Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_147

No pit left behind: closure pit water modelling at scale

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Abstract

Predicting long-term water quality in residual mine voids is a central challenge for closure planning, particularly where multiple pits exhibit contrasting hydrological and geochemical behaviours. This paper presents a scalable hydrogeochemical modelling framework applied to an Australian hard rock operation containing 11 post-closure voids, including both open pits and backfilled systems. The objective was to generate structured, defensible forecasts of pit water evolution over a 100-year closure horizon. The purpose was to support preliminary risk assessment and future regulatory engagement while acknowledging uncertainty through grouped scenarios based on median and 95th percentile source term representations and bounded water balance inputs.

The modelling integrates stochastic water balance simulations with equilibrium geochemical calculations. Daily rainfall–evaporation sequences were generated to simulate long-term hydrological behaviour, with separate conceptual models representing recharge-dominated open pits and through-flow backfilled voids. Annualised flow proportions were coupled to geochemical source terms derived from monitoring data, laboratory leach testing and field run-off characterisation. These inputs were processed using thermodynamic speciation modelling to account for evapoconcentration, mineral precipitation and adsorption reactions, enabling prediction of pH, salinity and trace element trends through time.

Scenario testing explored variability in infiltration rates and source term concentrations to bracket credible ranges of outcomes. Results highlight first-order contrasts between voids driven by material composition, groundwater interaction and hydrologic connectivity. While several voids are predicted to remain circumneutral and dilute, others show persistent acidity or elevated salinity under conservative assumptions. The modelling framework supports risk ranking across the pit portfolio and identifies priority targets for monitoring and adaptive management. At this stage, the model has not been calibrated against observed void behaviour or reviewed by regulators and therefore should be interpreted as providing first-order, risk-based predictions.

The study demonstrates that closure forecasting can be extended from single-pit assessments to site-wide systems without sacrificing transparency. By combining probabilistic hydrology, geochemical equilibrium modelling and structured uncertainty treatment, the approach provides a practical foundation for iterative closure planning and future regulatory engagement as additional data become available.

Keywords: *pit void, pit lake, hydrogeochemical modelling*

1 Introduction

Mine closure planning increasingly requires robust prediction of post-closure water quality to support regulatory approvals and long-term environmental risk management. In jurisdictions such as Queensland, closure frameworks (e.g. progressive rehabilitation and closure plans) require proponents to demonstrate that residual pit voids will not pose unacceptable water quality risks to downstream receptors. In practice,

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this requires predictive modelling of hydrogeochemical processes over timescales of hundreds up to thousands of years.

The modelling process is considerably more complex where multiple pit voids exist within a single operation. Each void may differ in geometry, hydrological setting, material composition, and connectivity to groundwater and surface systems. Commonly applied modelling approaches are widely described (Castendyk et al. 2015; Eshtawi et al. 2025; Herrell et al. 2022; Maest et al. 2020). These approaches highlight the limits of current methods and the need for a more integrated framework (Table 1).

Table 1 Commonly applied pit void modelling approaches

Approach	Typical characteristics	Limitations
Steady state	Fixed inflow and outflow conditions Steady-state water levels Constant water quality inputs	Limited or no geochemical processes Do not consider variability in climate and filling
Empirical	Comparison to existing pit lakes Extrapolate from monitoring data 'Rule of thumb' geochemistry	Depend heavily on availability of analogues Do not represent site-specific variability Difficult to justify when different analogues are used for different pits
Standalone	Detailed models (e.g. GoldSim, PHREEQC) Dynamic water balances Detailed geochemical processes Sensitivity analysis	Potentially inconsistent conceptualisation Variation in input datasets Differences in model structure and assumptions

These approaches need to be applied carefully to multi void systems to avoid loss of consistency or transparency. Differences in assumptions regarding hydrology, material behaviour and geochemical processes can cause difficulty with comparing results between voids, discriminating between true variability and artefacts of the modelling approach and relative risk ranking. In a regulatory context, clear justification of approaches and differences is required.

This paper presents a site-wide hydrogeochemical modelling approach developed for an anonymous hard rock mining operation containing 11 residual voids. The objective was to predict post-closure water quality over a 100-year period to inform closure planning and regulatory approvals.

The standalone approach was applied in parallel to the site voids by using standardised conceptual models and source term definitions. This allowed direct comparison of outcomes and relative risk. The modelling was designed to achieve an 'inferred' level of confidence suitable for decision-making.

2 Methodology

The modelling framework was consistent with the standalone approach described by Castendyk et al. (2015) and incorporates 4 main tasks: conceptual model development, followed by quantification of water fluxes, derivation of source terms, and simulation of geochemical evolution.

2.1 Conceptual model

The primary objectives of the modelling methodology were to develop a year-by-year accounting of the water flows identified in the site pit voids and to estimate the water quality in the pit voids for 100 years post closure.

The conceptual framework developed to achieve the objectives included 2 general scenarios that were based on the planned post-closure configuration of the site:

- Throughflow systems, which describe backfilled voids. In these systems, groundwater flow is the dominant control on water movement with additional water balance and solute mass components from percolation through covered or uncovered backfill materials. Backfill materials included non-acid forming (NAF) waste rock, mixed NAF and potentially acid-forming (PAF) waste rock and tailings. Five of the 11 voids were conceptualised as through-flow systems.
- Recharge systems, which describe open voids. These represent open pit lakes in which water and solute inputs are dominated by rainfall and run-off, with losses via evaporation, seepage and occasional overflow. Six of the 11 voids were conceptualised as through-flow systems.

This framework provided a standardised model structure across multiple voids while allowing the model to be configured for individual site conditions.

2.2 Water balance modelling

Water balance modelling was undertaken separately for open pit lakes and backfilled voids, reflecting their differing hydrological behaviour.

For recharge systems (i.e. pit lakes), a dynamic water balance model was developed using GoldSim software. Synthetic rainfall sequences were derived from historical statistics, which allowed multiple realisations of the 100-year post-closure model period to be simulated, each applying a different series of daily rainfall depths. Similarly, evaporation was estimated from climatic datasets. Climate change was implemented in the model by applying a uniform percentage change to the forecast climate realisations (rainfall and evaporation) based on the climate change data presented in the Queensland Future Climate Change Portal (Trancoso et al. 2024).

Void geometry was previously developed as part of the closure planning process and provided to the modelling team. This spatial data was used to develop 3 key water balance inputs:

- stage area storage curves which related the elevation of the top surface of the void water body with a volume of water stored
- the area of the pit walls above the water level that generate run-off
- the area of catchments beyond the pit walls that may contribute run-off to the void.

Run-off was generated from pit walls and surrounding catchments based on an estimated run-off factor of 0.7, which was limited to days when simulated rainfall was greater than 5 mm.

For backfilled voids, the water balance was simplified to an annual timestep calculated in an Excel spreadsheet. Steady-state groundwater conditions were assumed. Therefore, groundwater outflow balanced inflow which was estimated from the numerical hydrogeological model developed for the site and surrounds. Infiltration through the backfill top surface was included as a range that considered 'average' and 'high' conditions based on existing and planned cover scenarios for each backfill material (Table 2).

Table 2 Backfilled void cover infiltration estimates

Condition	Unit	Covered tailings	Covered PAF	NAF (uncovered)
'Average' infiltration	% annual rainfall	0.5%	0.4%	23%
'High' infiltration	% annual rainfall	7.4%	5.2%	50%

Infiltration estimates for the covered tailings and PAF were based on the designed cover system performance. Uncovered NAF infiltration is consistent with the post-breakthrough estimates of Williams (2008). To avoid double-counting, the recharge rate of 2% of annual rainfall assumed in the regional groundwater model was deducted from cover infiltration where applicable.

Outputs from both model types are expressed as annual flow volumes and relative mixing proportions, which were direct inputs to the geochemical mixing model.

2.3 Source term definition

Source terms represent the chemical composition of all inflows to each void, including groundwater, run-off, rainfall, pit wall leachate and backfill-derived waters. These were derived from a combination of monitoring data, laboratory leach testing and field wall wash samples.

Source term compositions were adjusted to achieve charge balance within ±25%. This was considered an acceptable tolerance for the 'inferred' level of confidence since the water quality data were sparse and the model purpose is to facilitate the preliminary identification of potentially significant water quality impacts.

2.4 Geochemical modelling

Geochemical evolution was simulated using on an equilibrium basis using the geochemical modelling code PHREEQC (Parkhurst & Appelo 2013). The model operated on an annual timestep over the 100-year simulation period, using the flow-weighted mixing proportions derived from the water balance.

At each timestep, inflows were combined and subjected to evapoconcentration where relevant. The resulting solution was equilibrated with respect to atmospheric carbon dioxide (pCO_2 = -3.37). Gaseous oxygen was allowed to interact with the pit void system to assign redox potentials relevant to the conditions (pe ≈ 7 for pit lakes and pe ≈ 0 for backfill porewater).

Secondary mineral phases as identified by Eary (1999) were allowed to precipitate, including iron and aluminium oxyhydroxides (represented by the ferrihydrite and gibbsite phases, respectively). Adsorption of aqueous chemical species linked to ferrihydrite surfaces was modelled using the diffuse double-layer surface complexation model of Dzombak & Morel (1990) included with PHREEQC. The *minteq.v4.dat* thermodynamic database was applied.

2.5 Treatment of uncertainty

The hydrogeochemical models included hundreds of parameters, making extensive sensitivity testing impractical and inconsistent with the 'inferred' level of confidence of the model. Therefore, the model inputs were grouped to represent credible ranges.

For backfilled pits, sensitivity was assessed by considering an 'average' infiltration into the backfill and a 'high' infiltration.

To address variability and uncertainty, 2 statistical representations were developed for each source: a median value representing typical conditions, and a 95th percentile value representing a conservative upper bound. This approach allows the model to bracket plausible ranges of water quality outcomes without requiring detailed probabilistic treatment of all inputs.

The modelling adopts simplifying assumptions, including instantaneous mixing, equilibrium reactions and temporally constant source terms. These assumptions are consistent with the intended level of confidence, which is to provide first-order predictions of long-term trends rather than precise forecasts.

3 Results

The modelling framework produced timeseries of water levels, flow components and water quality parameters for each void over the 100-year simulation period.

Hydrological results showed clear differentiation between recharge and through-flow systems. Pit lakes exhibited behaviour controlled by the balance between run-off inputs and evaporative losses, with some systems reaching steady-state conditions below spill elevation and others experiencing periodic or frequent overflow. Backfilled voids were characterised by relatively stable through-flow conditions, with porewater composition governed by the balance between groundwater flux and infiltration.

Water quality results indicated that pH, salinity and trace element concentrations varied widely across voids, reflecting differences in material composition and hydrological setting. Circumneutral conditions were generally associated with systems dominated by dilute inflows or effective buffering by secondary mineral phases. In contrast, acidic conditions developed where potentially acid-forming materials contributed significant solute loads and buffering capacity was limited.

Salinity was controlled by both source term composition and evapoconcentration, with elevated concentrations observed in systems influenced by saline groundwater or tailings-derived inputs (Figure 1).

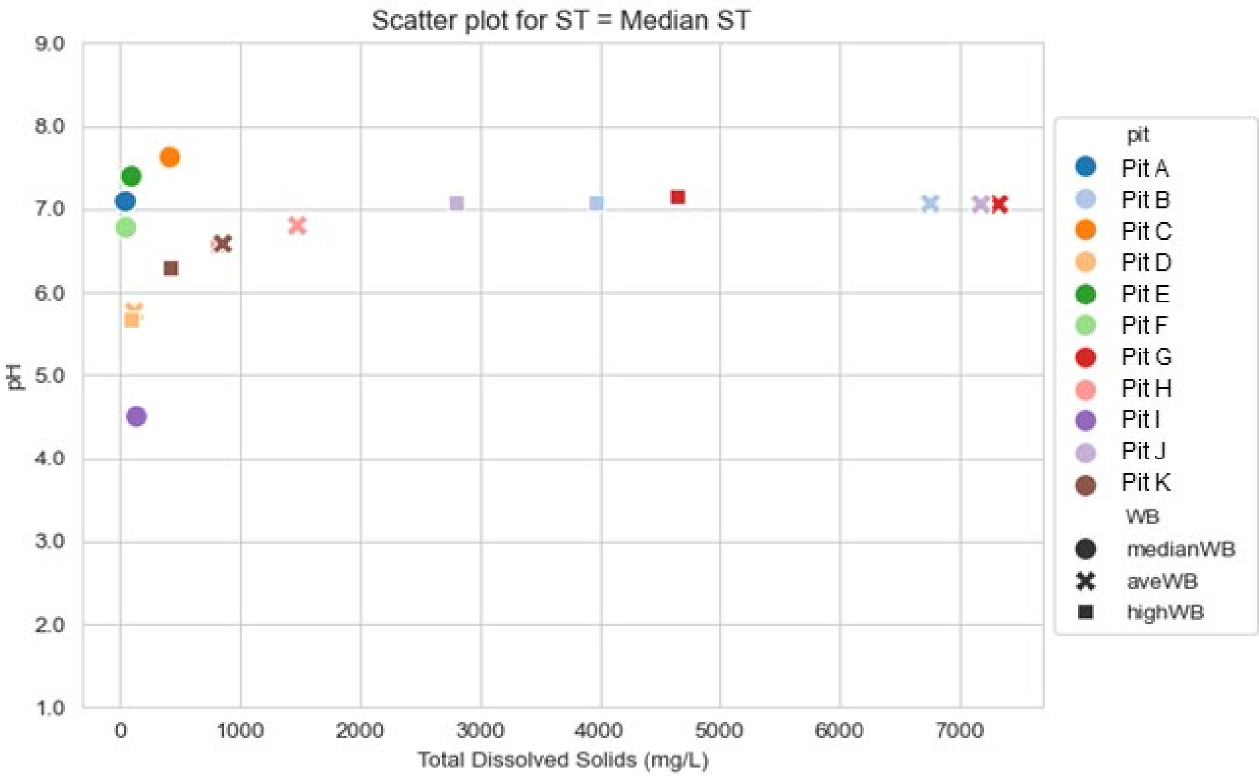

Figure 1 Salinity (as total dissolved solids) versus pH results using median source terms (ST) for 11 pit voids (Pits A through K) and 3 water balance (WB) scenarios

Trace metals and metalloids showed strong dependence on pH and sorption processes, with higher concentrations generally associated with acidic conditions (Figure 2).

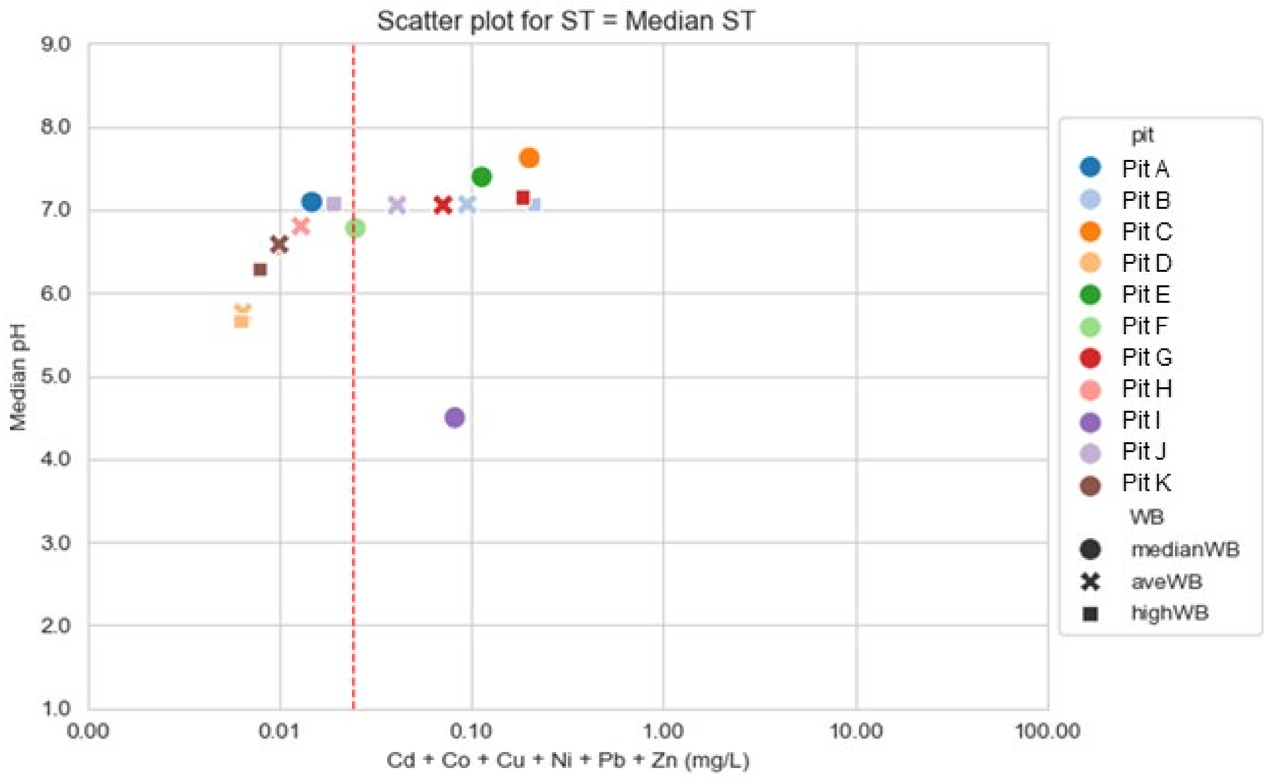

Figure 2 Ficklin diagram showing median source term (ST) results for 11 pit voids (Pits A through K) and 3 water balance (WB) scenarios

The results enabled differentiation of voids into relative risk categories based on predicted water quality and overflow behaviour.

4 Discussion

The framework presented here occupies a pragmatic middle ground between highly simplified screening models and fully coupled reactive transport simulations. By separating the problem into water balance and geochemical components, the framework achieves a level of process representation sufficient to capture first-order controls on water quality, while retaining transparency and flexibility. The use of flow-weighted mixing proportions allows the geochemical model to reflect dynamic hydrological conditions without requiring full spatial discretisation.

Consistent with the study objective, the framework is intended to provide first-order, scenario-based predictions to support risk differentiation across multiple voids rather than detailed, site-calibrated forecasts. A key strength of the framework is its scalability. The same conceptual architecture can be applied across a large number of voids, ensuring internal consistency while allowing for differentiation through parameterisation. This addresses a common limitation, where different voids are modelled using inconsistent assumptions or methods, undermining comparability and regulatory confidence.

Rather than attempting to eliminate uncertainty through increasingly complex modelling, the framework addresses uncertainty through grouped scenarios, including median and 95th percentile source term representations and bounded water balance inputs. This aligns with the objective of 'inferred' level of confidence. It is also consistent with the reality that long-term predictions are inherently uncertain, particularly where they rely on extrapolation from laboratory data to field conditions. In its current form, the framework supports risk-based screening and prioritisation, pending validation against observed void water quality.

The reliance on equilibrium geochemical modelling is considered justified. While kinetic processes are known to influence the evolution of mine waters, particularly in the early stages of weathering, the assumption of equilibrium over annual timesteps is generally appropriate for long-term closure assessments. Published evidence indicates that equilibrium models often reproduce the dominant features of mine water chemistry.

Limitations to the framework remain. The assumption of complete mixing ignores stratification in pit lakes, which may be important in deep or saline systems. Source terms are assumed constant over time, which may lead to conservative predictions where solute release declines as materials weather.

These limitations are not unique to this framework but are characteristic of most closure void water quality modelling. Since the limitations are acknowledged and managed within a structured methodology, the parameters can be refined as required. The framework is iterative. As additional monitoring data become available, source terms can be updated, hydrological inputs refined and model predictions improved.

In this sense, the framework should not be viewed as a static predictive tool, but as part of an iterative process through which predictions are refined as additional monitoring data improve site understanding. Its primary value lies in identifying dominant water quality trends and differentiating relative risk between voids. This is aligned with risk-based closure management approaches and continuous improvement over the life of a project.

5 Conclusion

A scalable hydrogeochemical modelling framework has been developed for the assessment of multiple post-closure pit voids on a single site.

The framework enables consistent treatment of multiple voids while accommodating site-specific variability in hydrology and material composition. It captures the key controls on water quality, including source term chemistry, evapoconcentration and secondary mineral processes, and incorporates uncertainty through scenario-based inputs.

Positioned between simplified screening tools and complex reactive transport models, the methodology provides a practical and transparent basis for preliminary closure planning at an inferred level of confidence. Its application supports risk differentiation, prioritisation of management actions and iterative refinement as new data become available.

At its current stage of development, the framework is not calibrated to observed field performance and should be applied as a first-order predictive tool. The approach is well suited to complex mining operations. It supports risk ranking across multiple voids and informs adaptive management strategies with outcomes intended to be refined progressively as additional data become available.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used ChatGPT and Copilot to improve the language and clarity of writing. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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