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

doi:10.36487/ACG_repo/2615_113

# From liability to legacy: understanding and managing post-closure pit lake water quality

**Brent Usher [a,*], Alex Fitzpatrick [a], Jiajia Zheng [a], Sue Vink [b]**

[a] *Klohn Crippen Berger, Australia*

[b] *School of Civil Engineering, The University of Queensland, Australia*

## Abstract

*Understanding long-term (multi-decadal to centennial, typically simulated over 100 years) water quality of pit lakes is critical for mine closure planning and relinquishment. Water quality influences post-mining land use options and determines the extent of ongoing management required to ensure stability and environmental protection. While acid mine drainage is usually of greater concern, most coal mine voids in Queensland and the Hunter Valley exhibit neutral to slightly alkaline conditions, shifting the primary risk toward increasing salinity driven by evaporation.*

*Two case studies are presented in this paper. For case study 1, field monitoring was combined with predictive modelling to evaluate the evolution of water quality, with 2 coal mine pit lakes as focus. This included vertical profiling of salinity, pH, dissolved oxygen, and temperature to assess seasonal stratification. Results indicated that both pits function as groundwater sinks, with no overflow expected under typical climatic conditions. Monitoring showed that salinity increases over time, reflecting evapoconcentration, while pH remains neutral, largely reducing metal solubility.*

*To predict long-term trends, coupled water balance and salinity models were developed using GoldSim as a water balance frame. Groundwater fluxes were informed by external groundwater models, while PHREEQC was used to assess hydrogeochemical controls on salinity evolution. The models incorporated site-specific data, spoil geochemistry and recent research on evaporation estimation. Calibration (~6 years of data) reproduced water levels within ±0.5–1.5 m (MAE <1 m) and salinity within ±10–20%, with deviations driven by unmodelled operational inputs. Monitoring indicates salinity increased to ~5,000 µS/cm over ~10 years (~500 µS/cm/yr), while pH remained neutral (8–9). Models predict salinity will reach ~20,000–30,000 mg/L total dissolved solids (TDS) within 100 years under evaporation-dominated conditions. Sensitivity analysis identified evaporation and spoil-related salt loads are the primary controls on salinity evolution for the voids.*

*A second case study evaluates a contrasting approach at a metal mine. Tailings is backfilled into a deep pit, rapidly inundated with river water to establish a >150 m water cover. The pit is later reconnected to the regional river system via controlled high-flow exchanges. Modelling indicates that periodic flushing limits salinity accumulation, and with the planned water cover, suppresses sulphide oxidation.*

*The findings support early integrated assessment of pit lake water quality to inform closure strategies. Proactive assessment allows environmental risks and post-mining options to be understood. Incorporating robust monitoring, predictive modelling and sensitivity analysis into closure planning provides improved basis for decision-making and supports sustainable outcomes. This study demonstrates how integrated monitoring and coupled hydrological–geochemical modelling can quantitatively predict salinity evolution and distinguish between closure paradigms, providing a robust basis for pit lake closure design. The primary scientific contribution of this study is the demonstration that contrasting closure designs can produce fundamentally*

[*] Corresponding author. Email address: BUsher@klohn.com

*different long-term water quality trajectories, and that coupled monitoring and modelling provides a quantitative basis for evaluating these outcomes during closure planning.*

**Keywords:** *pit lakes, water quality, modelling, legacy management*

# 1 Introduction

Pit lakes are among the most persistent and technically complex legacies of open cut mining. Their long-term (multi-decadal to centennial, typically simulated over 100 years) water quality influences environmental risk, post-mining land use options, and the likelihood of successful relinquishment. Unlike engineered facilities that can be removed or capped, pit lakes typically persist indefinitely, requiring water quality outcomes to be acceptable over multi-decadal to centennial timeframes.

Globally, pit lake research and management have focused heavily on acidic systems (Salmon et al. 2017; Denimal et al. 2005), where closure risk is dominated by acid mine drainage and metal mobilisation. In contrast, many Australian coal and metal mines occur in low-sulphur geological settings that result in neutral to mildly alkaline pit lakes. In these systems, long-term water quality evolution is controlled primarily by hydrology, evaporation and salt accumulation rather than acid generation.

This research addresses 2 key knowledge gaps. First, the long-term evolution of water quality in neutral to mildly alkaline pit lake systems remains comparatively under-studied, particularly with respect to evapoconcentration-driven salinity trajectories and their implications for closure. In addition, there is limited integration of field monitoring data with coupled hydrological and geochemical modelling to support reliable prediction of post-closure water quality. Second, this study evaluates contrasting closure approaches, including evaporation-dominated systems and actively managed systems involving tailings backfill and water management, to assess their influence on long-term water quality outcomes.

Despite low acidity risk, predicting pit lake water quality in these environments remains challenging. Key uncertainties include evaporation rates under future climates, spoil and tailings salt contributions, groundwater connectivity, and the implications of closure design decisions such as backfilling, water covers and surface water reconnection. In this study, these uncertainties are addressed through a combination of multi-year field monitoring, critical review of multidisciplinary outcomes, coupled water and salinity balance modelling, and sensitivity analysis to quantify their relative influence on long-term water quality prediction.

This paper presents 2 contrasting pit lake closure approaches, defined here as fundamentally different conceptual approaches to closure design that determine hydrological connectivity, water balance and long-term system behaviour, supported by field monitoring and integrated numerical modelling:

1. Coal mine pit lakes dominated by evaporation and internal salt loading.
2. A tailings-backfilled pit intentionally reconnected to a river system as an active component of the landscape.

The objective of this paper is to improve understanding of post-closure coal pit lake water quality by integrating field observations with coupled hydrological and geochemical modelling. The study aims to quantify long-term salinity trajectories, identify the dominant controls on water quality, and evaluate how alternative closure designs influence long-term outcomes. In doing so, the study supports a transition from viewing pit lakes as long-term liabilities to managing them as stable and sustainable legacy features.

# 2 Coal mine pit lake water quality

## 2.1 Coal mining regions of eastern Australia

Coal mine pit lakes across Queensland and the Hunter Valley commonly form under semi-arid to sub-humid climates where evaporation exceeds precipitation for much of the year. Regional reviews of pit lake monitoring data show salinity typically ranging from approximately 1,000 to 18,000 µS/cm (Zheng et al.

2024), with increasing trends observed at most long-lived pits over monitoring periods of approximately 10 years. In addition to chloride, sulphate is another significant anion, reflecting leaching of spoil materials and subsequent evapoconcentration. Importantly, sulphate increases are not coupled with declining pH, aligning with the generally low sulphide content of the sediments and coals in Australian coal fields. Long-term water chemistry is governed by salt concentrations, rather than acid generation.

Measured pH values across most coal pit lakes remain neutral to mildly alkaline (typically 8–9), reflecting low-sulphur coal measures, carbonate-bearing lithologies and alkaline spoil materials. Dissolved metals and nutrients are typically low (metals in the µg/L to low mg/L range), and concentrations often fall below guideline thresholds for ecosystem protection (e.g. ANZG (2018) 95% species protection trigger values for freshwater ecosystems).

These conditions suggest that pit lakes in eastern Australian coal basins may be manageable, in the sense that water quality meets agreed closure objectives such as maintaining neutral pH, low metal concentrations within guideline thresholds (e.g. ANZG 2018), and stable long-term conditions without ongoing active management, as stable water bodies, provided salinity is appropriately characterised and closure strategies account for long-term evapoconcentration.

# 3 Case study 1: closed coal pits and pit lakes

## 3.1 Site selection and monitoring objectives

Two Queensland coal mine pit lakes were selected as representative closed basin systems exhibiting neutral pH and increasing salinity. The 2 pits represent common variations in final void geometry, with one characterised by a relatively larger surface area and greater depth, and the other by a narrower and shallower configuration. The monitoring program was designed to support the study objectives of understanding and predicting post-closure water quality behaviour and informing management and closure strategies, and specifically to:

- characterise vertical and seasonal water quality dynamics
- assess stratification, mixing, and evaporative processes
- provide calibration data for long-term predictive models.

Monitoring was conducted between 2019 and 2023.

## 3.2 Field monitoring program

Monitoring frequency varied between the 2 pits, with water levels recorded daily and general water quality undertaken on a quarterly basis by site monitoring programs.

Monitoring included vertical profiling (~25 m) of temperature, electrical conductivity (as a proxy for salinity), pH, dissolved oxygen and where possible, Chlorophyll-a across multiple stations of each pit lake.

Depth-discrete samples were collected for major ions, metals, nutrients and stable isotopes of oxygen and hydrogen. This approach allowed discrimination between evaporative concentration, groundwater inflow and operational water inputs. Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) were analysed from surface water samples collected during targeted campaigns, with 2 events at Pit 1 and one at Pit 2.

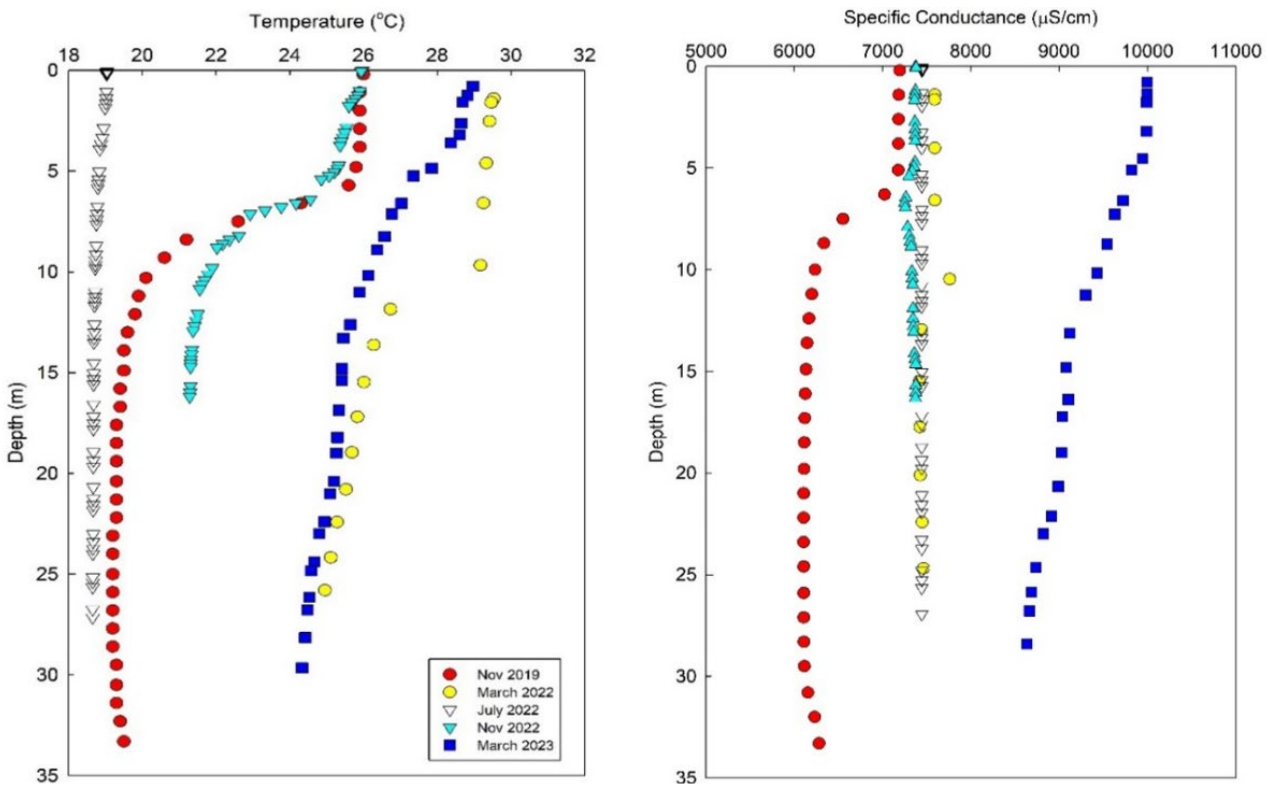
## 3.3 Observed hydrodynamics and water quality

One pit lake exhibited pronounced seasonal stratification during warmer months, breaking down during winter mixing. The second pit lake was shown to be more dynamic with more consistent mixing and remained largely polymictic across monitoring events, defined as undergoing frequent mixing without persistent stratification, as indicated by the absence of stable vertical temperature and conductivity gradients.

The observed stratification and mixing regimes have important implications for solute retention and salinity evolution. At Pit 1, monitoring data across multiple seasons show the development of stratification, with vertical gradients in temperature and conductivity during warmer periods indicating layering of the water column. Although water density was not measured directly, these gradients are consistent with density-driven stratification, which promotes solute retention at depth and enhances evaporative concentration at the surface. In contrast, Pit 2 was sampled only once during winter conditions, during which both pits exhibited polymictic behaviour with minimal vertical gradients, indicating well-mixed conditions. Temporal variability at Pit 1 reflects seasonal climatic controls, with stratification developing during warmer periods and breaking down during cooler conditions. Overall, stratification is episodic rather than persistent at the study sites, but when present it supports short-term solute partitioning and contributes to progressive salinity increase under evaporation-dominated conditions.

Salinity generally increased with depth in stratified periods, although distinct chemoclines were episodic and often related to operational water additions rather than density-driven separation. Figure 1 shows an example of these data. Stable isotope enrichment confirmed strong evaporative signatures in both systems.

Importantly, pH remained stable and neutral throughout the monitoring period, and dissolved metal concentrations were consistently low. Both pit lakes supported biological productivity, with plankton and microbial communities comparable to natural inland lakes.




(a) (b)

**Figure 1 Pit 1 vertical profiles of temperature and specific conductivity**

# 4 Modelling framework for coal pit lake closure

## 4.1 Integrated water balance and salinity modelling

Modelling is an important tool that provides information to support the planning and development of strategies for the rehabilitation and management of mine voids during operation and post-mine closure. A void closure plan must be included in the rehabilitation plan for the mine with residual voids (Department of Environment and Science 2021).

A coupled modelling framework was adopted to represent the key hydrological and geochemical processes controlling long-term salinity evolution. GoldSim was used for water balance simulation due to its ability to integrate climate, pit geometry and groundwater interactions over long timeframes. PHREEQC was used to evaluate geochemical constraints, including pH buffering and mineral equilibria. This combined approach enables robust prediction of long-term salinity and water quality stability.

The models incorporated:

- rainfall and run-off inputs
- evaporation losses
- groundwater inflows and outflows (derived from external seepage models)
- time-varying pit geometry
- spoil-derived salt loads.

Groundwater inflows were informed by site-scale groundwater models, while evaporation estimates were based on climate records, adjusted for pit geometry effects. The GoldSim water balance considers the contributing catchments and considers the climatic, surface water, potential groundwater and spoil contributions to the pit lake. The Australian Water Balance Water Model (AWBM; Boughton 2004) was used to simulate the process external to the pit. For these pits, climatic data from the SILO database (Queensland Government 2023) were included in the model for calibration and used as basis for the predictions. The components were sequentially coupled: run-off simulated using AWBM was input to the GoldSim water balance model, groundwater flows were incorporated from external groundwater models, and resulting pit lake water volumes and salinity concentrations were used to evaluate long-term water quality.

## 4.2 Geochemical constraints

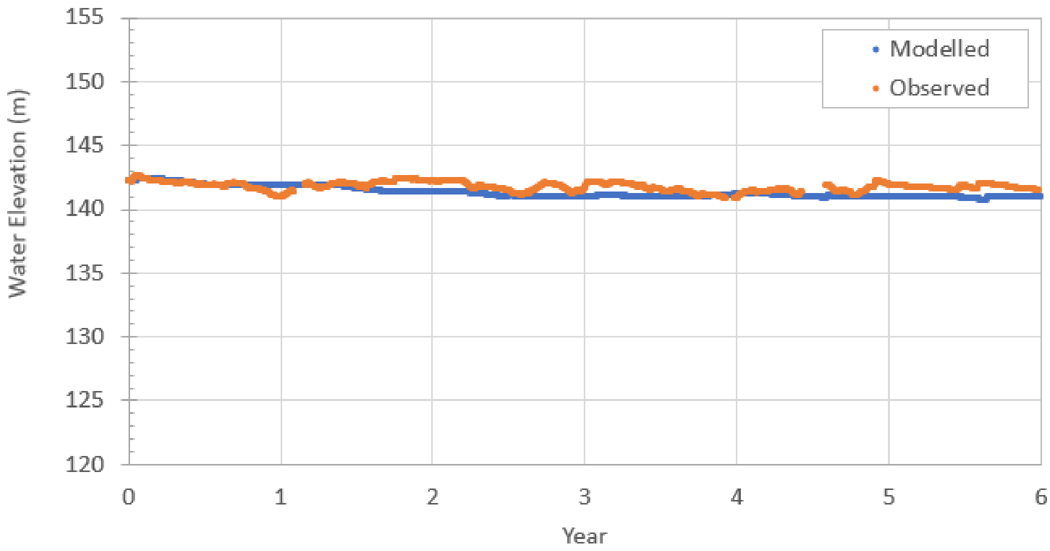
Hydrogeochemical modelling was undertaken using PHREEQC software (Parkhurst & Appelo 2013) and the phreeqc.dat database to assess pH buffering, mineral saturation states and metal solubility under increasing salinity. Simulations assumed equilibrium conditions and represented evaporation by progressively removing water from the system, thereby concentrating dissolved constituents. Major ion chemistry-controlled pH buffering and mineral saturation, with carbonate equilibria explicitly accounted for, and mineral saturation indices used to infer potential precipitation. Simulations were conducted across the range of observed pit lake water quality to evaluate impacts on speciation and mineral precipitation. This approach ensured that predicted salinity increases did not inadvertently result in metal mobilisation or acidification. For salinity and major ion loads, findings based on kinetic leaching experiments conducted by Edraki et al. (2019) were used as a basis, informed by the location of the study pit and feedback from the site geologists

The geochemical modelling assumes equilibrium conditions and simplified evaporation processes, and therefore does not explicitly represent kinetic reactions or mixing. Uncertainty may also increase at higher salinities due to limitations in thermodynamic data, which may influence predictions of long-term water quality relevant to closure management.

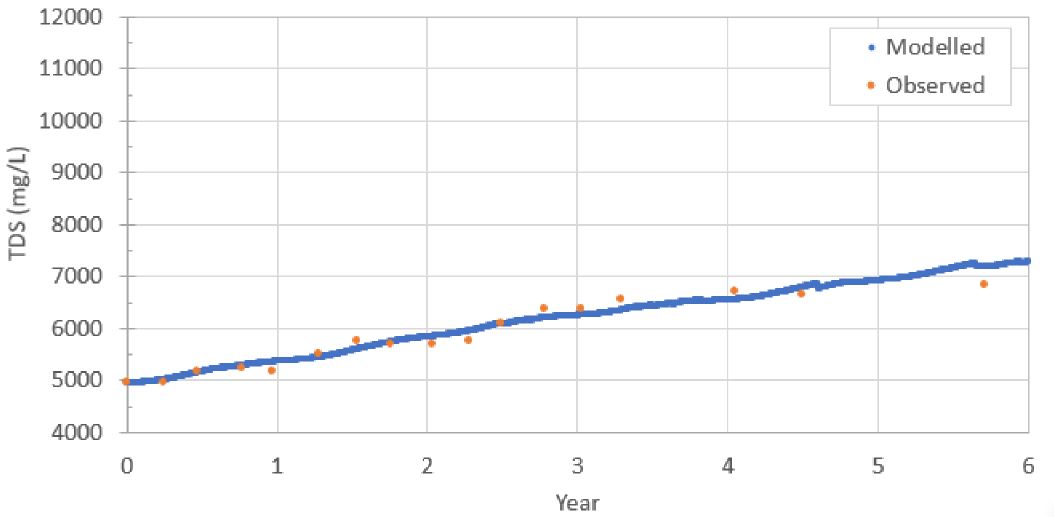
## 4.3 Model calibration

Models were calibrated against approximately 6 years of historical monitoring data, including daily water level records and quarterly salinity measurements, with salinity converted from field electrical conductivity to total dissolved solids (TDS). Simulated trends closely matched observed behaviour, with residual differences attributable primarily to short-term operational water movements not represented in closure scenarios.

Figure 2 shows that the model captures the overall trends in water level and salinity, reflecting the key processes controlling pit lake evolution. Minor deviations are associated with short-term operational influences not included in the model. Overall, the agreement supports the model’s application for understanding and managing post-closure coal pit lake water quality.




(a)




(b)

**Figure 2 Comparison of simulated and monitored results for Pit 2; (a) Water elevation; (b) Total dissolved solids**

# 5 Predicted long-term outcomes for closed basin pits

## 5.1 Water levels and hydrological behaviour

Model results indicate that both pit lakes act as long-term groundwater sinks, as simulated water balances show evaporation consistently exceeding key inflow components (rainfall, natural catchment run-off and groundwater inflows), resulting in net inward hydraulic gradients and no predicted overflow under typical climatic conditions. The models indicate that equilibrium water levels are reached below surrounding groundwater levels, supporting sustained inflow rather than outflow. Two-dimensional (2D) seepage modelling was performed using SEEP/W (GeoStudio 2021) and steady-state analytical solutions (Marinelli & Niccoli 2000) were used to estimate groundwater flows. While uncertainty in groundwater connectivity influences inflow estimates, sensitivity analysis indicates that its effect on the long-term water balance is secondary to evaporation. Across a plausible range of groundwater conditions, the system remains evaporation-dominated with inward hydraulic gradients, supporting the robustness of the groundwater sink prediction for post-closure water quality management.

Under post-closure conditions, evaporation consistently exceeds combined rainfall, natural catchment run-off and groundwater inflows, resulting in stable equilibrium water levels reached after approximately 50–70 years. The 2 dominant water inflows are rainfall and natural catchment run-off, with the total inflows from both inflow sources. Simulated groundwater flow was 10 ML/yr, whereas evaporation rates were approximately 20–30 times greater than groundwater flows. Consequently, groundwater inflows have a relatively minor influence on equilibrium lake levels compared with evaporative losses.

Overflow was evaluated using historical site climate data, stochastic GoldSim realisations, and sensitivity scenarios that applied scaling factors to key climate variables. In this context, 'rare extreme rainfall events' refer to conservative wet-climate conditions represented by upper-percentile rainfall/run-off realisations, rather than a single design storm. These scenarios were used to test whether sustained wetter conditions could raise pit lake levels to overflow. Overflow was only considered possible under highly conservative combinations of upper-percentile wet-climate scenarios where rainfall and run-off inputs exceeded the storage and evaporative capacity of the pit lake.

Climate-related uncertainty was also considered through evaporation sensitivity. Climate inputs were based on historical site data and published evaporation studies relevant to the reservoir systems in the study area (Helfer et al. 2012; McJannet et al. 2019), with variability represented by applying scaling factors in the sensitivity analysis built in GoldSim. Helfer et al. (2012) indicated that future evaporation may increase under higher air temperatures, while McJannet et al. (2019) showed that pit lake evaporation can be 15% less than that observed. These effects were incorporated through the pit lake evaporation coefficient and sensitivity ranges applied in GoldSim.

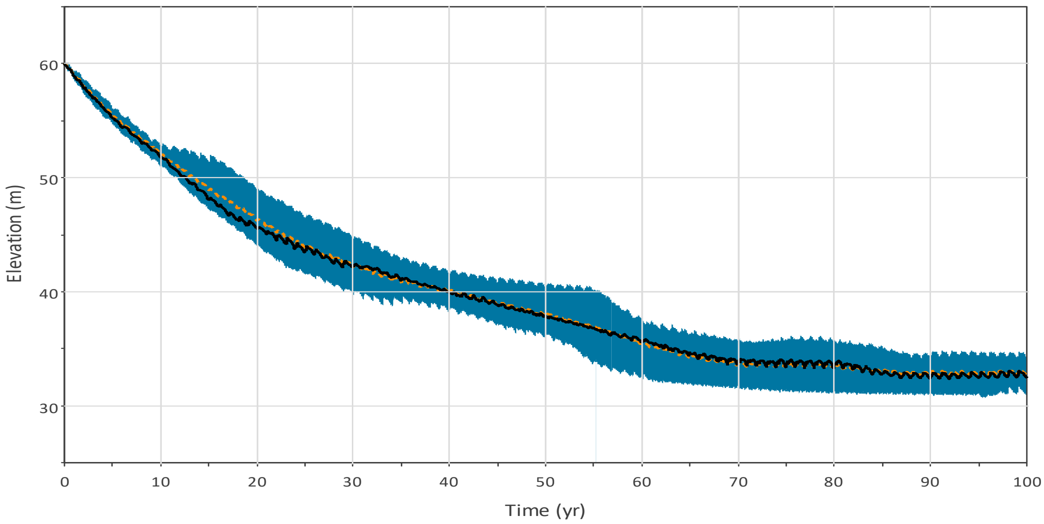
## 5.2 Salinity evolution

Salinity increases progressively due to ongoing evaporation:

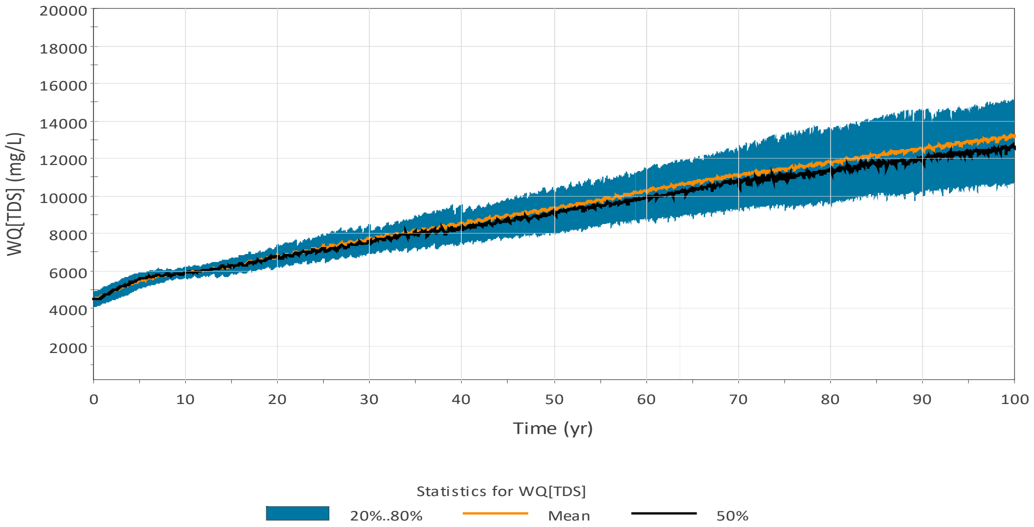
- One pit lake is predicted to reach approximately 30,000 mg/L TDS within 100 years.
- The second pit lake is predicted to stabilise closer to 20,000 mg/L TDS.

The difference in predicted salinity between the 2 pits reflects differences in pit geometry, water balance, and solute inputs. Despite high salinity, PHREEQC simulations indicate that circumneutral pH is maintained through carbonate buffering and alkaline spoil materials. Sensitivity analyses indicate that uncertainty in spoil geochemical properties may influence long-term predictions (Zheng et al. 2024); however, geochemical modelling suggests that metal mobility remains limited because pH buffering and mineral equilibrium processes constrain dissolved metal concentrations (Stumm & Morgan 1996; Parkhurst & Appelo 2013). These pit lakes therefore evolve into neutral pH, elevated salinity water bodies with low concentrations of dissolved metals (Stumm & Morgan 1996).

Figure 3 shows the simulated evolution of water level and salinity, demonstrating convergence toward equilibrium conditions and progressive salinity increase driven by evapoconcentration. The range of stochastic outcomes reflects model uncertainty, but consistently indicates elevated salinity with stable pH conditions over the long term, supporting the understanding and management of post-closure coal pit lake water quality. Neutral pH is maintained by carbonate buffering and alkaline spoil materials, with the high salinity dominated by Na–Cl ions resulting from evapoconcentration and long-term solute leaching. In low-sulphur systems, this process increases ionic strength without driving acidification and metal mobility is typically constrained by carbonate buffering and precipitation of secondary mineral phases (e.g. Stumm & Morgan 1996).




(a)




(b)

**Figure 3 Stochastic predictions of; (a) Water elevation; (b) Salinity in a coal mining void**

At higher salinity, density-driven stratification may strengthen, reducing vertical mixing and promoting solute accumulation in deeper waters. This effect may be enhanced during warmer periods due to thermal stratification, although its extent will depend on pit geometry, inflows, wind-driven mixing and future salinity gradients. As the case study 1 model represents bulk whole-lake salinity and does not explicitly simulate vertical stratification, this process should be treated as a modelling limitation and monitored through ongoing vertical profiling.

Very high salinity (~30,000 mg/L TDS) is likely to limit ecological viability, restricting aquatic communities to salt-tolerant species and reducing overall biodiversity. Under the ANZG (2018) guidelines, salinity is recognised as a key physical–chemical stressor, and departures from natural background conditions represent a risk to aquatic ecosystem values and biodiversity. From a closure perspective, such conditions may constrain beneficial post-mining land uses and require acceptance criteria focused on long-term stability and containment, rather than restoration to freshwater ecosystem conditions.

## 5.3 Sensitivity analysis and uncertainty

No models can predict the future with 100% accuracy. Data collection, model design and subsequent modelling activities must aim to minimise and quantify predictive uncertainty. Sensitivity analyses were applied by varying key input parameters over defined ranges using scaling factors in GoldSim, with results evaluated across multiple simulations and summarised using tornado plots. Consistent with Zheng et al. (2024), significant impacts of climatic conditions and material-related salt loads were identified as the significant controls on long-term salinity outcomes. Sensitivity analysis was conducted to understand the factors that have the greatest control on the salinity.

Key model input variables were critically reviewed, and the defined ranges of each parameter were based on literature findings. Ten factors were assessed representing variations in climatic, physical and chemical changes in the model input data. Ranges were informed by site observations and literature reviews, especially for factors such as laboratory to field scaling [McIntyre et al. (2021) and Vriens et al. (2020)], fractions of fine and coarse spoils (Edraki et al. (2019), and pit void evaporation (e.g. McJannet et al. 2019). These 10 factors were selected because they represent the dominant processes controlling pit lake water balance and salinity and provide a structured basis for assessing model uncertainty over the 100-year prediction period based on scientific justification. Further detail on the assessment of uncertainty and sensitivity for these case studies can be found in Zheng et al. (2024).

An overall assessment of the range of variables influencing simulated TDS in Pit 1 was conducted across literature-based and predefined ranges, with the results presented using tornado plots (Figure 4). Sensitivity analysis shows that spoil-related parameters dominate uncertainty in Year 100 salinity, with field scaling and spoil type each contributing up to ~90,000–100,000 mg/L variation in TDS. In contrast, evaporation and groundwater inflow magnitude and groundwater salinity were secondary in comparison, with most remaining factors contributing <5,000 mg/L (Figure 4).

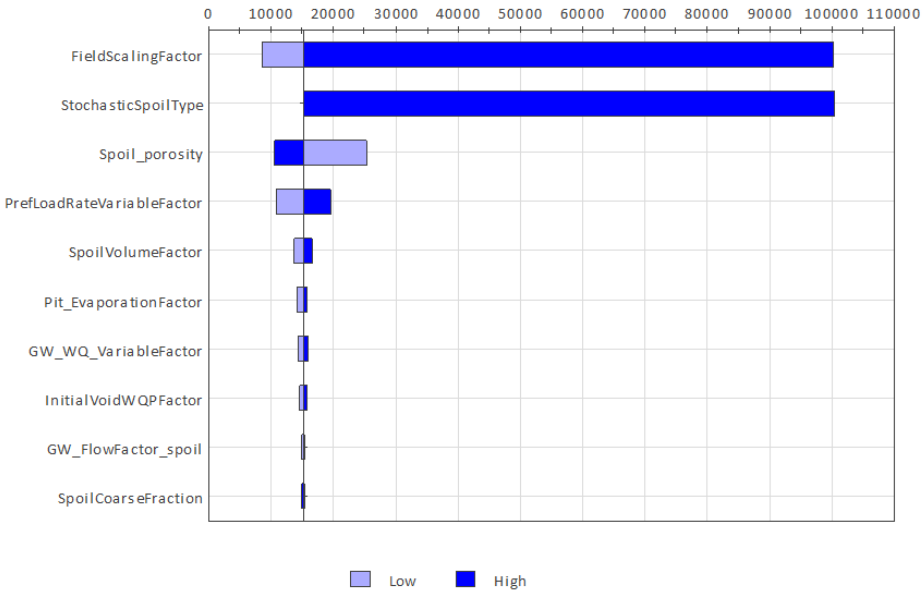



**Figure 4 Tornado sensitivity plot for simulated TDS (mg/L) at Pit 1 at Year 100**

These results reinforce the importance of robust climate analysis, spoil characterisation, and conservative assumptions in closure modelling.

# 6 Case study 2: in-pit tailings backfill with river reconnection

## 6.1 Closure concept and objectives

A markedly different closure strategy was evaluated at a large open pit metal mine in the Northern Territory, where pit lake closure objectives focused on long-term ecosystem integration rather than isolation. The closure design involves progressive relocation of tailings from external facilities to the very deep pit. After placement, the pit is rapidly filled with river water to establish a permanent water cover (more than 150 m depth). The rapid fill is intended to limit additional sulphide oxidation, with the significant depth of water cover intended to provide an anoxic environment, where the depth of water cover above the backfilled tailings is intended to prevent oxygen reaching the tailings and where the flow conditions would be stable. As outlined in Section 6.2, these assumptions were tested through a battery of models. After water quality stabilisation has been demonstrated through active monitoring of the pit water quality, engineered levees are proposed to enable controlled inflows and outflows during high-flow river events. This reconnection transforms the pit from a closed basin into system where the shallow pit lake becomes an actively flushed water body when surface flow conditions are high enough. The pit lake can exchange water with the surface water flow system and maintain neutral pH and low salinity (with low dissolved metal concentrations), with the intent that for early periods after operations have ceased (in the active closure stage), monitoring of the pit water would continue to verify that pit water is suitable for release). The pit lake is therefore designed as an active feature rather than a passive containment structure.

## 6.2 Modelling approach

Long-term water quality was simulated using a coupled GoldSim–PHREEQC framework in conjunction with hydrodynamic modelling using ELCOM.

The GoldSim–PHREEQC modelling includes:

- tailings consolidation and porewater release
- groundwater rebound
- evaporation
- river inflows and controlled outflows
- geochemical reactions under submerged conditions.

The water quality modelling was iterative with hydrodynamic modelling using the numerical model ELCOM (Estuary, Lake and Coastal Ocean Model; Hodges & Dallimore 2015). The hydrodynamic was completed to simulate the temporal behaviour of the potentially stratifying water bodies with environmental forcing (TWS 2016) imposing the climate data from 1973 to 2006, including high-resolution modelling of extreme events such as the 1984 tropical cyclone Kathy event. These results, which included simulation of proxy tracers, suggested that vertical mixing was limited to a depth ~50 m or less even in extreme events, and that stable conditions at the depth of the tailings could be expected, meaning surface outflows and water quality would be dominated by incoming river water quality rather than deep pit chemistry. In addition, over time, the river connection progressively adds sediment to the system, which would settle to further reduce the interaction between the tailings and the shallower active flow system. The hydrodynamic modelling also shows that after connection with the river has been re-established, stratification of the mine pit lake could be expected, allowing greater dilution ratios in the shallower portions of the water body where active interaction with the surface water inflows would occur.

Tropical Water Solutions (TWS) provided a limnological assessment of the mine pit lake for several scenarios, outlining the likely degree of stratification that may develop in the pit lake over time. To incorporate the TWS results, a layered pit lake system was built in GoldSim that allows water exchange and mixing between layers and simulates the development of stratification based on the TWS assessment (TWS 2016). The pit lake was modelled using an epilimnion and hypolimnion, with inflows partitioned between the upper and lower lake in accordance with the elevation at which inflows occur and the results of the TWS modelling. Inflows were also partitioned according to chronology, as inflows cannot be assigned between layers until stratification develops. The hydrodynamic modelling indicated that a significant thermocline is maintained at approximately 0 to −10 m AHD during summer months, with seasonal winter deepening associated with partial mixing extending to approximately −50 m AHD (TWS 2016). These results formed the basis for the representation of stratification and deeper-level mixing in the GoldSim water quality model and enabled the influence of a deep (approximately 150 m) water column on pit lake water quality to be considered.

Watercourse modelling for the project provided inputs to the mine pit lake water quality model, including simulation of interactions between the pit lake and the river system. A 1,000-year synthetic climate sequence based on the SILO dataset for the site was used to evaluate long-term hydrological variability. There are 2 stages to the pit refill. The first stage involves tailings deposition and gradual filling of the pit with selected waste rock, tailings and water. During this period, excess water is pumped out, generally maintaining a water cover of up to 5 m on the deposited tailings to reduce oxygen availability and limit sulphide oxidation. The second stage of pit refill is marked by rapid additions of river water of up to 500 ML/day during wet-season flood events, where engineered levees have been proposed to direct excess flow to the pit only during periods of high surface water flow.

To provide an indication of the likely water quality envelope, median and 95$^{th}$ percentile scenarios were simulated. This range is provided by applying the statistical variance in the geochemical loading rates derived from the tailings kinetic test results, together with the stochastic inputs from the associated surface water model that was completed. In addition, GoldSim was used to assess the range of sensitivities for aspects including loading from exposed pit wall, groundwater loading factor, stratification and mixing, secondary mineral accumulation in the pit prior to tailings placement and subaqueous loading rates.

### 6.3 Predicted performance of the river-connected pit

Model results indicate that near-neutral pH conditions are maintained throughout a long-term post-closure simulation period. Initial elevated concentrations (for example sulphate concentrations in the thousands of mg/L when the tailings is placed) in the water body during and immediately after tailings placement are rapidly reduced by dilution (diversion of the flows when the river exceeds a specified threshold allowing up to 500 ML/day during flood periods) during proposed rapid filling of the pit and once connected to the surface water, with ongoing river inflows. Modelling suggests that sulphate concentrations in the overlying water would be reduced to below 100 mg/L at depth and lesser values in the active shallow system. Simulations indicate that longer term metal concentrations will be low (for example ~0.02 mg/L Zn and ~0.001 mg/L Cu). The simulations suggested that at concept level, the periodic flushing offsets evapoconcentration, preventing long-term salinity accumulation. The deep tailings mass and water cover suppress sulphide oxidation, substantially reducing long-term metal loading. Predicted outflow water quality is below the established downstream water quality criteria, and the pit outflows would be further diluted by the river flows that bypass the pit during high-flow events, supporting integration with the river ecosystem during these periods of high flow that are commonly experienced in this part of Australia.

# 7 Comparison of pit lake closure approaches

The 2 case studies illustrate fundamentally different pit lake behaviours driven by consideration of site conditions and informed closure design rather than geochemical or geological factors alone. Closed basin Australian coal pits evolve as evaporation-dominated systems. These voids may provide a period during which water quality is suitable for some operational or managed uses. These voids but over longer timeframes they are expected to become elevated salinity water bodies as a result of persistent water deficit and progressive evapoconcentration. In contrast, the river-connected tailings backfill case demonstrates an approach in which potentially more reactive mine waste is rapidly submerged, isolated beneath a deep water cover, and incorporated into a periodically flushed surface water system in a wetter climate. Rather than relying on passive containment, this approach deliberately changes the post-closure water balance and limnological behaviour of the pit lake so that dilution, flushing, stratification and sediment accumulation become part of the closure design.

The opposing approaches rely on climatic, pit morphology and stored mine waste differences. For the water deficit cases, the approach for these shallow voids is to deliberately limit impact outside of the void by designing a system that acts as a long-term water sink whereas the wetter climate, deep pit and available higher flow river provide opportunities for the pit lake to form part of the post-closure surface water system. While these differences can be viewed as a contrast between isolation and containment on the one hand, and active integration and exchange on the other, these design choices are driven by the environmental and physical factors. The closed basin coal pit strategy seeks to maintain the pit lake as a hydraulically inward-gradient feature, thereby reducing the likelihood of offsite release. Its success depends on demonstrating that the pit will remain a groundwater sink, that overflow is improbable, and that water quality will remain stable enough to meet agreed closure objectives in the short term, despite increasing salinity. The river-connected strategy, by contrast, accepts controlled hydrological exchange as a design objective. Its success depends on demonstrating that inflows and outflows occur only under suitable hydrological conditions, that receiving-water criteria can be met, and that the deep tailings mass remains effectively isolated from oxidising conditions and from exchange with the active surface water layer.

These approaches address different dominant risks. For neutral coal pit lakes, the principal long-term issue is not acidification but progressive salinity accumulation and the associated limitation places on ecological values, beneficial use and relinquishment criteria. For the tailings-backfilled metal mine pit, the principal risk is the potential mobilisation of acidity, sulphate, metals and tailings porewater constituents if the tailings is not rapidly submerged, if the water cover is disturbed, or if deep water chemistry becomes connected to the outflow zone. The first approach manages risk primarily by limiting exposure pathways; the second manages risk by combining geochemical suppression, hydrodynamic separation, dilution and controlled discharge. Table 1 provides an overview of the approaches and considerations.

**Table 1 High-level comparison of alternative pit closure approaches**

| | **Closed basin coal pit lakes (water deficit, non-acid generating waste, shallow void)** | **In-pit tailings backfill with river reconnection (wetter climate/deeper pit)** |
|---|---|---|
| Closure philosophy | Passive containment and long-term stability within the final void | Active landscape integration through engineered reconnection and controlled exchange |
| Hydrological setting | Evaporation-dominated water balance with inward groundwater gradients and low likelihood of overflow or groundwater outflows | Managed surface water connectivity, with high-flow inflows and outflows used to promote dilution and flushing |
| Dominant water quality process | Evapoconcentration of salts and ongoing spoil-derived solute release | Dilution, periodic flushing, geochemical suppression of sulphide oxidation, and hydrodynamic separation of deep and shallow waters |
| Principal closure risk | Increasing salinity and restricted post-mining land or water use, despite neutral pH and low metal mobility | Potential release of tailings-derived constituents if water cover, stratification, or controlled discharge assumptions are not maintained |
| Water quality modelling focus | Long-term water balance, evaporation, salinity trajectory, spoil salt loads, groundwater sink behaviour, and sensitivity analysis | Tailings porewater release, geochemical evolution, hydrodynamic mixing depth, stratification, river exchange, and discharge quality |

| | Closed basin coal pit lakes (water deficit, non-acid generating waste, shallow void) | In-pit tailings backfill with river reconnection (wetter climate/deeper pit) |
|---|---|---|
| Monitoring emphasis | Water level/ free board, salinity (and neutral pH), inward groundwater gradients, and evidence of long-term stability | Tailings consolidation, water cover depth, vertical mixing, sulphate and metal concentrations, river flow triggers, and outflow quality |

From an Australian closure planning perspective, neither paradigm is universally preferable. The appropriate approach depends on climate, pit geometry, hydrogeological setting, waste geochemistry, receiving-environment sensitivity, regulatory expectations, stakeholder values, and the practicality of maintaining engineered controls. National and state-level guidance increasingly emphasises risk-based closure assessment, long-term stability, non-polluting outcomes and realistic post-mining land use. Recent Australian pit lake research initiatives also highlight the need to evaluate both residual risks and potential beneficial uses rather than treating all pit lakes as liabilities. In this context, the closed basin coal pit approach may be appropriate where the system can be shown to remain internally contained and where elevated salinity is acceptable within the agreed closure objective. The river-connected approach may be appropriate only where there is sufficient confidence in hydrological controls, receiving-water protection and long-term geochemical stability of submerged mine waste.

The comparison also shows that the timing of design decisions is critical. Once final void geometry, waste placement, catchment connection and water management infrastructure are fixed, the range of feasible closure options narrows substantially. Early planning allows pit morphology, backfill sequencing, water cover design, surface water diversions and monitoring programs to be aligned with the intended closure outcome. In the coal pit case, early design attention should focus on reducing uncertainty in evaporation, spoil salt release, groundwater gradients and long-term salinity acceptance criteria. In the river-connected case, early design attention should focus on tailings placement, consolidation behaviour, water cover permanence, stratification, sedimentation, discharge triggers and downstream water quality protection.

Overall, the 2 paradigms demonstrate that pit lake closure should not be framed simply as a choice between leaving a void open or backfilling it. Rather, closure planning should define the intended long-term hydrological role of the pit lake: whether it is to function as an internally contained terminal sink, a managed water resource, a submerged mine waste repository, or an actively exchanged component of the catchment. This distinction provides a clearer basis for selecting completion criteria, designing monitoring programs, communicating residual risk, and assessing whether the resulting landform can support relinquishment.

# 8 Conclusion

Pit lakes can be significant components that need to be considered in mine closure, with potential negative water quality outcomes to the environment if designed and managed without recognising the risks and options that are available. The case studies presented in this paper demonstrate that long-term pit lake behaviour may be influenced by operational conditions and more strongly by the hydrological setting that allows controls to be established during closure design.

In eastern Australian coal mining regions, pit lakes typically exhibit neutral to mildly alkaline conditions, with low metal mobility and limited acid generation risk. For these systems, evaporation-driven salinity increase is the primary long-term water quality concern. Integrated field monitoring and predictive modelling show that closed basin pit lakes are likely to evolve into saline but geochemically stable water bodies, functioning as long-term groundwater sinks with minimal risk of overflow. While elevated salinity (TDS in the tens of thousands or higher as evapoconcentration effects manifest over time) may constrain post-mining water use options, these systems can be used in the shorter-term (decades or longer, depending on the site-specific water balance) to support various external water uses.

For the Australian coal pits, the sensitivity analyses highlight that uncertainty in long-term outcomes is dominated by evaporation rates, pit geometry and spoil-related salt loads. These findings emphasise the importance of early assessment of pit morphology, climate exposure and spoil geochemistry, as well as implementation of appropriate prediction processes to provide confidence in selection of the preferred response. Understanding the impact that uncertainties such as laboratory-to-field scaling or climate variability have on water quality projections can assist in targeting where better characterisation or quantification of inputs is needed.

The contrasting case study illustrates an alternative closure approach in which deep in-pit tailings placement and intentional reconnection to a river system can be used in a deeper pit where a seasonally wetter climate can provide a positive water balance and the system can be engineered to allow rapid filling once mine waste has been placed deep in the pit. By rapidly inundating reactive materials, maintaining long-term water cover, and enabling periodic flushing, improved water quality can be achieved. Modelling indicates that this approach can suppress sulphide oxidation, limit salinity accumulation, and produce acceptable outflow water quality that may be amenable to controlled release during high-flow conditions. Once monitoring has shown that the shallow pit water quality is within acceptable ranges, the river-connected pit can become actively managed and eventually an ecologically integrated component of the landscape rather than a passive containment facility.

These case studies demonstrate that pit lake closure outcomes are strongly influenced by early conceptual design decisions and by understanding the constraints for differing environmental and mining contexts.

# Acknowledgement

The authors are grateful to the Australian Coal Association Research Program (ACARP) for funding this project (ACARP C29047) and Glencore for consenting to inclusion of an alternate case.

# References

ANZG 2018, *Toxicant Default Guideline Values for Aquatic Ecosystems. Australian and New Zealand Guidelines for Fresh and Marine Water Quality*, https://www.waterquality.gov.au/anz-guidelines

Boughton, W 2004, 'The Australian water balance model', *Environmental Modelling & Software*, vol. 19, no. 10, pp. 943–956.

Denimal, S, Bertrand, C, Mudry, J, Paquette, Y, Hochart, M & Steinmann, M 2005, 'Evolution of the aqueous geochemistry of mine pit lakes – Blanzy–Montcau-Les-Mines Coal Basin (Massif Central, France): origin of sulfate contents; effects of stratification on water quality', *Applied Geochemistry*, vol. 20, no. 5, pp. 825–39, https://doi.org/10.1016/j.apgeochem.2004.11.015

Department of Environment and Science 2021, *Progressive Rehabilitation and Closure Plan Guideline (ESR/2019/4964)*, Queensland Government, Brisbane.

Edraki, M, McIntyre, N, Baumgartl, T & Hilton, M 2019, *Prediction of Long-Term Salt Generation from Coal Spoils*, ACARP report C25039, The University of Queensland, Brisbane.

GeoStudio 2021, *SEEP/W*, https://www.geoslope.com/products/seep-w

Helfer, F, Lemckert, C & Zhang, H 2012, 'Impacts of climate change on temperature and evaporation from a large reservoir in Australia', *Journal of Hydrology*, vol. 475, pp. 365–78 https://doi.org/10.1016/j.jhydrol.2012.10.008

Hodges, BR & Dallimore, C 2015, *Estuary, Lake and Coastal Ocean Model: ELCOM*, v3.0 User Manual.

Marinelli, F & Niccoli, WL 2000, 'Simple analytical equations for estimating ground water inflow to a mine pit, *Groundwater*, 38 (2): 311–14. https://doi.org/10.1111/j.1745-6584.2000.tb00342.x.

McIntyre, N, Jain, KR & Edraki, M 2021, 'Modelling of salt leaching from coal mine spoils at two scales', *Mine Water and the Environment*, vol. 40, no. 4, pp. 902–18, https://doi.org/10.1007/s10230-021-00797-9

McJannet, D, Hawdon, A, Baker, B, Ahwang, K, Gallant, J, Henderson, S & Hocking, A 2019, 'Evaporation from coal mine pit lakes: measurements and modelling', in AB Fourie & M Tibbett (eds), *Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 1391–1404, https://doi.org/10.36487/ACG_rep/1915_109_McJannet

Parkhurst, DL & Appelo, CAJ 2013, 'Description of input and examples for PHREEQC version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations', *U.S. Geological Survey Techniques and Methods*, book 6, chapter A43, p. 497.

Queensland Government 2023, *SILO Climate Database*, Long Paddock, viewed 9 May 2023, https://www.longpaddock.qld.gov.au/silo/

Salmon, U, Matthew, RH, Geoffrey, WW, Gregory, NI & Oldham, CE 2017, 'Quantifying lake water quality evolution: coupled geochemistry, hydrodynamics, and aquatic ecology in an acidic pit lake', *Environmental Science & Technology*, vol. 51, no. 17, pp. 9864–75, https://doi.org/10.1021/acs.est.7b01432.

Stumm, W & Morgan JJ 1996, *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters*, 3rd edn, John Wiley & Sons, New York.

TWS 2016, Hydrodynamic modelling report provided to client.

Vriens, B, Seigneur, N, Mayer, K & Beckie, RD 2020, 'Scale dependence of effective geochemical rates in weathering mine waste rock', *Journal of Contaminant Hydrology*, vol. 234, 103699, https://doi.org/10.1016/j.jconhyd.2020.103699

Zheng, J, Fitzpatrick, A & Usher, B 2024, 'Reducing uncertainty in long-term void water quality predictions for coal opencut final void management', *Proceedings of 13th International Conference on Acid Rock Drainage*, Halifax.