Mine Water and the Environment
https://doi.org/10.1007/s10230-026-01124-w

TECHNICAL ARTICLE

Tailings Storage Facility Iterative Simulation Model (TSFISM): A Dynamic Simulator

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Received: 12 September 2025 / Accepted: 7 May 2026

Abstract

The tailings storage facility iterative simulation model (TSFISM) is a dynamic water-balance simulator that was developed in Microsoft Excel 365®. The TSFISM workbook has a user-friendly interface that incorporates all natural and mine-related inflows and outflows to and from a tailings storage facility (TSF). TSFISM simulates TSF pool stages and free-water volumes by solving iteratively for changes in pool stage and volume at the end of each time step. TSFISM reliably accounts for the dynamic changes in TSF-pool geometry during operations by distributing tailings volumes proportionally by tailings-production mass. Free-water volumes are calculated from frequent bathymetric surveys and tailings production, which negates complexities associated with variably saturated flow, computation of water entrainment, and dry/wet beach evaporation. TSFISM predicts bathymetric surveys at user-specified time intervals for future scenarios. A regression between cumulative tailings production and measured pool-bottom elevations is used to estimate future bathymetries from projected tailings production. TSFISM also dynamically simulates TSF beach and catchment runoff, allowing the beach area, catchment area, and runoff coefficient to vary with time. TSFISM has robust capabilities to simulate a variety of site-specific TSF conditions and can run an unlimited number of water-management scenarios under climatic uncertainty.

Keywords Microsoft excel · TSF · Water balance · Bathymetry prediction · Climatic uncertainty

Introduction

A tailings storage facility (TSF) is an engineered containment structure designed to store and manage tailings and the effluent from mining operations (Williams 2016). Tailings are the fine-grained, mine-waste byproduct that remain after economic minerals are extracted from ore processing (Cacciuttolo and Valenzuela 2022). Conventionally, tailings are deposited into a TSF as a water slurry with a solids content < 60% (Cacciuttolo and Valenzuela 2022; East and Fernandez 2021; Williams 2016). Excess slurry water forms a supernatant pool in the TSF, and water pumped from this pool to support milling operations is referred to as reclaim water (East and Fernandez 2021).

Proper management of TSF water and tailings is essential to ensure efficient water use during mining operations, prevent uncontrolled releases of TSF water to the environment, and prevent potential oxidation and acid–water generation for water covers atop closed TSFs (Cacciuttolo and Valenzuela 2022). Therefore, mine sites with TSFs require a water balance model. A TSF water balance model is more than a data-tracking tool. Rather, a robust TSF water balance model is calibrated to historical data and used for future projections, where the goodness-of-fit to the historical period provides confidence in the model's predictive capability. TSF water balance models typically address the following: (1) planning of the future schedule of dam embankment raises or construction of new TSFs; (2) ensuring that future TSF reclaim water can support mine operations during dry periods without exceeding allowable freshwater withdrawal;

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Published online: 18 May 2026

(3) ensuring that future TSF pool levels remain below the maximum operating water level (MOWL), or freeboard, to prevent loss of hydraulic containment during extreme events, such as the probable maximum precipitation or environmental design flood; (4) understanding dynamic changes in TSF pool levels and volumes for closed TSFs with water covers; and (5) testing future water management scenarios for mine operations and closure (Cooper et al. 2018).

TSF water balance models typically are developed as part of a site-wide water balance using either GoldSim (e.g. Cooper et al. 2018; Nalecki and Gowan 2008; Schmidt 2023; Tuff et al. 2015), Microsoft Excel® (e.g. Coffey et al. 2021; Ford 2010; Hertel 2018; Janowicz 2011), or a coupled GoldSim-Excel approach (Firmani 2024; Janowicz 2011). Whichever the case, the TSF is treated as a reservoir and all inflows and outflows are tracked to and from the TSF supernatant pool. In many cases, the TSF water balance assumes a static bathymetry (i.e. stage-area-volume relation) to compute precipitation on the pool, evaporation from the pool, and surface-water runoff. As tailings are deposited after this static bathymetry, the stage-area-volume relation becomes less valid with time. Donnelly (2023) proposed the use of a series of historic bathymetric surveys, basically a look-up table, to account for the evolving TSF beach and pool geometry. Even with the incorporation of multiple historical bathymetric surveys, calculation of the free-water volume has inaccuracies because the tailings solids are not tracked and discounted between surveys. Cooper et al. (2018) recognized these limitations and proposed the coupling of GoldSim with a three-dimensional deposition model (Muk3D), which is computationally intensive and cannot feasibly be used by TSF water managers.

If the TSF water balance includes entrainment, which is the volume of water that is stored in the pore space with tailings deposition, the simplified assumptions are invalid (Lopes and van Zyl 2006). For example, using a fully saturated simplified assumption or assuming entrainment losses are a constant does not adequately capture the dynamic behavior of TSF pool stages and volumes, which are constantly evolving from tailings deposition during active mining operations. The result is a model with a TSF pool stage and volume prediction that is not always reliable for water-management decisions. To calculate entrainment, more complex equations and models are required to adequately account for variably saturated flow and consolidation conditions within a TSF (Solgi 2017). Wels and Robertson (2003) developed a "water-recovery model" to simulate the dynamic behavior of water losses, including entrainment losses on initially inactive beaches; evaporation and rewetting losses from active-beach flooded areas; and evaporation and seepage from the supernatant pool. Even though the water-recovery model was able to simulate water losses from TSFs in semi-arid to arid regions (Wels and Robertson 2003; Wels et al. 2004), the approach requires an accurate estimation of the actively flooded beach areas with time, extensive field and laboratory testing of geotechnical and hydrologic tailings properties, and soil-atmosphere modeling.

The tailings storage facility iterative simulation model (TSFISM) described herein provides a functional alternative to manage the water balance and tailings accretion of a TSF in a Microsoft Excel 365® macro-enabled workbook. TSFISM uses an unconventional, but accurate, approach to dynamically simulate the TSF water balance and tailings accretion with tailings production, repeat bathymetric surveys, TSF pool stages, and readily measured quantities at a mine site. All natural and mine-related flow components for a TSF are specified through standard tabular data. TSFISM includes the following features: (a) a flexible simulation time, where user-defined data inputs and TSFISM time steps of stages and volumes can differ; (b) simulation of TSF pool stages and volumes by solving iteratively for changes in pool stage and volume at the end of each user-defined time step; (c) estimation of TSF water seepage through non-synthetically lined foundations, where seepage rates change dynamically based on TSF pool area; and (d) dynamic simulation of surface-water runoff, allowing the beach area, catchment area, and runoff coefficient to vary with time to reflect land-use and vegetation condition changes. Dynamically simulating the runoff is required to reflect water-management changes that frequently occur during the mining operation and closure phases, where runoff is a function of TSF pool stage, such that runoff from the beach area decreases as the TSF pool stage and area increase. The TSFISM model can accurately simulate historic pool stages and free-water volumes and predict pool stages and free-water volumes within climatic uncertainty. TSFISM can be applied to active, inactive, and closed TSFs to simulate the water balance of the pool.

Mathematical formulations of the TSFISM model are programmed in Visual Basic for Applications (VBA) within the TSFISM workbook and do not require additional software beyond Excel. An Excel-based model provides a practical and transparent alternative to complex 2D or 3D numerical simulations. All VBA code is accessible and can be reviewed directly by mine operators, consultants, and regulators, which facilitates regulatory review, quality control, and communication with stakeholders, thereby reducing the risk of hidden errors and increasing confidence in the results. Because Excel is widely available and familiar to professionals in the mining industry, TSFISM can be used without specialized software or extensive training.

The TSFISM model documentation described in this paper uses data and results from the East TSF at Gold

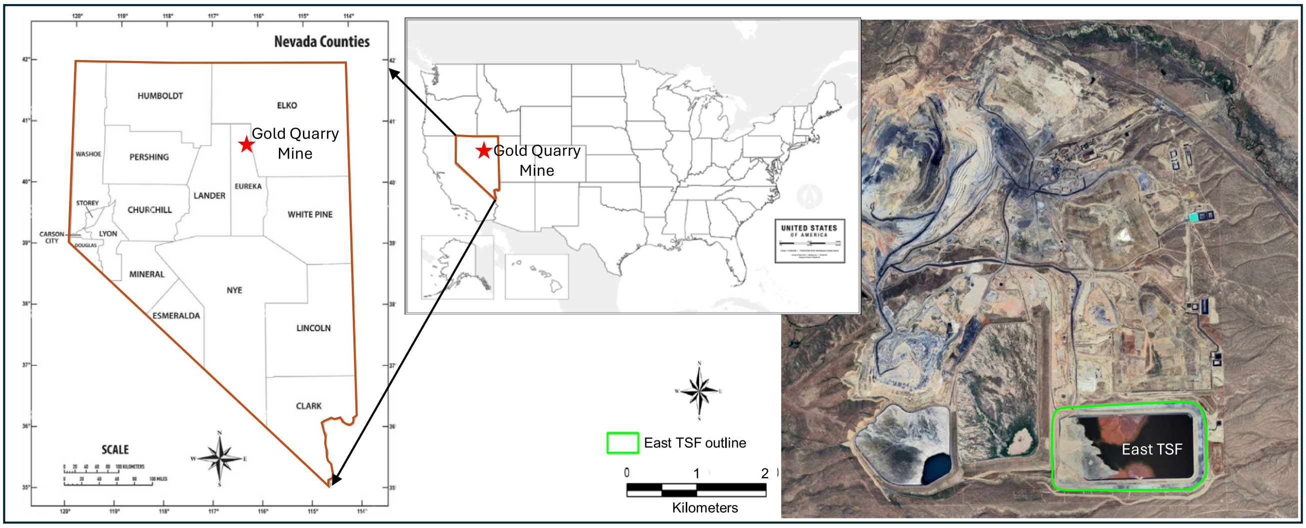


Fig. 1 Location of the East TSF at Gold Quarry Mine, Nevada, USA

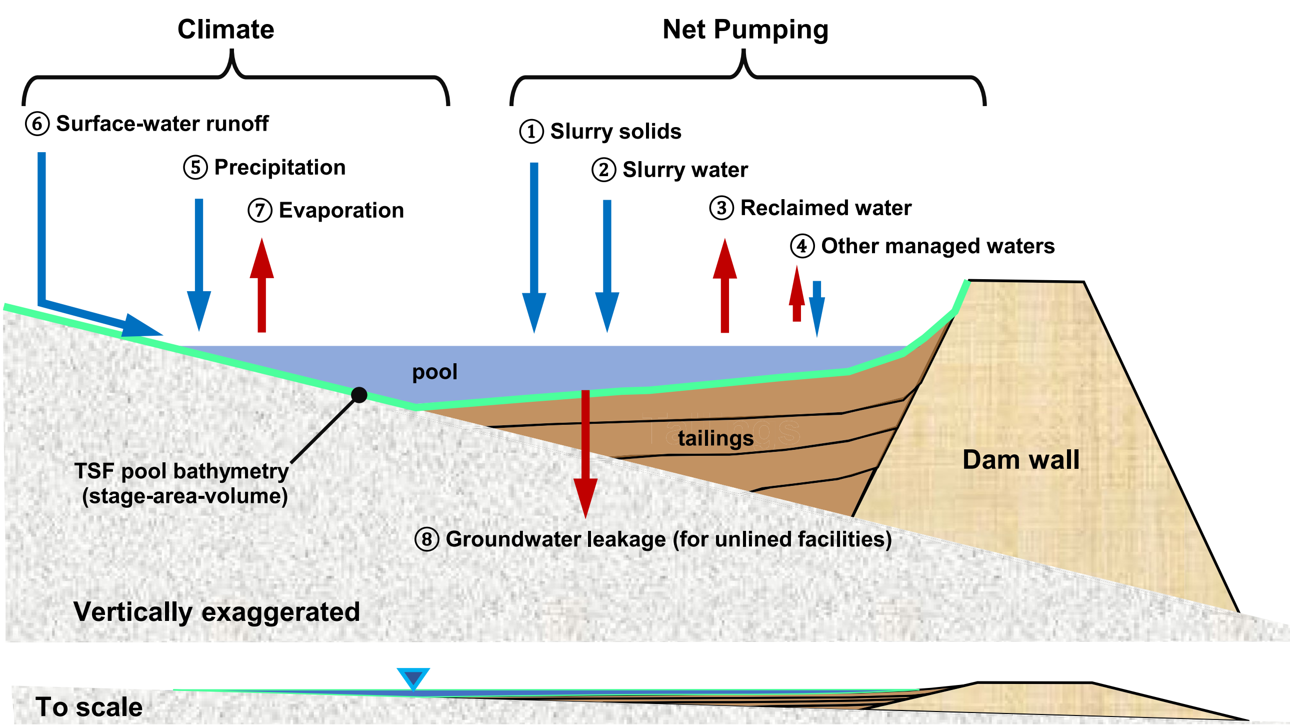


Fig. 2 Schematic of inflow and outflow terms for the water balance of a tailings storage facility

Quarry Mine in northeastern Nevada, USA (Fig. 1), as a case-study example, for demonstration purposes and validation. A complex case-study example also is presented from an undisclosed TSF in western Africa, which is an unlined TSF that had periods of active slurry-water inflow and periods of inactivity where the pool went dry.

TSF Water Balance

The TSF water balance consists of "pumping", climatic, and groundwater components (Fig. 2). The "pumping" component includes all mine-related inflows and outflows. Principal "pumping" inflows are tailings discharged into the TSF pool as a slurry consisting of slurry solids ① and slurry water ② (Fig. 2). Slurry-solids tracking is described in the section "Computation of Free-Water Volume". The principal "pumping" outflow is reclaimed water ③ pumped from the TSF pool. Other managed waters ④ include site-specific components, such as seepage outflow to drains, or water treatment intake and rejection (i.e., RO permeate outflow and concentrate reject inflow). Slurry solids, slurry water, reclaimed water, and other managed flows are collectively classified as "net pumping" (Fig. 2). Climatic components include direct precipitation on the pool ⑤, surface-water runoff to the pool ⑥, and open-water evaporation from the pool ⑦ (Fig. 2). Flow rates of these three climatic terms depend on the pool surface area, which changes dynamically as tailings are deposited. A TSF may have a groundwater component that accounts for uncaptured leakage to the groundwater system ⑧ for non-synthetically lined facilities (Fig. 2).

Climatic Components

Direct precipitation on the pool (Q_p, [L^3/T]), open-water evaporation from the pool (Q_E, [L^3/T]), surface-water runoff to the pool from the beach ($Q_{RO,beach}$, [L^3/T]), and surface-water runoff to the pool from the catchment ($Q_{RO,catch}$, [L^3/T]) are computed as:

$$Q_p = PA \tag{1}$$

$$Q_E = EA \tag{2}$$

$$Q_{RO,beach} = (P - P_{thresh,beach}) * RO_{beach}(A_{TSF} - A) \tag{3}$$

$$Q_{RO,catch} = \sum_{i=1}^{n} (P - P_{catch-thresh,i}) * RO_{catch,i}\,(A_{catch,i}) \tag{4}$$

where P is the precipitation rate, [L/T]; E is the open-water evaporation rate, [L/T]; A is the pool area, [L^2]; $P_{thresh,beach}$ is the threshold precipitation rate at which runoff occurs from the TSF beach area, [L/T]; RO_{beach} is the precipitation-runoff efficiency of the TSF beach area, dimensionless; A_{TSF} is the total area of the TSF, [L^2]; i is the number of different catchment areas around the TSF, dimensionless; n is the total number of different catchment areas around the TSF, dimensionless; $P_{catch-thresh,i}$ is the threshold precipitation rate at which runoff occurs from catchment area i, [L/T]; $RO_{catch,i}$ is the precipitation-runoff efficiency of catchment area i, dimensionless; and $A_{catch,i}$ is the area of catchment i, [L^2].

The precipitation rate, P, is the measured precipitation, in the form of rain and snow, that is used to compute precipitation on the TSF pool (Eq. 1). However, the precipitation rate, P, can be the effective precipitation rate for surface-water runoff (Eqns. 3 and 4), where contributions from snow are included when snow melts rather than when snow accumulates. For surface-water runoff, effective precipitation differs from measured precipitation when snow accumulation and snowmelt occur in different months. Differences in timing between snow accumulation and snowmelt are estimated externally from TSFISM. Note that the flow rates of the climatic components depend on the TSF pool surface area, which changes dynamically as the pool stage changes.

Surface-water runoff to a TSF pool is estimated from time series of P and catchment characteristics. Catchments are defined by area, runoff percentage, and threshold precipitation. These characteristics can change during the life of a TSF and, accordingly, are defined as time series (e.g., $RO_{catch,i}$; $A_{catch,i}$; $P_{catch-thresh,i}$). TSFISM allows catchment characteristics to change at user-specified times to reflect land-disturbance changes. Surface-water runoff uses "available precipitation", defined as $P - P_{thresh}$, which is limited to 0 if threshold precipitation exceeds effective precipitation. In addition, surface-water runoff from the catchment area is a summation of individual catchment areas with their respective runoff coefficients and precipitation thresholds. As an example, the total catchment area to a TSF may have different landform types, slopes, and hydrologic properties that need to be specified individually.

Groundwater Component

Groundwater leakage is uncaptured TSF leakage to the groundwater system, which occurs only for unlined (e.g., clay-lined) TSFs that lack an impermeable synthetic liner. Groundwater leakage [Q_{GW}, (L^3/T)] can be computed from Darcy's Law (Bear 1979), using either hydraulic conductivity [L/T] or hydraulic conductance [1/T], as shown in the equations below.

$$Q_{GW} = KA\frac{dh}{dl} \tag{5}$$

$$Q_{GW} = CDA\frac{dh}{dl} \tag{6}$$

where K is the hydraulic conductivity, [L/T]; C is the hydraulic conductance, [1/T]; D is the TSF pool depth, [L]; and $\frac{dh}{dl}$ is the vertical hydraulic gradient, [L/L], which is equal to 1 (vertically downward leakage).

Hydraulic conductivity is specified if tailings are assumed to control leakage (Eq. 5). Hydraulic conductance is specified if the clay liner beneath the TSF is assumed to control leakage (Eq. 6). Synthetically lined TSFs have a groundwater leakage of zero, which is set by specifying either hydraulic conductivity or hydraulic conductance as zero.

Pumping Components

Slurry water, slurry solids, reclaimed water, and other managed flows are summed and referred to collectively as "net pumping". Reclaimed water and other managed flows typically are measured quantities from flowmeter readings, whereas the slurry components are calculated. Tailings discharged as part of a slurry result in a volume displacement of the pool level. Thus, the tailings-production mass is converted to a solids volumetric rate, Q_{solid} [L^3/T], from the expression:

$$Q_{solid} = \frac{T}{\rho_w S_g} \tag{7}$$

where T is the tailings tonnage rate to the TSF, [M/T]; ρ_w is the density of water, [M/L^3]; and S_g is the measured specific gravity of the tailings, dimensionless. Slurry-solid volumes are reasonably certain because the specific gravity of gold and copper tailings typically averages 2.7 and has a limited range between 2.5 and 3.0 (Vermeulen 2001). The slurry-water volumetric rate, Q_{slwtr} [L^3/T], is expressed as:

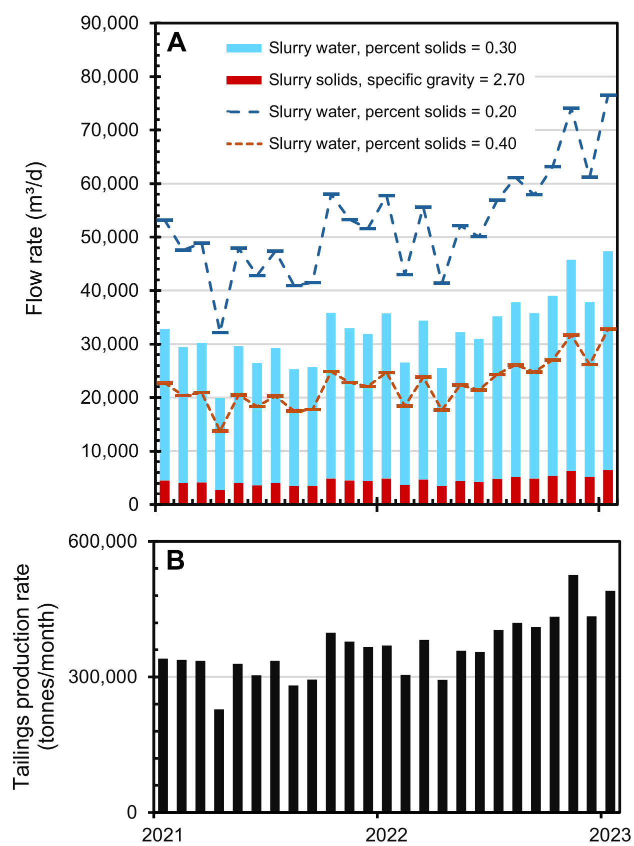


Fig. 3 Comparison of slurry-water flow rates for different percent-solids ranges, using data from the East TSF at Gold Quarry Mine, Nevada, USA. **A** Volumetric flow rates of slurry solids and slurry water from monthly tailings production with estimates of 0.2, 0.3, and 0.4 for percent solids. **B** Monthly tailings production rate

$$Q_{slwtr} = \frac{T}{\rho_w}\left(\frac{1-PS}{PS}\right) \tag{8}$$

where PS is the tailings-slurry percent solids, expressed as a mass fraction. Estimated slurry-water volumes are sensitive to PS. For example, using data from the Gold Quarry Mine East TSF, the total slurry-water volume increases by 71% if PS decreases from 0.3 to 0.2 [(1/0.2–1)/(1/0.3–1)], whereas the slurry-water volume decreases by 36% if PS increases from 0.3 to 0.4 [(1/0.4–1)/(1/0.3–1)] (Fig. 3).

Computation of Free-Water Volume

When slurry water and slurry solids are discharged into a TSF, a portion of the slurry water becomes entrained within the pore space of the deposited tailings, whereas the remaining slurry water forms part of the pool volume, referred herein as the "free-water volume". Traditional TSF water-balance models use simplifying assumptions to compute entrainment, which can underestimate the free-water volume. TSFISM avoids the complexities associated with accurately accounting for water entrainment by use of frequent bathymetric surveys and tailings-production (i.e. slurry-solids) tracking. The following sections describe the concept of entrainment, typical shortcomings of simplistic methods to compute entrainment, and how TSFISM negates the concept of entrainment in the computation of free-water volumes.

Entrainment Concept

Water movement within tailings is characterized as variably saturated flow. Pore spaces are fully saturated immediately beneath the TSF pool, resulting in saturated-flow conditions and a phreatic surface within the TSF (Fig. 4). Unsaturated flow occurs in the beach area and above the phreatic surface, where upward and downward water movement are driven by capillary action, matric suction, osmotic potential, and the volumetric water content (East and Fernandez 2021). As tailings are deposited with time, fine-grained material consolidates, reducing the pore space. The proportion of the tailings that are saturated, unsaturated, and consolidate with time changes dynamically as tailings are deposited, which affects entrainment and the proportion of water that forms the TSF pool with time.

Computing Entrainment Loss with Fully Saturated Assumption

Assuming that all tailings are fully saturated within a TSF is an invalid assumption in most cases, especially for non-synthetically lined TSFs. When assuming fully saturated

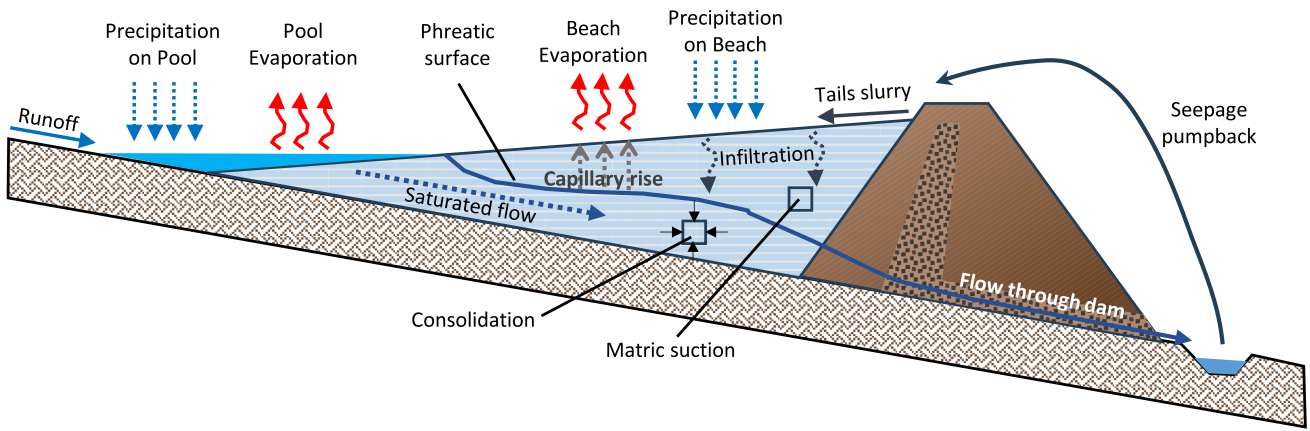


Fig. 4 Schematic of variably saturated flow conditions in a tailings storage facility

tailings, the entrainment loss (*EL*) equates to the saturated volumetric water content (or porosity) of the tailings and is expressed as (Wels and Robertson 2003):

$$EL = (S_g - \frac{\rho_{dry}}{\rho_w})/S_g \tag{9}$$

where ρ_{dry} is the tailings dry density, [M/L^3], and EL is expressed as a fraction. A typical entrainment loss for gold tailings is between 0.45 and 0.55.

The entrainment volumetric rate ($Q_{entrain}$) is the total volume of slurry water that is stored in the tailings pore space. Expressed as a fraction, slurry-water entrainment is the ratio of the entrainment volume to the total slurry-water volume. As a demonstrative example, consider a mine site with a tailings production rate of 10,000 tonnes/day at 30% solids and an entrainment loss of 0.48. The slurry-water volumetric rate equates to 23,333 m^3/d (Eq. 8), whereas the entrainment volume is computed as shown in Eq. 10.

$$Q_{entrain} = EL\left(\frac{T}{\rho_{dry}}\right) = 0.48\left(\frac{10{,}000 tonnes/d}{1.4 tonnes/m^3}\right) = 3{,}439 m^3/d \tag{10}$$

The ratio ($Q_{entrain}$ / Q_{slwtr}) is 15%, meaning that 15% of the total slurry water discharged to the TSF each day becomes entrained in the pore space. However, in reality, the tailings are not fully saturated and the volume entrained is less than 15%. This simplified assumption will result in water-balance predictions that underestimate the pool volume and are unreliable for TSF water management, especially for a non-synthetically lined TSF.

TSFSIM Approach — Bathymetry and Tailings-Production Tracking

In TSFISM, a user is expected to conduct a field bathymetric survey at regular intervals, ideally every three months, to map the TSF surface, from the bottom of the supernatant pool up to the top of the dam embankment. A stage-area-volume (SAV) relation is developed from the bathymetric-survey data to quantify changes in the tailings-surface geometry with time. For a given measured pool stage, the pool surface area and free-water volume are interpolated by use of frequent bathymetric surveys and tailings-production (i.e., slurry-solids) tracking. As shown in Fig. 5, the minimum TSF pool-bottom elevation (i.e. the deepest part of the pool) is the lowest measured stage in each SAV. An increase in the minimum TSF pool-bottom elevation between bathymetric surveys is correlated with tailings-production-volume accumulation with time (Fig. 5). Using this concept, the free-water volume of a TSF pool can be computed, which discounts entrainment and consolidation losses. Free-water volume, V_{Free} [L^3], is defined as:

$$V_{Free} = V_{SAV} - V_{tails} \tag{11}$$

where V_{SAV} [L^3] was the pool volume at the time of the bathymetric survey (SAV), calculated by interpolation from a pool stage, and V_{tails} [L^3] is the tailings-production volume since the bathymetric survey. Note that after a bathymetric survey, continued discharge of slurry water and slurry solids into the TSF causes the V_{SAV} term to be a composite of the slurry-water volume and slurry-solids volume, which is why the slurry-solids volume (V_{tails}) must be discounted to compute the free-water volume.

Tailings-production volumes that result in a volume displacement of the TSF pool are estimated each time a new bathymetric survey is measured. First, the total tailings-production volume is computed from the difference in volumes between consecutive SAVs (Fig. 6). Note that some tailings are deposited on the beach above the pool and these beach tailings must be discounted to provide an accurate estimation of the free-water volume. Thus, the next step is to compute the tailings-production volume *beneath the*

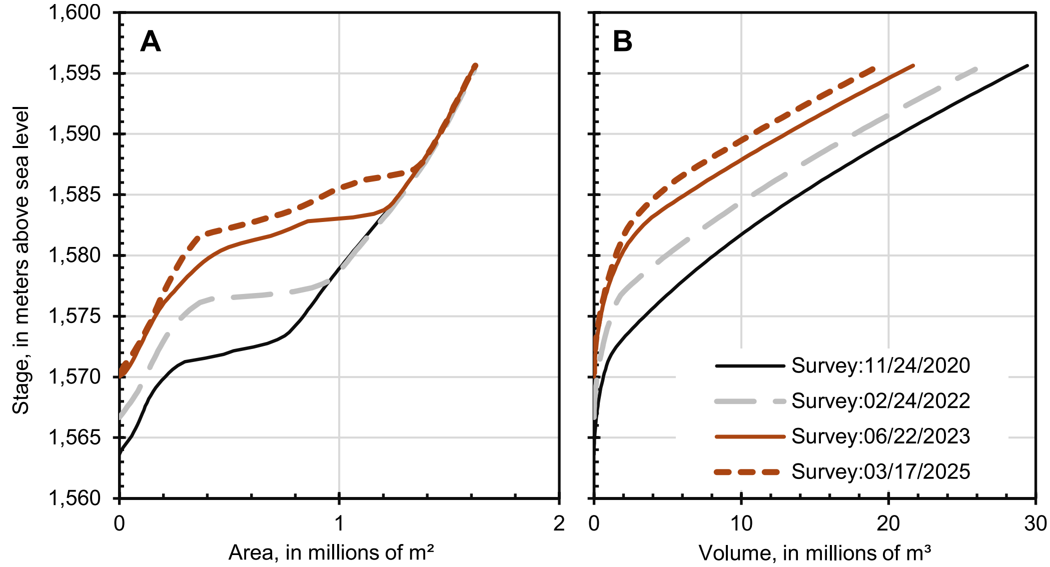


Fig. 5 Multiple stage-area-volume (SAV) relations from repeated bathymetric surveys. **A** Stage and area relations. **B** Stage and volume relations. Example uses data from the East TSF at Gold Quarry Mine, Nevada, USA

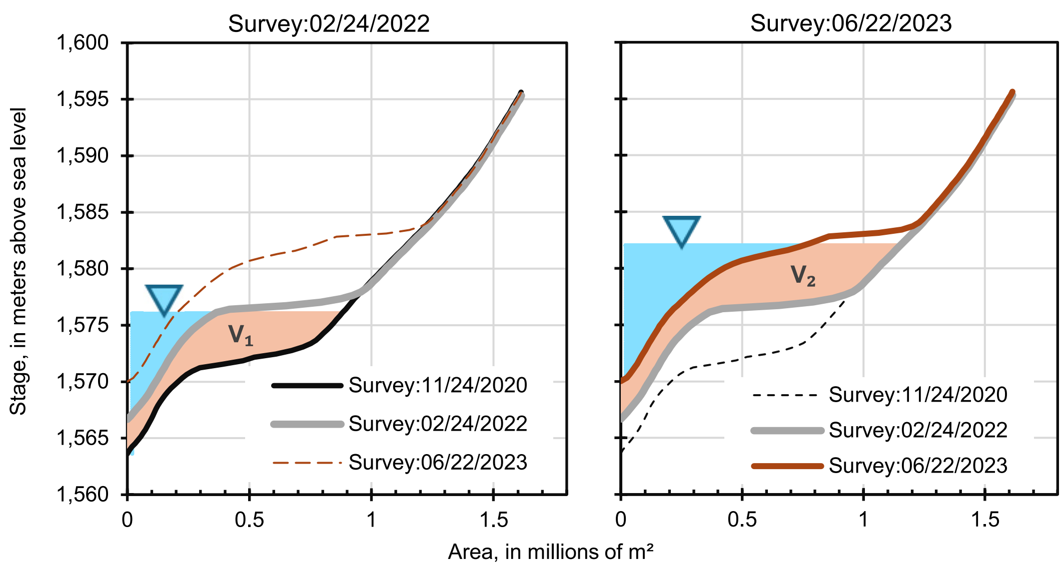


Fig. 6 Schematic of tailings-production volumes (V_1 and V_2) estimated from bathymetric surveys. Example uses data from the East TSF at Gold Quarry Mine, Nevada, USA

measured pool stage by interpolation using the new surveyed pool stage, and volume differences between the new and previous bathymetric surveys (Fig. 6). For example, bathymetry was measured on 06/22/2023 when the pool stage was 1,582.5 m. Pool volume from the 06/22/2023 SAV was 3.4 million m^3 (Mm^3) and equalled the free-water volume. Pool volume (V_{SAV}) is equal to free-water volume (V_{Free}) because negligible slurry discharge was assumed to occur during the bathymetric survey and above the pool stage. Pool volume (V_{SAV}) would have equalled 7.7 Mm^3 from the 02/24/2022 SAV for the same stage of 1,582.5 m. The difference between these two volumes, V_2, equalled a tailings-production volume (V_{tails}) of 4.3 Mm^3 that was deposited during the 483 days between bathymetric surveys (Fig. 6).

The difference in tailings-production volume (i.e. V_2 in Fig. 6) is redistributed between bathymetric surveys using a mass-weighted distribution approach (Fig. 7). As shown in the Fig. 7 example, tailings-production tonnage is tabulated monthly, and the cumulative tailings production is tracked with time (Fig. 7B). For the time period spanning the 02/24/2022 and 06/22/2023 bathymetric surveys, a total of 5.3 million tonnes (MT; 10.9–5.6 MT) was deposited, as measured from site data at the Gold Quarry Mine (Fig. 7B).

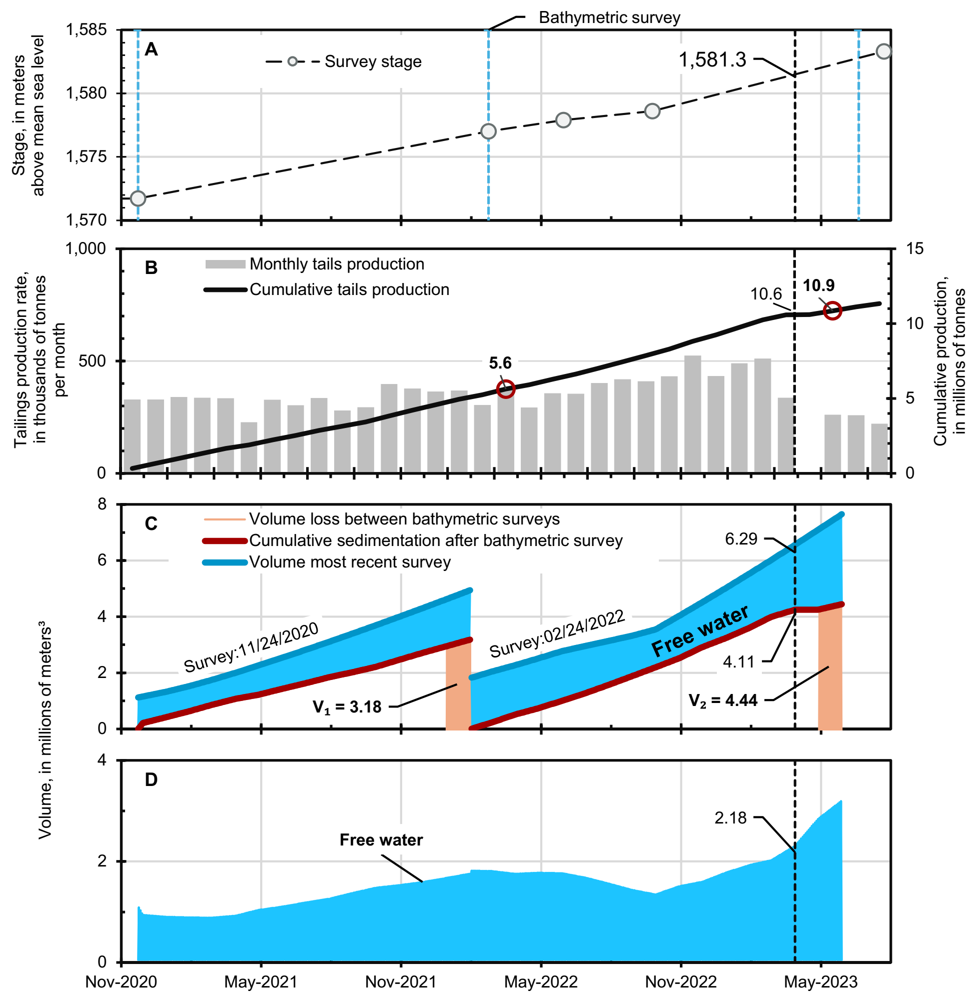


Fig. 7 Mass-weighted-distribution approach to estimate free-water volumes, using data from the East TSF at Gold Quarry Mine, Nevada, USA. **A** Measured pool stages for each bathymetry survey, and dates of repeated bathymetric surveys. **B** Monthly and cumulative tailings production. **C** Cumulative tailings-production volumes and free-water volumes, as computed from surveyed pool stages and repeated bathymetry surveys (tailings-production volumes V_1 and V_2 estimated in Fig. 6). **D** Estimated free-water volumes

To find the free-water volume corresponding to a pool stage on 03/31/2023, the following steps are applied.

1. Linearly interpolate the pool stage on 03/31/2023 from surveyed pool stages, which equates to 1,581.3 m (Fig. 7A).
2. To find V_{SAV}(Eq. 11), use the pool stage on 03/31/2023 (1,581.3 m) to find the corresponding interpolated volume from the most recent SAV prior to 03/31/2023 (02/24/2022 bathymetric survey), which equals 6.29 Mm^3 (Fig. 7C).
3. To find V_{tails}(Eq. 11), find the cumulative tailings production between the 02/24/2022 and 06/22/2023 bathymetric surveys. Cumulative tailings production on 03/31/2023 totalled 10.6 MT or 95% of the 10.9 MT of tailings production between the 02/24/2022 and 06/22/2023 bathymetric surveys (Fig. 7B). Using Eq. 7, the tailings tonnage of 10.6 MT has a corresponding tailings-production volume of 4.11 Mm^3 (Fig. 7C).
4. The free-water volume is 2.18 Mm^3 on 03/31/2023 (Fig. 7D), which is the 6.29 Mm^3 from the 02/24/2022 bathymetric survey (V_{SAV}) minus 4.11 Mm^3 of cumulative tailings production (V_{tails}; Fig. 7C).

TSFISM Numerical Approach

The TSFISM water-balance approach solves iteratively for changes in pool volume and stage at the end of each time step (Fig. 8). This approach is identical to the water-balance model of pit lakes (Jackson et al. 2026). The change in pool volume, ΔV, during a time step is:

$$\Delta V = \Delta t[Q - Q_{GW} + A_{mean}\,(P - E) + \sum_{i=1}^{n}(P - P_{catch-thresh,i})\; RO_{catch,i}\,(A_{catch,i}) + (P - P_{thresh,beach}) * RO_{beach}\,(A_{TSF} - A_{mean})] \tag{12}$$

where Δt is the time-step duration, [T]; Q is net pumping that sums rates of slurry addition (solids and water), reclaimed water subtraction, and other mine-related components, $[L^3/T]$; Q_{GW} is the groundwater-leakage rate, computed using A_{mean} in Eqns. 5 and 6, $[L^3/T]$; and A_{mean} is the pool area from averaging pool areas at the beginning and end of a time step (Fig. 8), $[L^2]$.

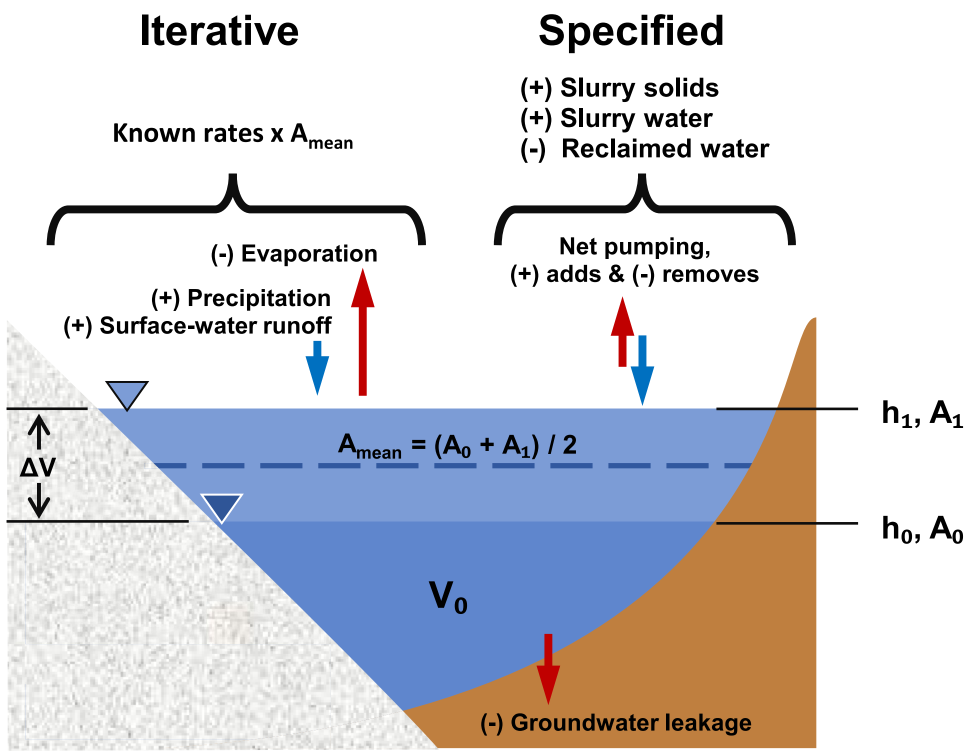


Fig. 8 Schematic of stresses, stage, area, and volume changes in TSF pool water balance during a time step

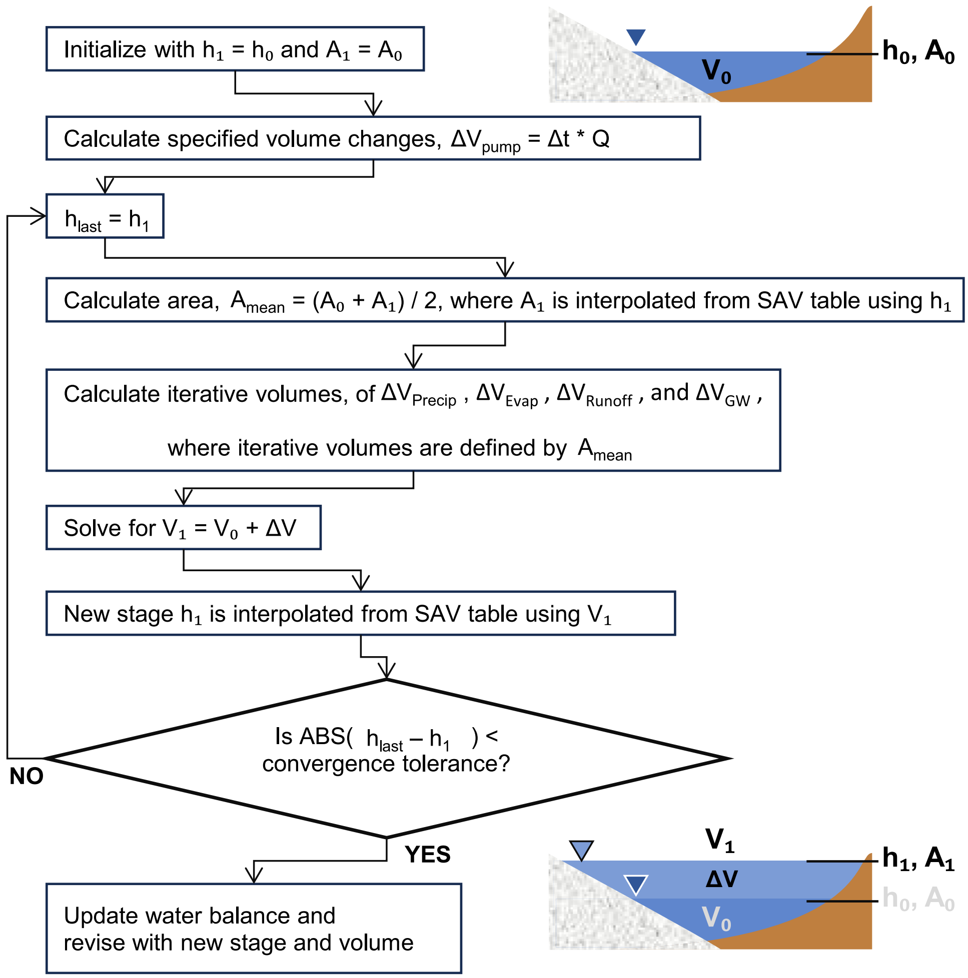
TSFISM sums all of the time-series of mine-related inflows and outflows to compute net pumping. The user specifies the time series of tailings-production rates [M/T], percent solids, and specific gravity for the computation of slurry water and slurry solids. Reclaim water and other managed flows to and from the TSF also are user-defined as separate time series. Precipitation (P), open-water evaporation (E), precipitation thresholds ($P_{thresh,beach}$ and $P_{catch-thresh,i}$), runoff coefficients (RO_{beach} and $RO_{catch,i}$), and catchment areas ($A_{catch,i}$) are also user-specified as time series. The measurement frequency of these user-defined times series can differ from the time-step frequency simulated by TSFISM.

Changes during a time step are solved by initially assuming no change in pool stage ($h_1=h_0$), such that initial (A_0) and final surface areas (A_1) are the same during the first iteration (Fig. 9). The pool surface area affects estimated precipitation, evaporation, groundwater leakage, and surface-water runoff during a time step (Eq. 12). Change in pool volume, ΔV, is solved with Eq. 12 and added to the existing pool volume, V_0 (Fig. 9). Pool stage at the end of a time step, h_1, is interpolated from the SAV relation with the new volume, $V_0+\Delta V$. A revised pool area at the end of the time step, A_1, is interpolated from the SAV with the new pool stage h_1, and is used to revise A_{mean}. The updated A_{mean} is used to revise the climatic stresses in Eq. 12, and subsequently, estimates of ΔV and h_1. This process is repeated until the simulated pool stage converges on a single value at the end of the time step (Fig. 9). After simulated pool stages, areas, and volumes (V_{SAV}) are estimated for each time step, the method described for computing free-water volumes is applied (see Figs. 6 and 7), with the exception that the mass-weighted interpolation uses simulated stages rather than surveyed pool stages (Fig. 7).

The water balance is solved differently if the TSF pool goes dry, which occurs when ΔV is negative, and the magnitude exceeds V_0 (Fig. 9). The ΔV initially is reduced by curtailing groundwater leakage (Q_{GW}), but curtailment cannot exceed the magnitude of groundwater leakage. Next, the magnitude of ΔV is reduced by curtailing net pumping, so that V_1 equals zero. Thus, specified and simulated net pumping can differ when the simulated TSF pool goes dry.

Stage and volume changes in a time step are simulated with two periods when a time step straddles a bathymetric survey (Fig. 10). The first period simulates the stage and volume change from the beginning of the time step to the bathymetric survey date using the previous SAV. The second period simulates change from the bathymetric survey date to the end of the time step using the new SAV. The simulated, cumulative tailings-production volume is computed at the bathymetric survey date by differencing volumes from previous and new SAVs. Again, this is the same method used to estimate surveyed free-water volumes (see Figs. 6 and 7), except that the mass-weighting interpolation uses simulated stages rather than surveyed pool stages (Fig. 7).

Fig. 9 Flow chart of iterative stage, area, and volume changes as the water balance of a TSF pool is solved during a time step



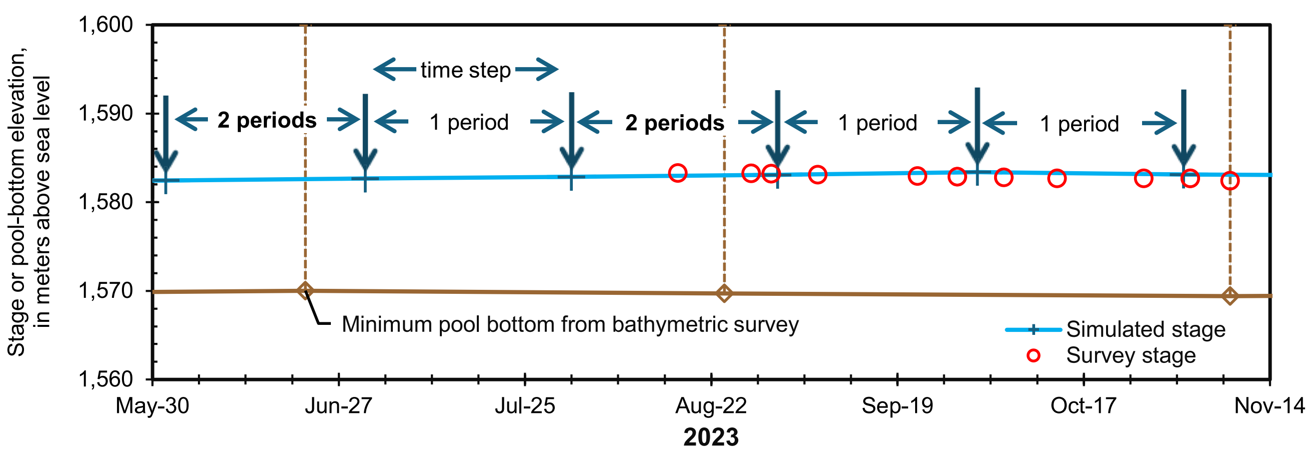


Fig. 10 Splitting time step into two periods when time step straddles a bathymetric survey. Example uses data from the East TSF at Gold Quarry Mine, Nevada, USA

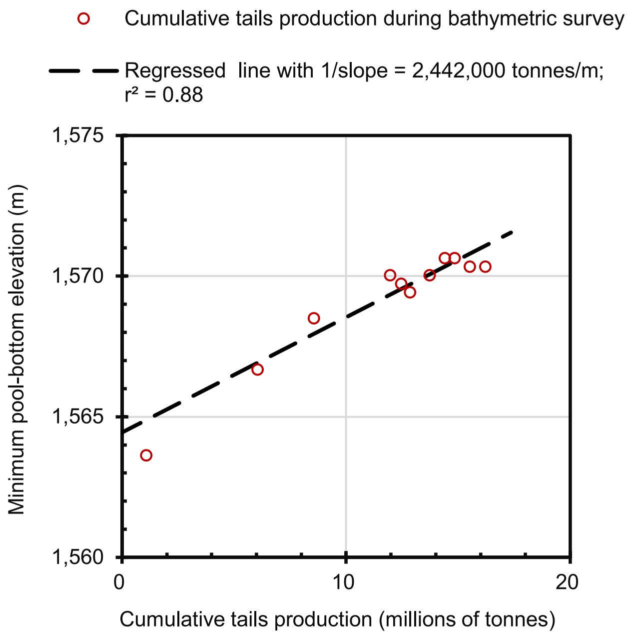


Fig. 11 Correlation between minimum pool-bottom elevation and cumulative tailings production. Example uses data from the East TSF at Gold Quarry Mine, Nevada, USA

Future Predictions

Future predictions of TSF pool stages and free-water volumes require user-defined inputs for all pumping components. Historical climatic data are used to provide predictive scenarios that account for climatic uncertainty. The same mass-weighting scheme is used to calculate free-water volumes, but the methodology uses projected bathymetric surveys and the future schedule of tailings-production rates.

Projected Bathymetry

The TSFISM water-balance approach depends on bathymetric surveys to quantify changes in pool stage and free-water volumes. The approach works well in the historical period, but additional analysis is required to predict future changes in TSF pool geometry. Note that measured minimum pool-bottom elevations from bathymetric surveys are correlated with cumulative tailings production (Fig. 11). Thus, future minimum pool-bottom elevations can be predicted from a regression between the minimum pool-bottom elevation and cumulative tailings production that are tabulated for each bathymetric survey. For example, using data from the Gold Quarry Mine East TSF, the minimum pool-bottom elevation increases 1 m with each additional 2.442 MT of tailings (Fig. 11). A one-dimensional correlation between elevation and cumulative tailings production works because TSF pool-surface-area changes are minimal, relative to vertical changes in a TSF.

Future bathymetry can be predicted by assuming historical deposition plans are representative of future deposition and the pool is simply shifted upward, in parallel, as tailings are added to a TSF (Fig. 12). Future SAV relations remain the same as the SAV from the last field-measured bathymetric survey, except stages are shifted upward. Minimum pool-bottom elevations increase proportionally to forecasted tailings production. For example, after March 2025, an additional 6.2 and 13 MT of tailings were forecasted to be added by May 2027 and June 2029, respectively, when using data from the Gold Quarry Mine East TSF. This raised the forecasted SAV by 2.5 and 5.3 m in May 2027 and June

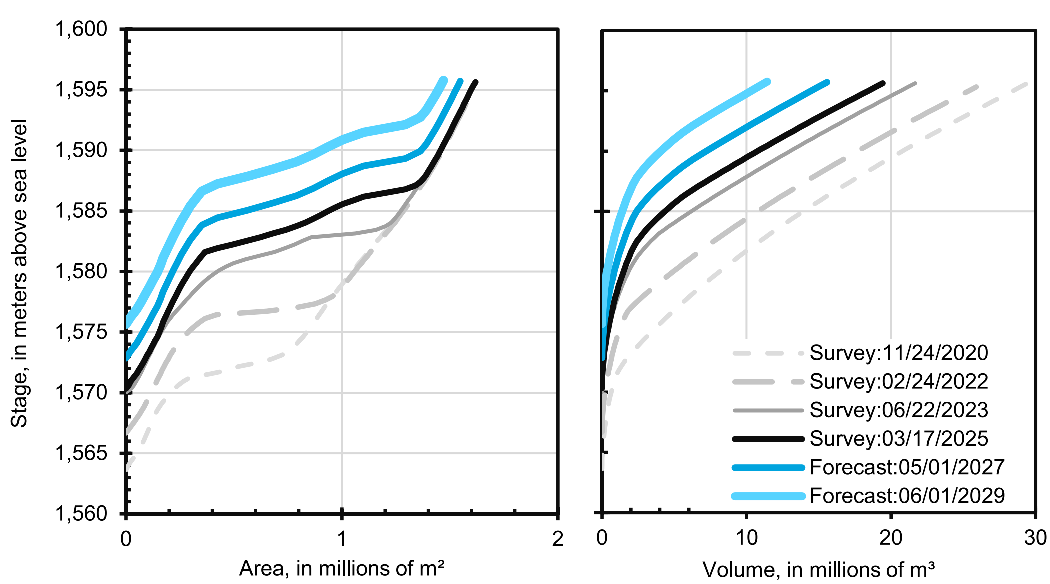


Fig. 12 Forecasted stage-area-volume relations from last bathymetric survey on 03/17/2025. Example uses data from the East TSF at Gold Quarry Mine, Nevada, USA

2029, respectively, since the last bathymetric survey measured on March 17, 2025 (Fig. 12).

Future deposition plans can change from historical plans and alternative methods of estimating future bathymetries may be needed. Future SAV relations can be estimated with other methods and added to the existing series of surveyed SAV relations. In TSFISM, surveyed and externally predicted SAV relations are differentiated so that only the measured minimum pool-bottom elevations are correlated with cumulative tailings production (Fig. 11).

Both externally and internally predicted SAV relations can be used in a single simulation. For example, surveyed, externally predicted, and internally predicted minimum pool-bottom elevations create a continuous pool-bottom elevation (Fig. 13A). Pool-bottom elevations are surveyed during the measured period. Externally predicted pool bottoms (from a Muk3D model) rise steeply in 2025 and 2026 due to pool relocation. Internally predicted SAV relations define the forecasted pool bottom during the predicted period after mid-2026, using a regression developed between measured (and externally predicted) pool-bottom elevations and cumulative tailings production.

TSFISM has built-in tailings-production tracking, where cumulative tailings production and measured minimum pool-bottom elevations are tabulated between bathymetric surveys. If a user changes the future tailings-production tonnage, then TSFISM will update the future bathymetry and reforecast the water-balance projection. The user can set the frequency of processed future bathymetric surveys, which are developed from a regression (see Fig. 11), using both time interval and future tonnage constraints. For example, assume that a user set the time interval to six months and future tonnage limit to 1 MT between these future six-month bathymetric surveys. TSFISM will generate a new future

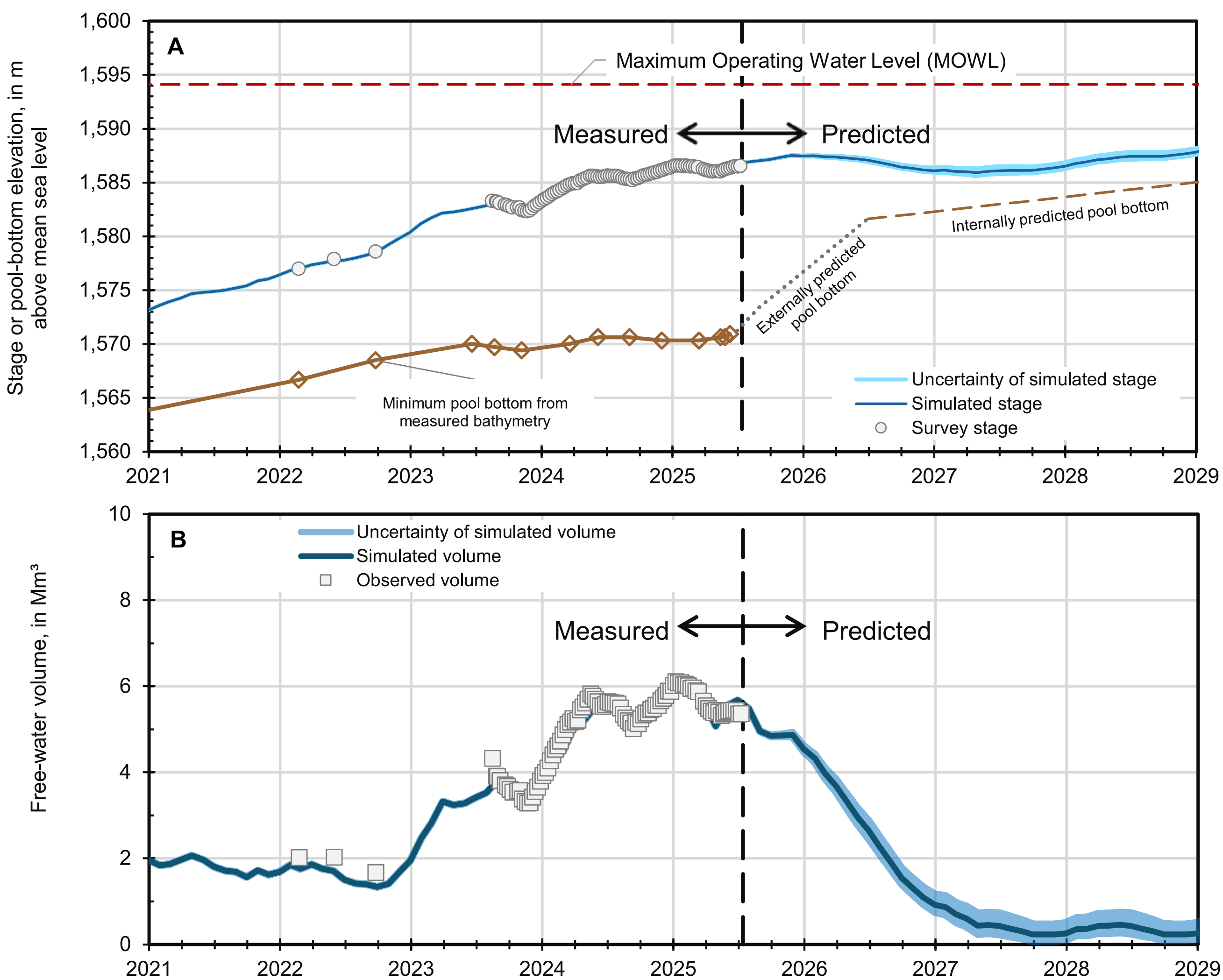


Fig. 13 TSF water balance for East TSF at Gold Quarry Mine, Nevada, USA. **A** Comparison of measured (surveyed) and simulated TSF pool stages, and predicted pool stages with uncertainty in forecasted precipitation. **B** Comparison of measured and simulated TSF free-water volumes, and predicted free-water volumes with uncertainty in forecasted precipitation. Measured free-water volumes estimated from the method described in section "Computation of Free-Water Volume" (see Figs. 6 and 7)

bathymetric survey every six months, starting from the last bathymetric survey date. This condition will be over-ruled if the predicted future tonnage is greater than the 1 MT within a six-month period, and additional future bathymetric surveys will be generated at intervals less than six months, based on the timing of when the 1 MT limit is reached.

Future Predictions of Water-Balance Data

Predicting future TSF stages and free-water volumes requires predicted rates of all water-balance inputs. Tailings production, reclaimed water, and other managed waters are user-defined inputs based on operational plans or water-management scenarios. To account for future climatic predictions, the default methodology in TSFISM is to use the historic records of precipitation and evaporation to compute long-term monthly averages, which assumes an average climatic condition (Fig. 14). Computing long-term monthly averages works well for evaporation because evaporation is relatively consistent from year to year. However, precipitation and surface-water runoff are highly variable. Therefore, TSFISM allows predicted precipitation to be estimated with external models, where external results supplant the projected long-term monthly averages.

Uncertainty in predicted pool stages and free-water volumes principally reflects uncertainty in precipitation forecasts. Therefore, TSFISM has a subroutine that opens and reads a separate Microsoft Excel® workbook with lower and upper uncertainty bounds for monthly average precipitation. The user inputs are monthly average precipitation and a long-term (20+year) dataset of annual average precipitation. Equations within the workbook compute precipitation uncertainty ranges using the log-Pearson Type III and Gumbel (extreme value type I) distributions. The user can select confidence intervals ranging from 75 to 95%, and either the log-Pearson Type III or Gumbel distribution for the climate uncertainty forecast.

Uncertainty in predicted pool stages and free-water volumes can be estimated with alternative frequency distribution models, external to TSFISM. For externally developed ranges of uncertainty bounds for monthly average precipitation, the user can replace the values in the workbook called by TSFISM with their independently calculated estimates. Regardless of the frequency-distribution model selected, minimum and maximum precipitation within a specified confidence interval can be simulated in TSFISM. Predicted precipitation in a frequency-distribution model scales long-term monthly averages by the ratio of predicted to average annual volumes of precipitation. This approach preserves seasonal variations in precipitation, which can be significant. For example, annual precipitation averaged 336.8 mm (Fig. 14). The 95% confidence interval of annual precipitation from this distribution ranged between 188 and 495.3 mm, or 56 and 147% of average. Predicted pool stages depart within 1 m from the average simulated pool stage, where annual precipitation ranges between 188 and 495.3 mm (Fig. 13A). A similar range of uncertainty also is reported for free-water volumes (Fig. 13B).

Annual precipitation can vary markedly between years (Fig. 14), which affects TSF pool stages. For the East TSF example, uncertainty of annual precipitation was estimated with the log-Pearson Type III distribution (Fig. 14), which is used prevalently for flood-frequency analysis (England et al. 2018; Gotvald et al. 2012). Uncertainty of annual precipitation is reported as a range, where 95% confidence exists that annual precipitation during a given year will be within the estimated range.

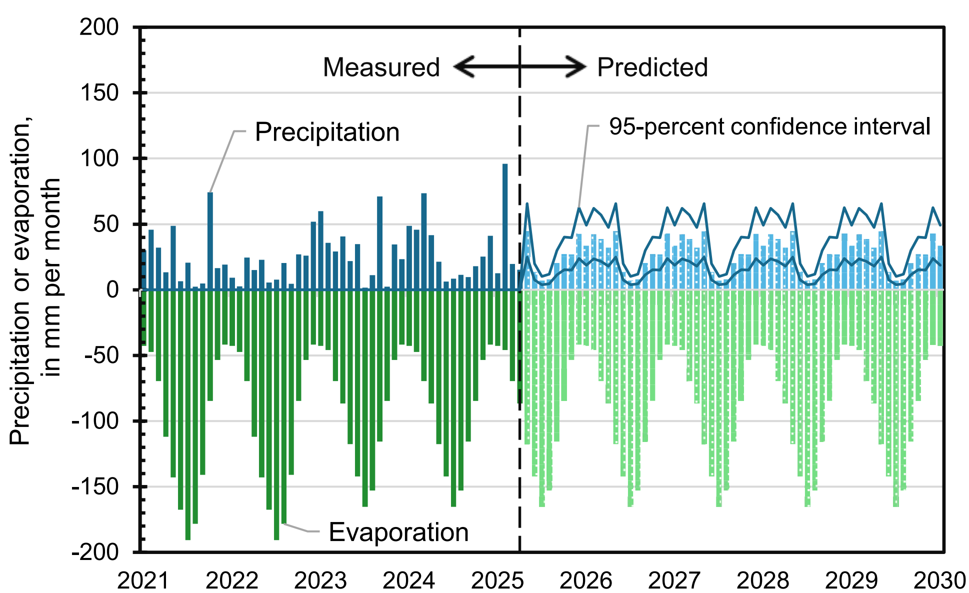


Fig. 14 Example of precipitation and evaporation data that define historic (measured) and predicted climatic water-balance components, using data from the East TSF at Gold Quarry Mine, Nevada, USA

Table 1 TSFISM parameters used in the East TSF water-balance model, Gold Quarry Mine, Nevada, USA

TSFISM parameter	Unit	Value
Long-term average precipitation	mm/yr	336.8
Long-term average pool evaporation	mm/yr	1,170.8
Precipitation threshold	mm/yr	0.0
Beach runoff coefficient	%	70
Catchment (TSF) area		
Jan 01, 2019 – Jul 31, 2025	m^2	1,588,642
Aug 01, 2025 – Jan 01, 2027	m^2	1,904,512
Jan 01, 2027 – Jan 01, 2033	m^2	2,118,189
Hydraulic conductivity	m/d	0

A Case Study Validation Example

TSFISM has been validated extensively using measured pool stages and flow data from TSFs in northeastern Nevada (USA), Canada, and Africa, covering a large variation of climates. In this paper, the East TSF at Gold Quarry Mine was used to demonstrate development and calibration of a TSF water-balance model (Fig. 1). TSF pool stages were related to pool surface areas and volumes by interpolation from historical (e.g., Fig. 5) and future projected stage-area-volume relations (e.g. Figure 12).

TSFISM parameters used to calibrate the East TSF water-balance model are listed in Table 1. Long-term average pool evaporation (1,170.8 mm) is about 3.5 times the long-term average precipitation (336.8 mm). Hydraulic conductivity is set to zero because the TSF is a synthetically lined facility; thus, there is no groundwater leakage (Table 1). The catchment area ($A_{catch,i}$) is not considered because surrounding surface-water diversions capture all runoff ($RO_{catch,i}$); thus, only beach runoff from the TSF area is simulated. The beach runoff coefficient was estimated during model calibration. TSFISM accounts for changes in TSF area with time due to future anticipated dam embankment raises (Table 1).

Simulated pool stages and free-water volumes match measured data (Fig. 13). For the historical calibration period, from January 2021 to July 2025, the user-specified mine-water inputs include slurry discharge (water and solids), reclaim water, and a minor component of forced evaporation beginning in 2024 (Fig. 15A). These mine-water components are summed and referred to as net pumping in Fig. 15B. User-specified climatic inputs include monthly precipitation and open-water evaporation (Fig. 14). Climatic inputs are used to compute water-balance outputs of precipitation on pool, beach runoff to the pool, and evaporation from the pool (Fig. 15 B).

The future projection is a water-management scenario that considers use of a water-treatment plant to remove excess water. The proposed water-treatment plant is assumed to have a throughput of 27,260 m^3/d with 50% efficiency, producing 13,630 m^3/d of RO permeate outflow and 13,630 m^3/d of concentrate reject inflow back into the East TSF (Fig. 15A). The proposed water-treatment plant maintains the water balance with a free-water volume between 0.2 and 0.7 Mm^3 after the first quarter of 2027 (Fig. 13B).

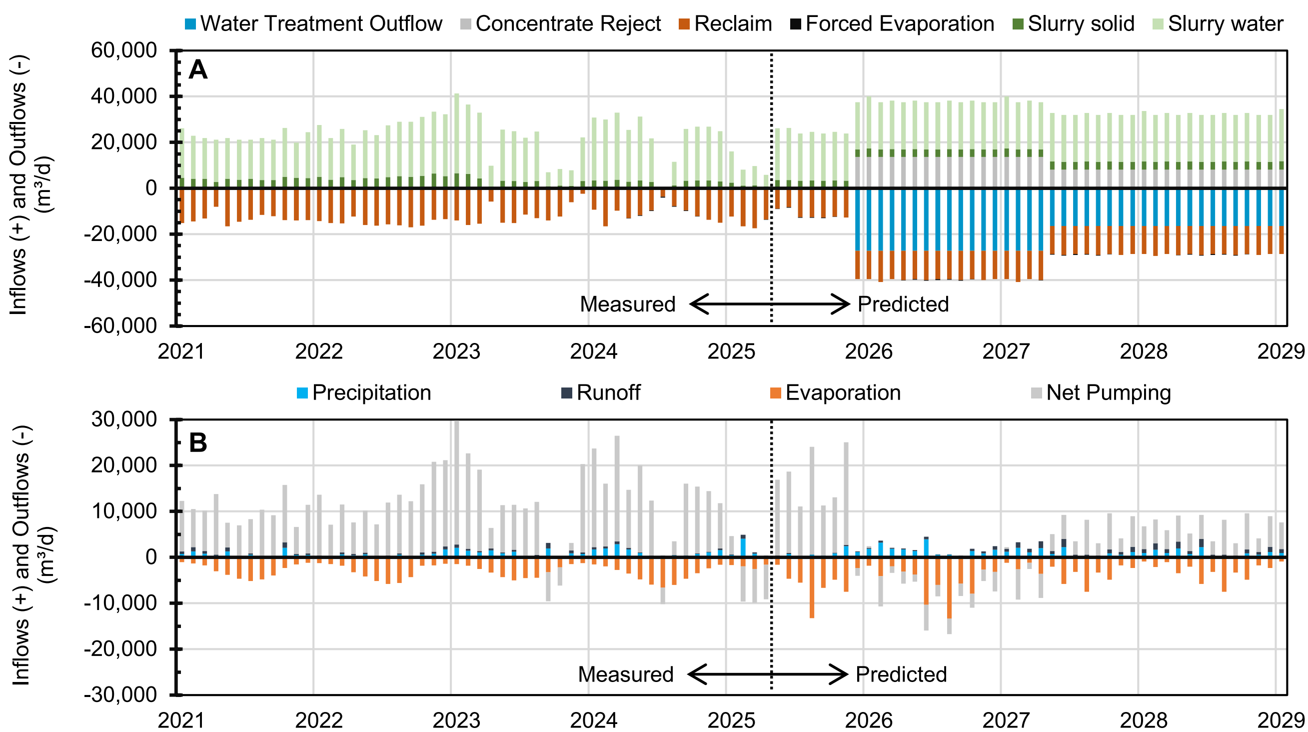


Fig. 15 East TSF water-balance model inputs and outputs. **A** Monthly rates of user-defined data inputs. **B** TSFISM water-balance outputs, which include net pumping and climate (precipitation, runoff, and evaporation) components

A Complex Case-Study Example

A water-balance example from an undisclosed TSF in western Africa is presented to demonstrate that TSFISM can accurately simulate a non-synthetically lined facility with complexities, such as periods of active slurry-water deposition and periods of inactivity where the TSF pool goes dry.

The TSFISM parameters used to calibrate the water-balance model are listed in Table 2. Long-term average open-water evaporation (1,551.8 mm) is ≈ 1.7 times the long-term average precipitation (923.1 mm). Hydraulic conductivity and the beach-runoff coefficient were calibration parameters in TSFISM, whereas the initial water level was assigned (Table 2). The TSF was constructed atop a leaky foundation of silty material, which has a model-estimated hydraulic conductivity of 0.02 m/d (Table 2). The catchment area ($A_{catch,i}$) is equivalent to the TSF footprint; thus, only beach runoff from the TSF area is simulated.

The TSF water balance includes climate, net pumping, and groundwater components. Precipitation and open-water evapotranspiration were measured from an on-site weather station (Fig. 16A), and were monthly data inputs used to compute direct precipitation on the TSF pool, evaporation from the TSF pool, and surface runoff from the TSF beach (Fig. 16C). During periods of active tailings deposition between 2019 and 2026, TSF inflows included slurry water and slurry solids, whereas the TSF outflows were reclaim from the supernatant pool and seepage to the drains (Fig. 16 B). These TSF inflows and outflows comprise the user-defined “net pumping” component of the TSF water balance. The groundwater component is uncaptured seepage through the leaky foundation, which was estimated to range between 460 to 8,300 m^3/d during the period of active tailings deposition (Fig. 16C). Net pumping is the dominant component of the TSF water balance (Fig. 16C).

Simulated pool stages and free-water volumes match measured data (Fig. 17). For the historical calibration period, from January 2019 to May 2025, the TSF pool remained relatively shallow during active slurry water inflow, with a maximum depth of about 2 m and a free-water volume that averaged about 48,000 m^3 (Fig. 17). During inactive periods with no slurry-water inflow, the TSF pool went dry. Note that TSFISM can account for this condition, as demonstrated in Fig. 17.

The future projection considers a condition where the TSF remains inactive from June 2025 through December 2028. Uncertainty in TSF stages and free-water volumes was estimated by applying the log-Pearson Type III distribution to the monthly precipitation data. The projections indicate that the TSF will remain dry during the dry season (December to March) and that the TSF pool will remain below the maximum operating water level during the rainy season (April to November), even with climatic uncertainty (Fig. 17).

Table 2 TSFISM parameters used in an undisclosed TSF water-balance model, Western Africa

TSFISM parameter	Unit	Value
Long-term average precipitation	mm/yr	923.1
Long-term average pool evaporation	mm/yr	1,551.8
Precipitation threshold	mm/yr	0.0
Beach runoff coefficient	%	40
Catchment area		
Jan 1, 2017 – Jan 1, 2029	m^2	1,275,000
Hydraulic conductivity	m/d	0.02
Initial TSF pool level	m	164.5

Strengths and Limitations

TSFISM is a transient analytical model that was developed as a functional alternative between complex numerical approaches and simplistic analytical models. Numerical approaches can estimate transient water-balance components but are computationally intensive and require extensive climatic and hydrologic data. Analytical water-balance models have reduced accuracy if simplifying assumptions regarding entrainment are used, or tails accretion is not considered with bathymetric surveys. A simplifying assumption of fully saturated tails for the computation of entrainment will underestimate the TSF free-water volume. Some analytical approaches artificially “close” the water balance by assuming the change in storage is the entrainment term, which neglects free-water volume surpluses and deficits. Many analytical water-balance models use stage-area-volume relations as lookup tables in a step-function approach between bathymetric surveys to compute the dynamic free-water volume, which over-estimates the true volume because of tails accretion. TSFISM accounts for the complexities associated with entrainment, consolidation, and variably saturated flow with temporal interpolation between frequent bathymetric surveys and cumulative tails tracking.

TSFISM can simulate the water balance of a TSF under a large variety of conditions. This paper demonstrates that TSFISM can match measured pool stages and free-water volumes for active or inactive TSFs, regardless of whether the facility has an impermeable synthetic liner or is non-synthetically lined. Examples are provided herein for TSFs in semi-arid and humid climates. One limitation of TSFISM is that this model can only be used to simulate the TSF water balance of a pool, either during operations or closure. TSFISM is not an appropriate tool for estimating tailings draindown.

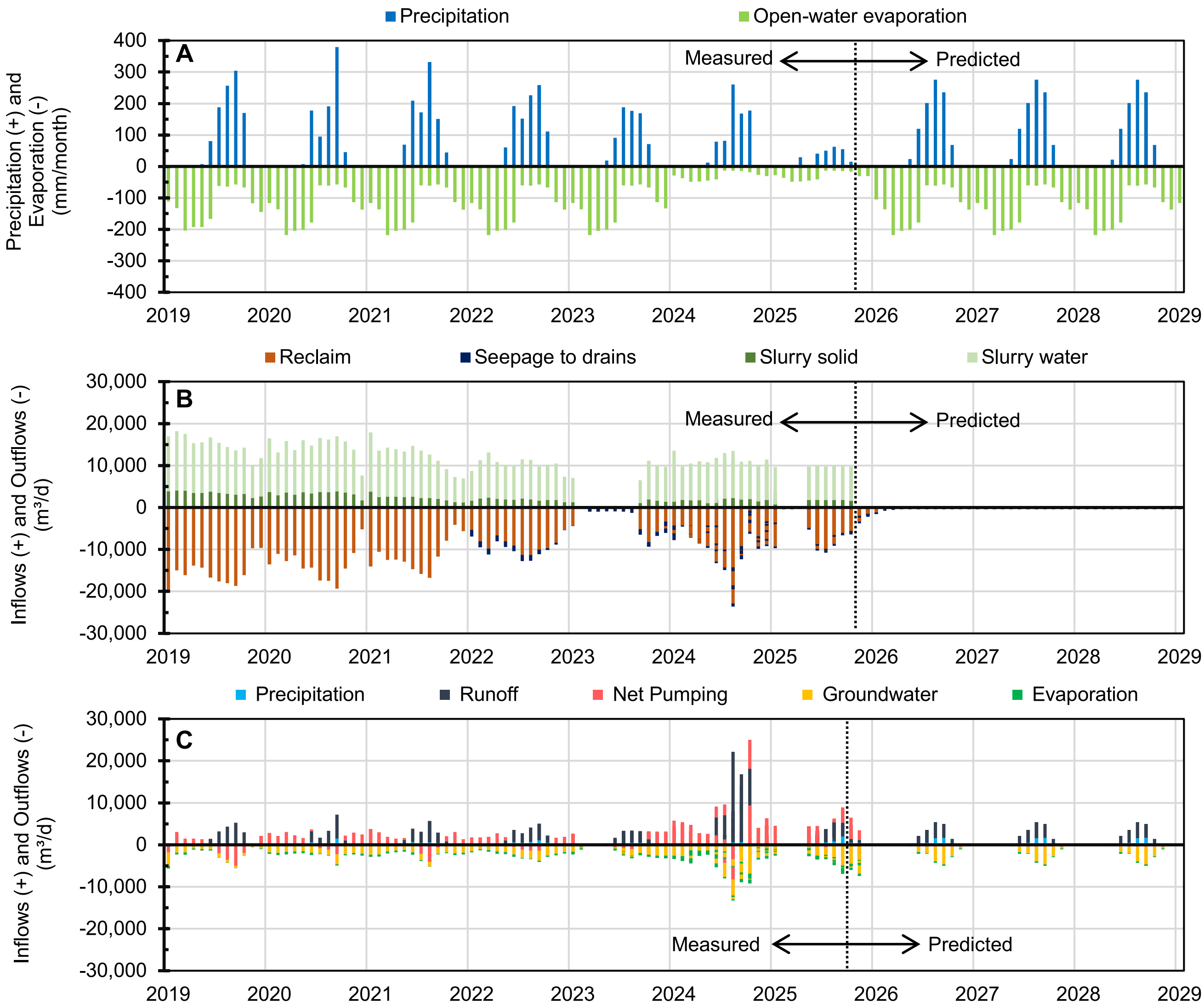


Fig. 16 Undisclosed TSF water-balance model inputs and outputs. **A** Monthly rates of measured precipitation and open-water evaporation data inputs. **B** Monthly rates of user-defined data inputs. **C** TSFISM water-balance outputs, which include net pumping, groundwater, and climate (precipitation, runoff, and evaporation) components

Conclusions

TSFISM was developed as a functional alternative to manage the water balance and tailings accretion of a TSF with existing software, Microsoft Excel 365®, and minimal data and computer-skill requirements. All Excel VBA code is accessible and can be reviewed directly by mine-industry professionals and regulators, which facilitates regulatory review, quality control, and communication with stakeholders, thereby reducing the risk of hidden errors and increasing confidence in the results. The TSFISM workbook incorporates all mine-related and climatic flow components of a TSF through a user-friendly interface. Mine-water components include slurry water, slurry solids, reclaimed water, and other managed flows. Climatic components include evaporation, precipitation and surface-water runoff rates that dynamically change as the pool-surface area changes.

TSFISM simulates TSF pool stages and free-water volumes by solving iteratively for changes in pool volume and stage at the end of each user-specified time step. TSFISM reliably accounts for the dynamic behavior of TSF pool geometry by mass-weighting the distribution of tailings-production volumes with time. The mass-weighting scheme uses frequent bathymetric surveys and tailings-production tracking. This approach negates the complexities associated with variably saturated flow, consolidation, entrainment losses, and the wetting and drying of TSF beach areas. For future predictions, TSFISM generates future bathymetric surveys at user-specified time intervals, based on a regression of historic minimum pool-bottom elevations from

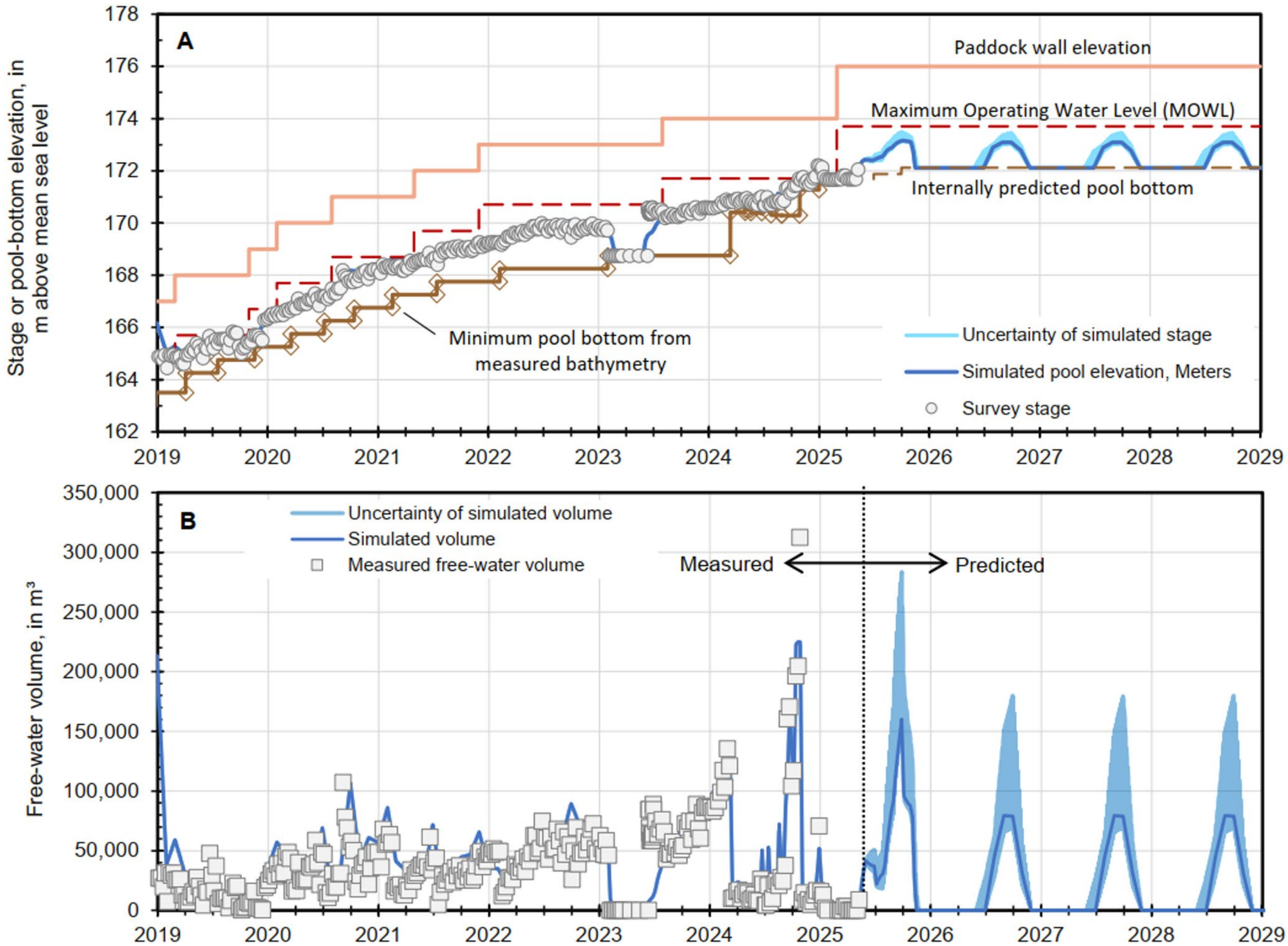


Fig. 17 TSF water balance for undisclosed TSF in western Africa. **A** Comparison of measured (surveyed) and simulated TSF pool stages, and predicted pool stages with uncertainty in forecasted precipitation. **B** Comparison of measured and simulated TSF free-water volumes, and predicted free-water volumes with uncertainty in forecasted precipitation. Measured free-water volumes estimated from method described in section "Computation of Free-Water Volume" (see Figs. 6 and 7)

bathymetric surveys to cumulative tailings production. The one-dimensional correlation works because pool surface-area changes are minimal relative to vertical changes in a TSF. TSFISM also dynamically simulates TSF beach and catchment runoff, allowing the beach area, catchment area, and runoff coefficient to vary with time. Note that runoff is a function of TSF stage, such that runoff from the beach area decreases as the TSF stage increases.

TSFISM has been validated extensively using measured pool stages and flow data from synthetically lined and clay lined TSFs in areas with different climate conditions. This paper used the East TSF at Gold Quarry Mine in northeastern Nevada as a demonstrative example to document the approach. In the East TSF case-study example, simulated pool stages and free-water volumes match measured data, and future projections account for climatic uncertainty. The TSFISM model and associated data used to develop the East TSF water balance model are available for download from the Halford Hydrology website: https://halfordhydrology.com/tsfism/. The undisclosed TSF in western Africa is used to demonstrate that TSFISM can simulate the water balance of an unlined TSF that has periods of active and inactive water management. TSFISM has robust capabilities to simulate a variety of site-specific TSF conditions and can run an unlimited number of water-management scenarios. Furthermore, TSF water-balance models can be easily set up, and various scenarios can be run "on the fly", where solutions are generated in less than a minute.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10230-026-01124-w.

Acknowledgements The authors thank Nevada Gold Mines LLC and Barrick Mining Corporation for allowing the data and TSFISM to be published. We thank Eyob Fessahatzion, Marie Howes, and Armando Vasquez-Aranda (Nevada Gold Mines LLC) for providing bathymetric-survey, climate, pool stage, and flowmeter data to develop and calibrate the East TSF water balance model.

Declarations

Conflict of Interest The authors have no competing non-financial or financial interests related to this work. The TSFISM VBA-macros were developed in Microsoft Excel® 365 and are not backward compatible to earlier versions of Excel. This is because user-defined functions use previously unavailable SPILL functionality to return two-dimensional arrays. TSFISM can be downloaded from the Halford Hydrology website: https://halfordhydrology.com/tsfism/. The file TSFISM.v11b.zip contains three files: (1) TSFISM.v11b.xlsm, which is a macro-enabled Excel workbook with the TSFISM model; (2) FullRainfall-StormAnalysis.xlsx, which is an example of an annual precipitation uncertainty analysis to estimate the range of predicted pool stages and volumes in a TSF; and (3) TSFISM-EXPLAIN.v11b.pdf, a readme document explaining how to use the TSFISM workbook.

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