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

doi:10.36487/ACG_repo/2615_91

Integrating water and load balance modelling for mine closure

Karan Jain [a,*], Tom-John Nelis [b], Ryan Burgess [b], Leonardo Navarro Valdivia [c], Clare Miller [a], Eric Chen [a], Simone Hoodhills [c], Paul Weber [c]

[a] *Mine Waste Management, Australia*

[b] *Hydro Geochem Group, New Zealand*

[c] *Mine Waste Management, New Zealand*

Abstract

Mine closure planning requires a robust understanding of geoenvironmental source hazards, solute generation processes, water movement, management controls and closure objectives. Water and load balance models (WLBMs) provide a practical approach for integrating these elements and supporting risk-based closure decisions. This paper presents a framework for developing closure-focused WLBMs, supported by practical examples that demonstrate how conceptual site models, water balance components, domain-based source terms, engineering controls and scenario analysis can be integrated to assess closure risks. The paper highlights that WLBMs are most valuable when used as decision-support tools rather than static compliance models. Key limitations include uncertainty in source terms, climate inputs, net percolation, treatment performance and the availability of site-specific monitoring data. These limitations can be addressed through scenario analysis and adaptive management, whereby model predictions are progressively updated as new monitoring data become available.

Keywords: *modelling, acid and metalliferous drainage, geochemistry, hydrogeochemistry, closure, mining, prediction*

1 Introduction

Mine closure is increasingly recognised as a life of mine planning process rather than a late-stage rehabilitation activity. Australian guidance (Commonwealth of Australia 2016a, b) emphasises that closure planning should prevent or minimise long-term environmental, physical, social and economic impacts. Complementary guidance on acid and metalliferous drainage, rehabilitation, monitoring and risk management similarly frames closure performance in terms of control effectiveness, monitoring and continuous improvement (International Network for Acid Prevention [INAP] 2012). Current International Council on Mining and Metals (ICMM) guidance similarly promotes integrated closure planning through progressive risk assessment, stakeholder engagement, closure option evaluation, performance monitoring and periodic review across the mine life cycle. More recent guidance, including the ICMM INAP acid rock drainage and metal leaching tool (ICMM & INAP 2025; ICMM 2025), further supports the integration of water quality considerations throughout the mining life cycle.

For water-related closure risk, the main technical challenge is that mine systems do not converge on a single stable mode of behaviour. For example, generic pit lake modelling shows that climate and hydraulic conductivity can strongly influence final pit lake behaviour, while groundwater-focused studies show that post-closure pit lakes may remain terminal sinks or develop into through-flow systems, depending on evaporation, hydraulic gradients and hydraulic conductivity. Hydrological studies focusing on pit lakes show

* Corresponding author. Email address: karan.jain@minewaste.com.au

that high-flow events can dominate metal fluxes, whereas dry periods can intensify concentrations within retained waters (Kemanga et al. 2024).

Predicting long-term water quality can be a key challenge in mine closure planning unless a systematic approach that considers uncertainty and risk is undertaken. Water and load balance models (WLBMs) are commonly used to assess the effects of mine-impacted water at closure by integrating:

- geochemical processes (e.g. solute generation and release)
- hydrological processes (e.g. rainfall, run-off, seepage)
- site infrastructure and engineering controls
- receptors and water quality objectives.

Recent studies (e.g. INAP 2012; Kemanga et al. 2024) emphasise the importance of linking geochemical processes with hydrological pathways to improve prediction reliability. However, this requires a comprehensive assessment of geoenvironmental hazards associated with the conceptual site model (CSM) and the development of appropriate source terms (static and dynamic) to integrate with hydrological pathways. This paper presents a practical framework for WLBM development and application, with illustrative examples highlighting how modelling can identify key closure risks and inform triggers for adaptive, risk-based management strategies.

The contribution of this paper is the integration of these components into a practical closure-focused WLBM framework that explicitly links source–pathway–receptor conceptualisation, domain-based source terms, engineering controls, scenario testing and adaptive management. The framework is not presented as a new numerical modelling method but as a practical structure for developing and applying WLBMs so that model outputs can directly inform closure design, trigger criteria and management decisions. Practical examples are used to demonstrate how the framework can identify key closure risks, including changes in the hydrological regime, dominant source areas and the sensitivity of closure outcomes to management control performance.

2 Framework for water and load balance model development

A structured and iterative approach is required for effective WLBM development. The proposed framework (Figure 1) integrates the key components required to assess closure risks and evaluate management strategies under a range of scenarios (operational and closure), including conceptual model development, water and load balance integration, representation of management measures and evaluation of uncertainty through scenario analysis. Rather than representing a linear modelling workflow, the framework emphasises the iterative nature of model development, where monitoring data and improved understanding are used to refine conceptual models, source terms, engineering controls and future closure strategies over time.

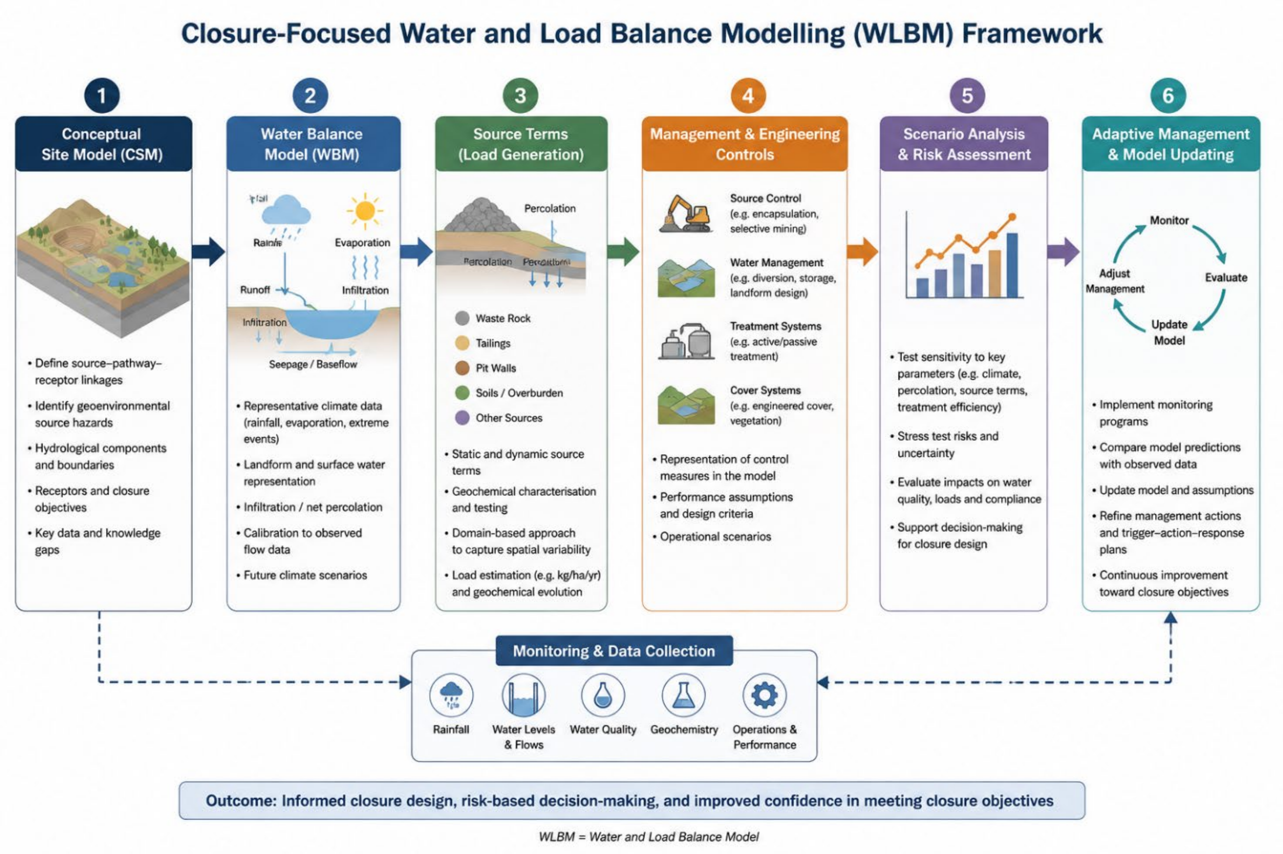

Figure 1. Proposed framework for the development and application of a closure-focused water and load balance model, illustrating the integration of conceptual site modelling, water and load balance processes, engineering controls, scenario analysis and adaptive management

2.1 Conceptual site model

The framework begins with development of a CSM, which provides the foundation for the subsequent water balance, load balance and scenario analyses. It should include:

- sources – waste rock, tailings, pit voids, low grade ore, mineralised waste, ROM pads, heap leach facilities, rejects, infrastructure areas (e.g. haul roads, processing plants), etc
- pathways – surface run- off, seepage (basal and toe) and groundwater. Sometimes this may include airborne pathways for dust migration
- management systems – water conveyance structures, retention ponds, water treatment systems, water takes and discharge facilities
- receptors – surface water bodies, groundwater systems, water quality compliance monitoring locations.

Particular attention should be given to the temporal variability in connectivity between sources and receptors, storage-release processes such as pit lakes and landform saturation (e.g. wetting up and draindown), and the role of rainfall events in driving system behaviour. A common limitation observed in practice is the underrepresentation of transient processes (e.g. storm-driven flushing events or first-flush mobilisation following dry periods), which can lead to the underestimation of peak loads and exceedance risks (Nordstrom 2011).

2.2 Water balance modelling

The water balance component quantifies the movement and storage of water within the system. The key inputs and considerations for water balance model development are summarised in Table 1.

Table 1 Key inputs and considerations for water balance modelling

Component	Key inputs	Key considerations
Climate data	Rainfall (historical and synthetic) and evapotranspiration (e.g. FAO-56; Allen et al. 1998)	Capture seasonal variability, represent extreme events (droughts and storm events), ensure datasets are representative of long-term conditions (including climate change)
Catchment and domain representation	Catchment areas Mine domains, e.g. pits, waste rock dumps (WRD), tailings storage facility (TSF) Water management systems e.g. sediment dams and voids, and conveyance	Appropriate spatial representation of domains and connectivity between components
Water balance processes	Inflows, e.g. run-on, rainfall, groundwater, water management processes Outflows, e.g. evaporation, seepage, discharge Storage, e.g. recycle and re-use (pumping to mine domains, dust suppression) Net percolation rates (WRD, TSF, etc.)	Accurate representation of flow pathways and interactions between domains
Engineering controls	Engineered landforms and source control Water management systems Water treatment systems (active and/or passive)	Engineering controls to ensure risks to receptors are managed
Receptor definition	Identification of key receptors Compliance monitoring locations	To understand potential effects and risks, and determine if additional engineering controls are required

2.3 Load and source term definition

The load component assigns source terms to the water balance elements to form a solute transport model. This allows for the understanding of potential effects and risks for water quality. Source term definition is a critical step and should account for spatial variability between material types, mine domains, the temporal evolution of geochemical behaviour, and differences between run-off and seepage pathways.

In practice, source terms may be represented using constant concentration assumptions, load-based fluxes (e.g. a rate in kg/ha/day) or time-dependent relationships derived from kinetic test work. Established guidance highlights the importance of integrating laboratory and field data to appropriately constrain these inputs and reduce uncertainty in predictions (INAP 2012; Maest et al. 2005). In our experience, the use of domain-specific source terms provides a more robust and defensible representation compared to uniform assumptions, particularly where materials exhibit variable geochemical characteristics and weathering behaviour.

2.4 Integration of engineering controls

Effective models explicitly incorporate management processes when required and these can include engineering controls to minimise oxygen and water flux, water treatment systems (both active and passive), seepage collection systems, cover systems and rehabilitation strategies. Representing these controls within the WLBM allows for a more realistic simulation of how the system will perform during operations and throughout closure phases, rather than relying on conservative or assumed end-state conditions. In particular, it enables testing of the timing of implementation (e.g. early versus deferred treatment), the required performance of individual controls (such as cover system net percolation targets or passive treatment system efficiency) and the interaction between multiple management measures operating across the site. This integrated approach provides a stronger basis for evaluating trade-offs between alternative closure strategies, identifying critical controls for achieving compliance and understanding where system performance is most sensitive to uncertainty.

2.5 Scenario analysis and uncertainty

Scenario modelling is a key component of WLBM development, enabling the evaluation of system sensitivity and identification of risks under a range of plausible conditions. It provides a tool for assessing the efficacy of management controls and allows for modelling variability in source terms that may be based on limited data.

Uncertainty in the model is typically driven by climate variability, net percolation rates, source terms and the performance of management measures such as water treatment. These factors can significantly influence both water balance outcomes and solute loads in the downstream receiving environment. Scenario analysis provides a structured approach to testing these uncertainties by varying key parameters and assessing their impact on model outputs, allowing identification of dominant risk drivers and the potential for exceedance of water quality limits at compliance monitoring locations. This approach also supports evaluation of the robustness of closure strategies under both base case and conservative assumptions (Dold 2014).

2.6 Adaptive management

Given the inherent uncertainty in long-term predictions, WLBMs should be supported by an adaptive management framework to ensure closure objectives are achieved (i.e. time-orientated learning processes). This involves collecting performance monitoring data (leading and lagging performance monitoring), comparing measured data with model predictions, and refining key inputs such as net percolation, source terms and treatment performance over time. This process reduces ongoing uncertainty and improves confidence in model results and expected closure outcomes. Adaptive management is widely recognised as best practice in mine closure, particularly where early-stage assumptions are required (Commonwealth of Australia 2016a). By linking model outputs to monitoring programs and trigger-action response plans, WLBMs can function as dynamic decision-support tools to guide operational water management decisions for closure planning.

3 Discussion

As shown in Table 2, 4 key regimes capture the main hydrological conditions that influence closure risk and management: storage-controlled, flow-through, evaporation-dominated and discharge-driven. This is not presented as a universal classification scheme; rather, it reflects a practical synthesis based on project experience for use in WLBM scenario design.

Table 2 Illustrative behavioural regimes for closure-focused water and load balance models

Regime	Model behaviour	Dominant controls	Closure implication
Storage-controlled	Large internal storages absorb inflows; releases are delayed, rare or episodic	Pit volume, freeboard, weak external connectivity, moderate inflows	Timing of spill, rebound or managed release becomes the critical uncertainty
Flow-through	Inflows and outflows are tightly linked; limited internal buffering	Strong surface or groundwater connectivity, filled storages, hydraulic gradient	Rapid transfer to receptors and reduced opportunity for attenuation
Evaporation-dominated	Net evaporation suppresses export for long periods; terminal sink behaviour persists	Arid climate, high evaporation rates, weak catchment contribution, low conductivity	Low discharge frequency but progressive solute concentration in storages
Discharge-driven	Frequent overflow or managed discharge; performance dominated by treatment and operating rules	Full or near-full storage, wet years, intense run-off, strong connectivity, underperforming controls	Compliance risk dominated by peak flows, event timing and treatment reliability

Note: A single site may occupy more than one regime at once or shift between regimes seasonally or over the mine life.

This multi-regime framing matters because closure risk depends not only on the magnitude of water fluxes but also on the timing and mechanism of release. For instance, pit lakes can behave differently under varying climatic and geographic conditions, and terminal sinks persist only under certain combinations of high evaporation, low hydraulic gradient and low hydraulic conductivity. Extreme rainfall and low freeboard can also force overflows from otherwise sink-like systems. In practice, a WLBM should therefore allow transition between regimes rather than embedding a single regime as a fixed assumption.

Source terms should then be aligned with these regime differences (Table 3). In storage-controlled or evaporation-dominated systems, load generation is largely controlled by in-storage evolution, concentration and delayed release, whereas inflow-through or discharge-driven systems, event mobilisation, seepage flux and treatment bypass risk become the dominant processes. Accordingly, pathway-specific source terms are generally more defensible than a single uniform concentration assumption. This is consistent with observations that internal structure, cover performance, climate and geochemical heterogeneity can significantly influence load evolution in covered tailings and heterogeneous waste rock systems (Zhang et al. 2024).

Scenario analysis becomes most powerful when it is explicitly organised around regime shifts and control failures (Table 4). Climate and hydraulic conductivity strongly influence pit lake class, hydrological drivers control metal transport, net percolation is primarily governed by meteorological conditions and cover hydraulic properties, and treatment selection depends critically on flow rate, acidity and loading. Together, these factors mean that the same mine can have very different closure outcomes under seemingly modest changes in hydrology or control performance.

Table 3 Illustrative source term representation for a closure water and load balance model

Source–pathway type	Typical mine domains	Preferred model form	Key data inputs
Mine-impacted water run-off chemistry	Exposed waste rock, disturbed catchments, haul roads, pit walls	Event mean concentration or load-per-event relationship	Event water quality sampling and land-disturbance mapping
Seepage chemistry	Waste rock landforms, backfill, rehabilitated structures	Load or concentration linked to seepage flux or net percolation	Static and kinetic tests, seepage monitoring, cover assumptions
Tailings storage facility (TSF) seepage or decant	Supernatant pond, underdrainage, embankments	Time-varying concentration with flow-dependent export	Porewater monitoring, decant chemistry, TSF water balance
Pit lake or residual void water quality	Final voids, pit lakes, connected storages	Dynamic storage node with mixing and evolving boundary exchange	Lake profiles, rebound assumptions, groundwater interaction, chemistry trends
Background inflows	Upstream catchment inflows, undisturbed groundwater	Seasonal baseline concentration or probabilistic distribution	Baseline monitoring and seasonal characterisation
Rehabilitated landforms	Covered landforms and revegetated surfaces	Reduced-load or reduced-concentration source linked to cover class	Cover design basis, flux modelling, monitoring and maintenance history

Note: this table is illustrative and is intended to guide model structure and disclosure rather than prescribe one mandatory input format.

Table 4 Illustrative scenario analysis and key risk drivers

Scenario	Key variable	Regimes most affected	Typical response	Management implication
Wetter climate or more intense event sequence	Rainfall distribution, run-off coefficient, storm clustering	Storage-controlled, discharge-driven	Faster filling, more event mobilisation, earlier overflow or managed discharge	Greater treatment capacity and higher event-compliance risk
Drier climate with higher evaporation	Net evaporation, longer dry seasons	Evaporation-dominated, storage-controlled	Slower filling, lower release frequency, higher retained concentrations	Lower discharge but greater risk of in-storage concentration
Higher net percolation through covers	Cover underperformance, infiltration increase	Flow-through, discharge-driven	Higher seepage flux and deeper mobilisation of stored contaminants	Cover performance becomes a primary closure control

Scenario	Key variable	Regimes most affected	Typical response	Management implication
Faster groundwater rebound or stronger connectivity	Hydraulic gradient, hydraulic conductivity, boundary connection	Flow-through, discharge-driven	Earlier transition from sink to through-flow; faster receptor connection	Less buffering time and earlier offsite transfer
Longevity of source terms	Increased load magnitude or persistence	All regimes	Higher concentrations or loads at similar water flux	Water quality becomes the limiting design condition
Delayed or reduced treatment performance	Lower removal efficiency, lower availability, late commissioning	Discharge-driven, flow-through	Higher concentrations at release points and lower resilience during events	Redundancy, contingency and staged treatment become critical
Alternative closure designs	Cover class, interception layout, storage rule, passive versus active treatment	All regimes	Different dominant controls and cost–risk trade-offs	Provides an explicit basis for option selection

Note: Table 4 is structured to test both hydrological and management uncertainty, which is usually necessary for closure decisions.

Across these scenarios, the key sensitivities are climate, net percolation, connectivity, source term changes and control performance. Predictions for heterogeneous mine waste are inherently uncertain, and internal waste rock structure and scale can significantly affect mass loading. Key limitations also arise from model assumptions, limited site-specific data and lack of validation.

3.1 Adaptive management

Adaptive management is embedded within the WLBM framework as a mechanism to link model predictions with ongoing site performance and decision-making. Rather than being treated as a separate implementation step, it operates through the integration of monitoring data, model updates and scenario reassessment.

Within this framework, model outputs inform the development of trigger criteria (e.g. water levels, discharge volumes or contaminant loads) while monitoring data are used to evaluate whether system behaviour is tracking within expected ranges. Where deviations occur, the WLBM provides a structured basis to test alternative scenarios, refine source terms or reassess key assumptions such as net percolation, connectivity or treatment performance.

This approach enables iterative refinement of both the conceptual and numerical representation of the system, ensuring that closure strategies remain responsive to observed conditions while maintaining alignment with long-term closure objectives.

4 Limitations

WLBMs are simplified representations of complex mine water systems, and their reliability depends on the quality of input data and the appropriateness of model assumptions. Key limitations include uncertainty in future climate forecasts, limited monitoring data, simplified representation of geochemical reactions, uncertainty in source term evolution, assumptions regarding net percolation and cover performance, and uncertainty in treatment system performance. WLBMs should therefore not be interpreted as precise forecasts but as decision-support tools that help identify key risks, sensitivities and management priorities.

These limitations can be managed through transparent assumption tracking, sensitivity analysis, scenario testing and adaptive management.

5 Conclusion

The water and load balance model framework is structured as an integrated system linking the conceptual site model, dynamic water balance, domain-based source terms, management controls, scenario testing and adaptive review. In application, this highlights 4 key principles: regime diversity should be explicitly represented in the model design; domain-based source terms provide a more defensible basis than uniform assumptions; climate, net percolation, connectivity and control performance are the primary drivers of long-term uncertainty; and model outputs should be directly linked to monitoring programs and trigger criteria to support practical, risk-based closure decision-making.

References

Allen, RG, Pereira, LS, Raes, D & Smith, M 1998, *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome.

Commonwealth of Australia 2016a, *Mine Closure: Leading Practice Sustainable Development Program for the Mining Industry*, Department of Industry, Innovation and Science, Canberra.

Commonwealth of Australia 2016b, *Evaluating Performance: Monitoring and Auditing: Leading Practice Sustainable Development Program for the Mining Industry*, Department of Industry, Innovation and Science, Canberra.

Dold, B 2014, 'Evolution of acid mine drainage formation in sulfidic mine tailings', *Minerals*, vol. 4, no. 2, pp. 621–641, https://doi.org/10.3390/min4030621

ICMM 2025, *Integrated Mine Closure: Good Practice Guide*, 3rd edn, viewed 3 July 2026, https://www.icmm.com/integrated-mine-closure

ICMM & INAP 2025, *Tool for Acid Rock Drainage and Metal Leaching Prevention and Management*, viewed 3 July 2026, https://www.icmm.com/en-gb/guidance/environmental-stewardship/2025/ardml

INAP 2012, *Global Acid Rock Drainage Guide*, viewed 3 July 2026, https://www.inap.com.au/gard-guide

Kemanga, B, McIntyre, N & Bulovic, N 2024, 'Hydrological classification of mine pit lakes using modelling experiments', *Journal of Environmental Management*, vol. 370, article 123057, https://doi.org/10.1016/j.jenvman.2024.123057

Maest, AS, Kuipers, JR, Travers, CL & Atkins, DA 2005, *Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-Of-The-Art*, Kuipers & Associates and Buka Environmental.

Nordstrom, DK 2011, 'Mine waters: acidic to circumneutral', *Elements*, vol. 7, no. 6, pp. 393–398, https://doi.org/10.2113/gselements.7.6.393

Zhang, A, Wilson, D, Ptacek, CJ & Blowes, DW 2024, 'Reactive transport modelling of tailings hydrogeochemistry under a composite cover', *Journal of Contaminant Hydrology*, vol. 261, article 104290, https://doi.org/10.1016/j.jconhyd.2023.104290