 m from the spigot point.

3.2.2 Tailings deposit thickness

The laboratory testing program included 1D consolidation testing, to support the tailing properties domains discretization with depth. The depth of tailings was determined based on the planned closure configuration of the TSFs. Testing was completed at surcharge pressures equivalent to 4, 25, and 73 m of tailings column. The lab data indicated a consistent nonlinear decrease in K_{sat} as the simulated tailings depth increased, in addition, lower percent fines generally correlated with a higher K_{sat} value.

The estimated tailing thicknesses are shown for the TSF in Figure 6. The projected maximum TSF thickness at closure is 75 m or less. The TSF thickness was broken into 15 m intervals (e.g., 15 m thick, 30 m thick, 45 m thick, etc.) and overlain with the permeability unit delineation to derive the area of each permeability unit as a function of tailings thickness. The resulting calculated areas were applied to the one-dimensional numerical draindown model representing that tailings type and thickness to convert model predicted unit flux rates to a TSF volumetric flux. For example, the Intermediate Permeability tailings type area that is 45 m thick was applied to the Intermediate Permeability, 45 m thick numerical draindown model results. There were 14 tailings type and thickness combinations. Figure 6 provides an example of the estimated permeability unit and areas by tailing thickness for Mill 5/6 West TSF.

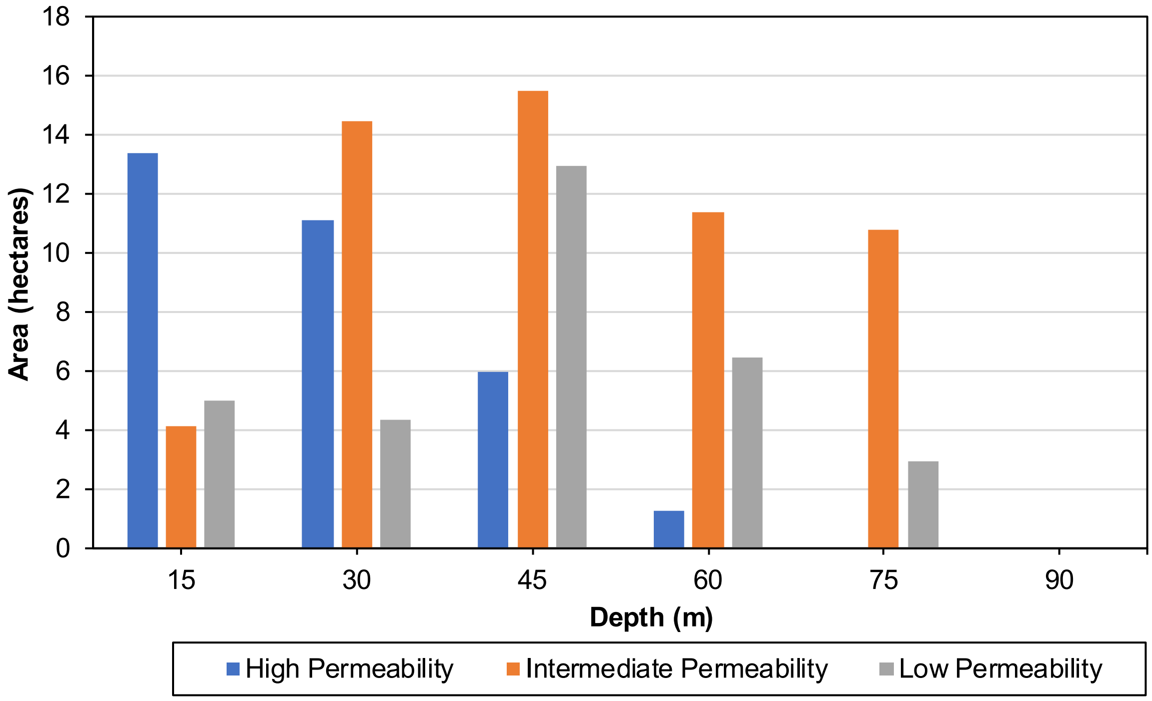


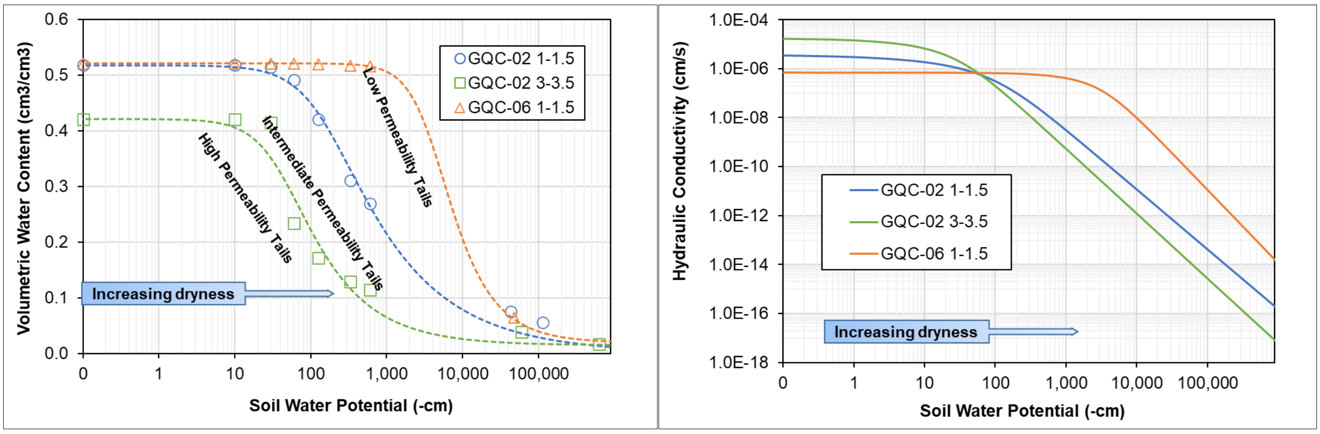
Figure 6 Mill 5/6 West TSF area as a function of permeability type and thickness

3.2.3 Tailings properties and model calibration

The measured and van Genuchten (1980) model-predicted soil water retention curves for the tailings samples are provided in Figure 8a. The finer-textured samples representative of Low Permeability tailings have higher saturated water contents and drain at more negative soil water potentials than the coarser- and intermediate-textured samples representative of High and Intermediate Permeability tailings. There is good agreement between the measured data and optimized van Genuchten model used to describe the MRC. The van Genuchten model-predicted unsaturated hydraulic conductivity functions are shown in Figure 7b.

The models were calibrated to measured seepage outflow. The tailings depth affects the long-term consolidation and draindown of the tailings, thus TSF seepage outflow rates were projected to the time of closure and the draindown models initial outflow rates were calibrated against these projected seepage outflow rates. Projection of seepage outflow rates were accomplished by first filtering the measured TSF outflow data using a Gaussian weighted smoothing kernel set to be 730 days and then fitted with an exponential regression, reaching 67 gpm at the end of tailings deposition.

Model calibration was achieved by adjusting for all tailings thickness layers the tailings K_{sat}, unsaturated hydraulic properties, and initial conditions such that model predicted TSF outflow on day one post-closure matched the projected seepage outflow rates at the end of tailings deposition, or approximately 67 gpm. The calibrated K_{sat} values are summarised in Table 1 while the tailings unsaturated properties are shown in Table 2.



(a) (b)

Figure 7 **Tailings properties charts: (a) Measured (symbols) and fitted (lines) moisture retention curves; (b) van Genuchten model-predicted unsaturated hydraulic conductivity functions**

The optimized van Genuchten model parameters of the tailings materials are provided in Table 2. Based on the general correlation of the samples with percent fines, representative permeability classifications of Low Permeability Tailings; Moderate Permeability Tailings; and High Permeability Tailings were assigned to each sample and mean parameter values calculated for each permeability classification prior to model calibration.

Table 1 **Calibrated saturated hydraulic conductivity**

Depth (meters below ground surface)	Saturated hydraulic conductivity (cm/s)				
	High permeability	Intermediate Permeability		Low Permeability	
	Calibrated	Uncalibrated	Calibrated	Uncalibrated	Calibrated
0 - 15	6.9E-05	1.2E-05	7.5E-06	6.4E-07	4.9E-07
15 - 45	1.7E-05	3.8E-06	2.4E-06	3.2E-07	1.4E-07
>45	6.0E-06	1.5E-06	9.4E-07	2.1E-07	1.0E-07

Table 2 Calibrated unsaturated hydraulic properties

Parameter	Depth (meters below ground surface)	Tailings permeability type		
		High	Intermediate	Low
Saturated water content (cm3/cm3)	0 - 15	0.470	0.470	0.551
	15 - 45	0.456	0.445	0.499
	>45	0.430	0.416	0.461
Residual water content (cm3/cm3)	>0	0.015	0.001	0.028
Alpha (1/cm)	>0	0.025	0.007	0.0004
N (-)	>0	1.649	1.449	1.641
L (-)	>0	-1	-1	-1

3.3 Draindown curves produced using the FEM method

3.3.1 Model domain and discretization

Post-closure draindown of the TSF was evaluated numerically using the HYDRUS-1D modeling platform (Šimůnek et al., 2013). A series of one-dimensional numerical models were constructed to represent TSF areas with High, Intermediate, or Low Permeability tailings material types and closure tailings thickness ranging from 50 ft to the maximum tailings thickness. An example model domain is presented in Figure 2. The tailings type remained constant with depth, however, the tailing type was subdivided into materials representative of 0 to 15 mbgs, 15 to 45 mbgs, and greater than 45 meters thick. The simulations were completed using tailings thicknesses in 15 m increments ranging from 15 to 75 m, such that 13 models were created. Model discretization ranged from 1 centimeter (cm) to 15 cm, typically being thinner near the top of the model and increasing as model thickness increased.

3.3.2 Boundary conditions

TSF reclamation plans include a 0.6 m thick store and release cover. The assigned upper boundary condition was a constant flux equal to 1% of the average annual amount of precipitation, or approximately 2.5 millimetres per year (mm/yr). This constant flux was specified based on analogues such as the observed cover system water balance at the Goldstrike AA Leach Pad (Zhan et al., 2014) and net percolation monitoring at the Phoenix Mine Copper Leach Pad Cover Test plot. The lower boundary condition was assigned as a seepage face boundary consistent with a coarse-grained drainage layer over the geomembrane lined base of the TSFs.

3.3.3 Initial conditions

The initial conditions for the TSF was developed for the assigned tailing types and depths found in each facility. The assignment of initial conditions was guided by measured piezometer data and model calibration to measured seepage outflow.

- Coarse-grained High Permeability tailings initial matric potentials were set equivalent to a net percolation flux of 5% of average annual precipitation in the pre-reclaimed, uncovered tailings surface. Net percolation flux of 5% of precipitation was conservatively used for the initial conditions since it represented conditions wetter than field capacity.

- The Intermediate Permeability tailings were assigned via model calibration to be tailings initial matric potentials equivalent to a net percolation flux of 5% of precipitation from 0 to 45 mbgs and 100% saturation at depths greater than 45 mbgs.
- The Low Permeability tailings were assigned to be saturated over the entire depth, consistent with ponded surface conditions that exist in the decant pond area represented by the Low Permeability tailings.

3.3.4 Model results

Post-closure, seepage is predicted to decline exponentially with time. The TSF draindown curve is comprised of multiple draindown curves representing different TSF tailings type and thickness models, as exemplified in Figure 8. As the tailings desaturate, the flux rate from the tailings decreases exponentially.

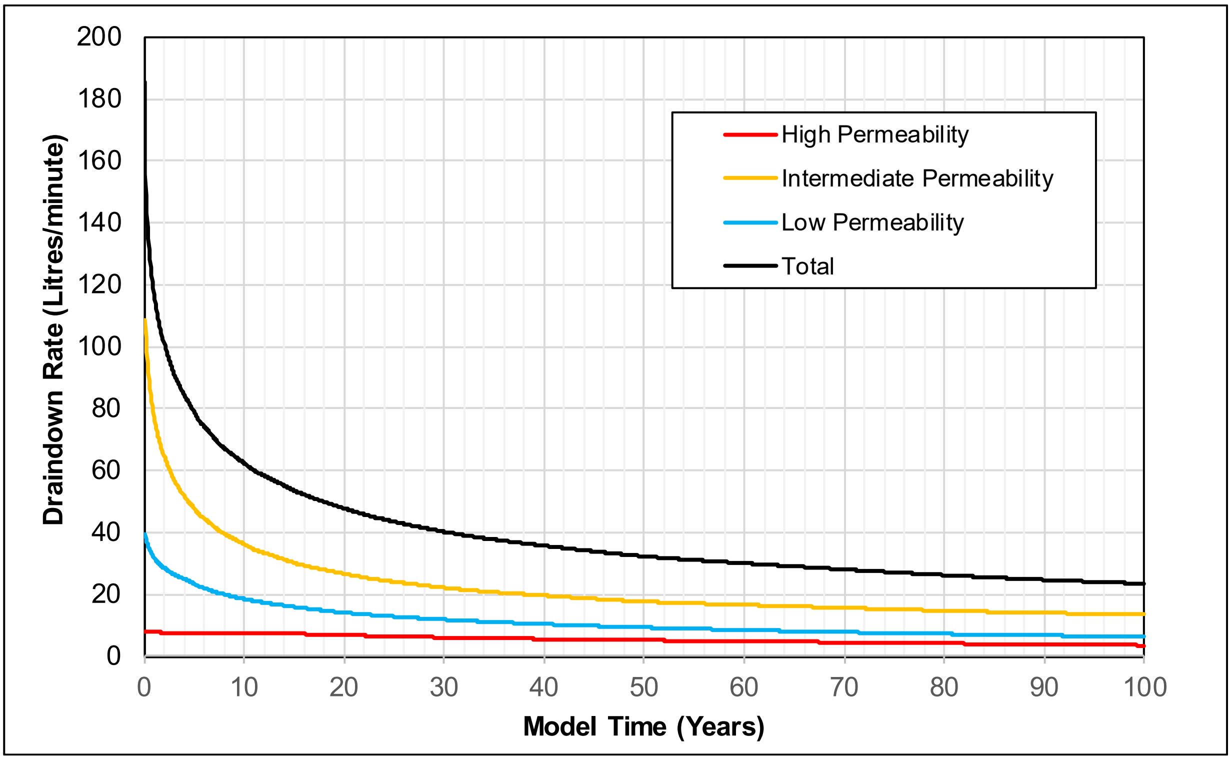


Figure 8 Mill 5/6 West TSF draindown rates predicted for each tailings type

3.4 Surface water balance model using analytical methods

3.4.1 Input data

The draindown curve implemented in the surface water balance model relies on predicting the relative unsaturated hydraulic conductivity and the moisture content based on the van Genuchten model. The analytical implementation is then calibrated to match the draindown curve generated in Hydrus.

Feedback from the reclaim pond water balance is then incorporated into the draindown curve, such that infiltration of recirculation solution that is not lost to evaporation is accounted for and the TSF draindown curve changes shape to reflect this.

The model was built as a Microsoft Excel spreadsheet and includes two interconnected functional modules: Surface Model and Draindown Model respectively. A monthly model timestep is applied.

The surface boundary parameters include the following:

- **Evaporation:** Average monthly total reference potential evaporation (ET_0) was acquired from the Desert Research Institute Climate Engine (ClimateEngine.org) between 1980 and 2020. Pond evaporation was approximated as being equal to 70% of the pan evaporation, which in turn was obtained from the ET_0 by applying a transformation coefficient of 1.271.
- **Precipitation**: Included as monthly totals, representing the average monthly totals computed from daily data recorded by the Gold Quarry Mine weather station between 1991 and 2021. The amount of precipitation was partitioned into direct precipitation onto the pond and precipitation on the non-ponded surface.
- **Run-off:** A run-off coefficient of 0.13 was applied to the calculated dry surface precipitation, which would then be accounted for as reporting to the pond. The run-off coefficient was estimated for the generic dry cover surface based on the SCS runoff curve number method (USDA 1986).
- **Net percolation:** Calculated as 1% of the precipitation applied to the dry surface (total footprint less pond surface). The volumetric amount of net percolation was dynamically adjusted to match the dry surface area of the TSF as the pond area is shrinking in time. The 1% of precipitation value was estimated based on GSA's experience with results from cover performance monitoring at other mines in the area, as well as published literature (Zhan et al, 2014).

Water management parameters are introduced as follows:

- **Recirculation:** For the duration of the active water management period it is assumed that the entire volume of TSF seepage, minus solution removed by forced evaporation, is recirculated to the the TSF surface pond. Start and end dates of recirculation period are user specified.
- **Forced evaporation**: An inventory sink term achieved by use of evaporators operating intermittently while active recirculation is enabled and evaporation efficiency is above 10%, i.e. forced evaporation is shut down during the winter months. The forced evaporation term is implemented using the following controls:
  - number of units
  - evaporator pump capacity
  - evaporator efficiency
  - daily operating time duration
  - start and end dates of evaporator operations period are user specified.

3.4.2 Draindown model results

Figure 9 shows example model results assuming the following solution management scheme:

- Three evaporators, each with a 25 cubic meters per hour pump capacity and operating 12 hours per day.
- Active evaporation for the first three years of draindown.
- Seepage outflow recirculation for the first 10 years of draindown.

The draindown is computed as the interplay between the draindown flux and the environmental and operational parameters. As long as recirculation is active, the amount of draindown seepage is increased relative to the no management condition because of a portion of the recirculated water infiltrates into the TSF and eventually becoming seepage outflow. This is evident in Figure 7, where the divergence between the pure draindown curve produced by the FEM modelling and the curve modeled here is due to the recirculation volumes. However, during this period a portion of seepage outflow is also being lost to active evaporation and passive evaporation from the pond. Once recirculation is stopped, the TSF reverts to the pure draindown state and follows the shape of the Hydrus-calibrated curve.

At the end of recirculation, the model predicts a seepage outflow rate of 83 litres per minute and continually decreases through the remainder of the 100-year model period. Assuming an annual average E-cell evaporation rate of 27 m^3/day/Ha, a 4.5-hectare sized E-cell would be required to passively manage the TSF seepage outflow.

In practice, multiple scenarios evaluating a range of quantities of evaporators, time length of active evaporation, and time length of recirculation are evaluated and incorporated into a cost-benefit analysis of active management capital and operations costs versus E-cell size and construction costs.

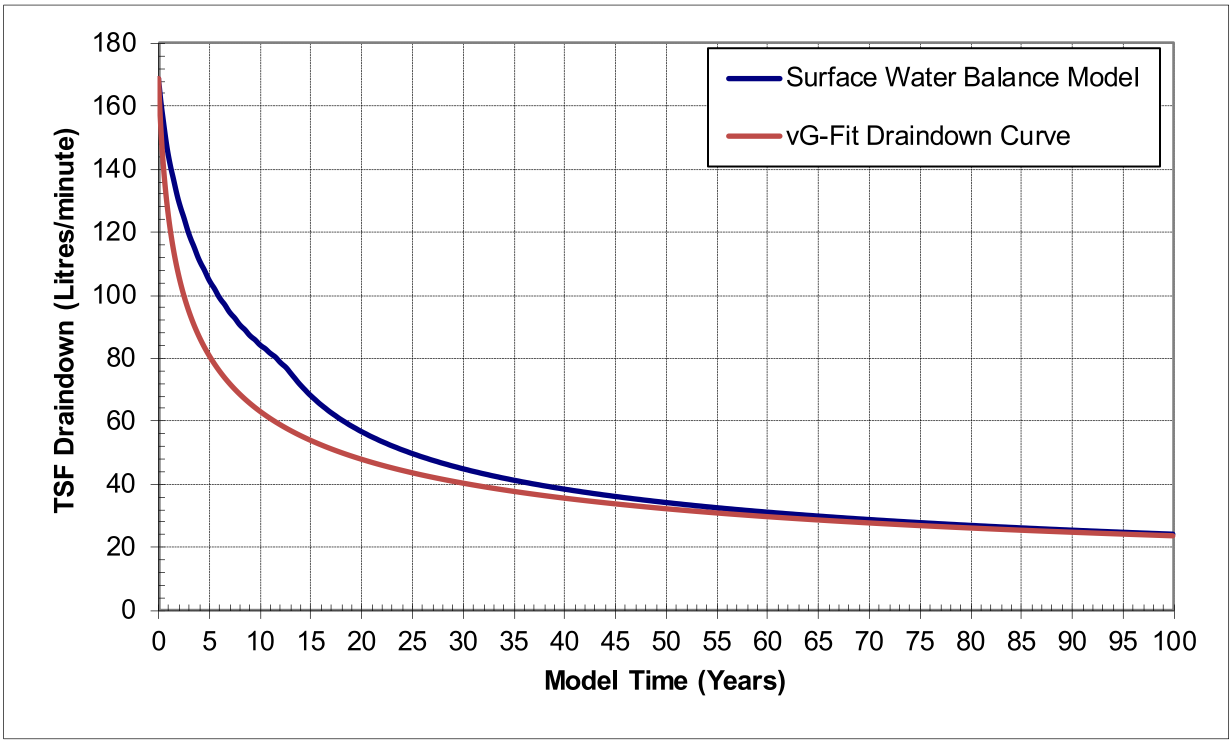


Figure 9 Illustration of difference between predicted TSF draindown (FEM draindown) and water balance draindown curves

4 Conclusion

A method to predict the TSF draindown is described in this paper, together with an example of how the method was implemented at a gold mine in Nevada. Unit draindown curves are generated using rigorous finite element numerical modelling for each of the tailings types generally encountered in hydraulically deposited tailings, which are then assembled into a single curve representative of the TSF as a whole. The representative draindown curve is used as an input to a surface water balance model which allows testing of various water management configurations in the closure and post-closure periods.

The model can be implemented for any climate, with the appropriate surface water management assumptions being included in the inputs. This flexibility is allowed by the fact that run-off and net percolation are dealt with as separate independent terms in the water balance. Climate change considerations could also be included in the model, by altering the surface boundary of the FEM predicting the draindown curves and/or adjusting the water balance inputs for climate change.

Generating the draindown curves using FEM methods requires considerable expertise and experience. However, once the draindown curves are created the analytical water balance model allows flexibility to implement a wide range of water management variables in a spreadsheet model easy to understand and change by mine personnel. Inclusion of cost estimations directly into the water balance model is also possible.

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References

ESRI (2023). ArcGIS v10.8, computer software, ESRI, Redlands, California, USA. Retrieved May 24, 2023, from https://www.esri.com/en-us/arcgis/about-arcgis/overview

Madariaga, P, Wels, Christoph and Robertson, Andy MacG. (2004). "Water recovery study for Pampa Pabellon tailings impoundment, Collahuasi, Chile." *Semathic Scolar* DOI:10.1201/9780203021637.CH10Corpus ID: 133443217.

Rykaart, Maritz E. Fredlund, Del G., Wilson, G. Ward (2002). Spatial surface flux boundary model for tailings impoundments. In Tailings and Mine Waste 2002: Proceedings of the 9th International Conference, Fort Collins, Colorado, (1st ed.). CRC Press. https://doi.org/10.1201/9781003078753

Silver, Richard L. (2013). Unsaturated Flow Analysis of Heap Leach Soil, MSc thesis, Boston College, Chestnut Hill Massachusetts, USA.

Šimůnek, J., M. Šejna, H. Saito, M. Sakai, and M. Th. van Genuchten (2013) The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.17, HYDRUS Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, pp. 342.

United States Department of Agriculture (1968) Natural Resources Conservation Service, Conservation Engineering Division, Technical Release 55: Urban Hydrology for Small Watersheds. June 1986.

van Genuchten, M.Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Am. Jour., 44:892-898.

Whitman, Spenser K. (2016). Inter-Code Comparison of Variably Saturated Fluid Flow and Prediction of Percolation through a Tailings Impoundment in Southeast Nevada, USA, MSc Tesis, University of Nevada, Reno, Nevada, USA.

Zhan, G., J. Keller, M. Milczarek, J. Giraudo (2014) 11 Years of Evapotranspiration Cover Performance at the AA Leach Pad at Barrick Goldstrike Mines, Mine Water and the Environment, DOI 10.1007/s10230-014-0268-6