

When Lakes Remember the Mine Through Multi-Century Evolution of Pit-Lake Hydrology and Closure Stability

Yohannes Yihdego¹

yohannesyihdego@gmail.com

La Trobe University

Research Article

Keywords: pit lake, mine closure, groundwater rebound, climate change, pit-lake evolution, groundwater modelling, water quality, groundwater-surface water interaction, contaminant transport, closure planning

Posted Date: October 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11041193/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Pit lakes represent one of the most visible and enduring legacies of mining and often persist as permanent hydrological features long after mine closure. Their evolution is governed by interactions between climate forcing, groundwater rebound, geological structures, pit geometry, seepage sources, and water-quality processes. Over centuries, pit lakes may transition between hydrological states, functioning as groundwater sinks, sources, or through-flow systems. These transitions have significant implications for closure stability, contaminant migration, groundwater protection, and long-term environmental performance. This paper synthesises current understanding of pit-lake hydrology, examines the importance of long-term simulation periods, and demonstrates how integrated groundwater, surface-water, climate, and geochemical workflows improve confidence in closure predictions. Results highlight the importance of evaluating pit-lake evolution beyond conventional post-closure timeframes and adopting adaptive approaches that account for climate uncertainty, groundwater recovery, and long-term water-quality risks.

1. Introduction

Pit lakes are among the most enduring hydrological legacies of mining and frequently remain as permanent landscape features following mine closure. Unlike many other mine components that are removed, capped, or rehabilitated, pit lakes may continue interacting with groundwater and surface-water systems for centuries after mining ceases. Their long-term evolution therefore plays an important role in closure planning, environmental management, groundwater protection, and post-mining land-use outcomes.

Historically, pit-lake investigations focused primarily on water-level recovery and attainment of hydraulic equilibrium. More recently, however, attention has shifted toward understanding the long-term behaviour of pit lakes as integrated hydrogeological and geochemical systems. Increasing regulatory expectations and closure obligations require proponents to demonstrate that pit lakes will remain environmentally stable under changing climatic, hydrological, and geochemical conditions over extended timeframes (McCullough et al., 2020; Nordstrom & Blowes, 2020).

Pit lakes are dynamic systems controlled by interactions among groundwater recovery, climate forcing, pit geometry, geological structures, recharge processes, evaporation, and geochemical evolution. Depending on site conditions, they may behave as groundwater sinks, groundwater sources, or through-flow systems, and these hydrological states may evolve through time as groundwater systems recover following closure (Castendyk & Eary, 2020; McCullough et al., 2020).

Climate change introduces additional uncertainty into long-term closure predictions. Variations in recharge, evaporation, drought frequency, and extreme rainfall events can significantly influence groundwater recovery, pit-lake water levels, and long-term water-quality trajectories. Recent studies have demonstrated that climate-driven groundwater responses may continue over multi-decadal and

centennial timescales, creating uncertainty in predictions based solely on present-day climatic conditions (Cuthbert et al., 2020; Taylor et al., 2022).

Water quality often remains the dominant environmental concern for many pit lakes. Long-term geochemical evolution may continue long after hydraulic conditions appear stable due to ongoing interactions between groundwater inflows, pit-wall weathering, waste-rock seepage, stratification processes, and geochemical reactions (Nordstrom & Blowes, 2020; Dold, 2014). Consequently, understanding pit-lake evolution requires integrated assessment of hydrology and geochemistry rather than consideration of water levels alone.

Studies of groundwater-connected natural lakes have similarly demonstrated that groundwater interaction can strongly influence long-term lake behaviour, climatic response, salinity evolution, and water-quality trajectories (Yihdego et al., 2015; Yihdego et al., 2016). These findings highlight the value of considering pit lakes as evolving hydrogeological systems rather than static post-mining landforms.

This paper synthesises current understanding of long-term pit-lake hydrology, examines the importance of multi-century assessment frameworks, and discusses how integrated groundwater, climate, water-balance, and geochemical approaches can improve confidence in closure predictions. Particular attention is given to groundwater recovery, hydrological-state transitions, climate sensitivity, water-quality evolution, and implications for long-term closure stability.

2. Background

2.1 Hydrological Roles of Pit Lakes

Pit lakes do not remain hydrologically static throughout closure. Their behaviour evolves in response to interactions among groundwater recovery, recharge processes, climate forcing, geological structures, and pit geometry. As groundwater systems recover following mining, pit lakes may transition through several distinct hydrological states.

These states generally include:

- groundwater sink conditions, where surrounding groundwater flows toward the pit lake;
- groundwater source conditions, where water moves outward from the lake into surrounding aquifers; and
- through-flow conditions, where groundwater enters one portion of the lake and exits through another.

The timing and sequence of these transitions vary between sites and may occur over decades, centuries, or longer. Failure to identify changing hydraulic behaviour may result in underestimation of groundwater impacts, contaminant migration pathways, closure risks, and long-term environmental liabilities (Castendyk & Eary, 2020; Zhou et al., 2021).

The conceptual evolution of pit-lake hydrological states is illustrated in Fig. 1, while associated risks and groundwater interactions are summarized in Table 1.

Table 1

Conceptual hydrological evolution of pit lakes and associated environmental risks during progressive closure and long-term groundwater recovery.

Closure Phase	Dominant Behaviour	Groundwater Interaction	Primary Risk
Early Closure	Sink	Inward flow	Solute accumulation
Transitional Recovery	Through-flow	Mixed inflow/outflow	Contaminant migration
Long-Term Recovery	Source	Outward flow	Receptor impacts
Equilibrium Phase	Stable state	Site specific	Long-term water quality

2.2 Climate Sensitivity

Climate represents one of the primary controls on long-term pit-lake evolution. Variability in precipitation, evaporation, drought frequency, groundwater recharge, and extreme rainfall events can alter groundwater recovery rates, pit-lake filling trajectories, and long-term hydrological stability.

Future climate conditions may affect:

- groundwater recharge;
- evaporation losses;
- groundwater gradients;
- pit-lake water levels;
- sink-source transitions; and
- contaminant mobility.

Recent studies indicate that changes in recharge can significantly affect groundwater systems over long timescales, particularly in regions subject to changing rainfall patterns and increasing climate variability (Cuthbert et al., 2020; Taylor et al., 2022). Consequently, pit-lake assessments should evaluate multiple climate scenarios rather than relying solely on historical observations.

Investigations of groundwater-connected lakes have similarly demonstrated that climatic variability can strongly influence long-term lake-level responses and hydrological behaviour where groundwater exchange forms an important component of the water balance (Yihdego et al., 2015).

2.3 Water Quality Evolution

Although water levels frequently receive primary attention during closure planning, long-term water quality may ultimately determine environmental performance.

Pit-lake chemistry is influenced by:

- groundwater inflows;
- pit-wall weathering;
- waste-rock seepage;
- tailings seepage;
- geochemical reactions;
- climatic conditions; and
- hydraulic residence times.

Water-quality evolution may continue long after hydrological equilibrium has been reached. Ongoing groundwater interactions, geochemical processes, and climatic variability can result in gradual changes in salinity, sulphate concentrations, dissolved metals, acidity, and stratification behaviour (Nordstrom & Blowes, 2020; Dold, 2014).

Long-term investigations of groundwater-throughflow lakes have demonstrated that water and solute balances may continue to evolve over extended periods despite relatively stable hydraulic conditions (Yihdego et al., 2016). This observation highlights the importance of integrating hydrological and geochemical considerations within pit-lake assessments.

Accordingly, robust closure strategies should evaluate both water-level evolution and long-term water-quality trajectories to support defensible risk assessments and environmental stewardship.

3. Methods and Assessment Framework

3.1 Multi-Century Assessment Approach

Reliable prediction of pit-lake behaviour requires assessment periods that extend well beyond operational and rehabilitation phases. While many closure evaluations focus on the first few decades following mine closure, important hydrological and geochemical transitions may occur much later as groundwater systems recover and approach long-term equilibrium.

A multi-century assessment framework was therefore adopted conceptually to evaluate the sequence of hydrological states that pit lakes may experience throughout their post-closure evolution. Rather than focusing on a specific prediction horizon, the approach emphasizes understanding long-term system behaviour, groundwater recovery, climate sensitivity, water-quality evolution, and closure stability.

The assessment framework recognises that pit-lake systems evolve continuously and that hydrological equilibrium does not necessarily coincide with geochemical equilibrium. Consequently, long-term closure evaluations should consider both groundwater-system recovery and ongoing water-quality evolution.

3.2 Integrated Workflow

Effective pit-lake assessment requires integration of multiple hydrogeological processes operating at different temporal and spatial scales.

The conceptual framework adopted in this study considers interactions among:

- groundwater rebound;
- pit-lake water balance;
- groundwater-surface water interaction;
- geological controls;
- climate forcing;
- seepage inputs;
- geochemical evolution; and
- receptor exposure pathways.

Groundwater recovery remains one of the principal drivers of pit-lake evolution because changes in hydraulic gradients directly influence whether a pit lake functions as a groundwater sink, source, or through-flow system. Similar groundwater-lake interactions have been documented in groundwater-dependent lakes where hydrological behaviour is controlled by long-term groundwater exchange and climatic variability (Yihdego et al., 2015; Yihdego et al., 2016).

The conceptual model provides the basis for evaluating long-term closure behaviour and identifying potential transitions between hydrological states.

The interactions among groundwater recovery, climate forcing, hydrological-state transitions, geochemical evolution, and closure performance are summarised conceptually in Fig. 2.

3.3 Hydrological Assessment Components

Long-term pit-lake behaviour is controlled by a combination of inflow and outflow mechanisms that collectively determine water-level evolution and hydraulic stability.

Key hydrological components include:

Inflows

- direct precipitation;
- groundwater inflows;
- catchment runoff;
- seepage from surrounding mine facilities;
- surface-water diversions.

Outflows

- evaporation;
- groundwater discharge;
- overflow spill mechanisms;
- seepage losses;
- surface-water connections.

The relative importance of these components may change substantially through time as climatic conditions and groundwater systems evolve. Consequently, pit-lake assessments should evaluate changing water-balance relationships rather than assuming static hydraulic conditions.

3.4 Groundwater Recovery and Hydraulic-State Transitions

Groundwater recovery is one of the most significant controls on long-term pit-lake evolution. Recent rebound studies indicate that post-closure groundwater recovery behaviour can often be approximated successfully using long-term recovery models that relate hydraulic response to storage and inflow characteristics (Rudakov et al., 2025).

During early closure, groundwater levels commonly remain depressed due to historical dewatering activities, causing pit lakes to behave as hydraulic sinks. As groundwater recovery progresses, hydraulic gradients gradually decrease and groundwater flow systems reorganise.

This recovery process may result in transitions from:

Sink Conditions → Through-Flow Conditions → Source Conditions

The timing of these transitions depends on factors such as:

- aquifer properties;
- recharge rates;
- climate variability;
- geological structures;
- pit geometry;
- surrounding water-management practices.

Previous investigations have demonstrated that delayed groundwater responses may significantly alter groundwater flow patterns and environmental behaviour over extended periods (McCullough et al., 2020; Zhou et al., 2021).

3.5 Climate-Change Assessment

Climate uncertainty introduces an additional layer of complexity into long-term pit-lake prediction.

Key climate variables influencing pit-lake evolution include:

- precipitation;
- evaporation;
- recharge;
- temperature;
- drought frequency;
- extreme rainfall intensity.

Recent studies indicate that groundwater systems may respond to climate variability over multi-decadal and centennial timescales, potentially influencing pit-lake recovery trajectories and hydraulic-state transitions (Cuthbert et al., 2020; Taylor et al., 2022).

Climate-informed pit-lake assessments should therefore consider multiple plausible future scenarios rather than relying exclusively on historical climatic observations.

Long-term investigations of groundwater-connected lakes have similarly shown that climatic variability can significantly influence groundwater interactions, lake levels, and hydrological stability (Yihdego & Webb, 2011; Yihdego et al., 2015).

3.6 Water-Quality Assessment Framework

Hydrological stability alone does not guarantee successful closure outcomes. Long-term pit-lake performance is also influenced by water-quality evolution.

Important processes include:

- sulphide oxidation;
- groundwater inflows;
- geochemical weathering;
- stratification;
- metal mobilisation;
- salinity accumulation;
- contaminant attenuation.

These processes often operate over timescales comparable to or longer than groundwater recovery. Consequently, water-quality risks may continue to evolve after hydrological conditions appear relatively stable.

Previous studies of groundwater-connected lake systems have demonstrated that water and solute balances frequently continue evolving long after hydraulic equilibrium has been approached (Yihdego et al., 2016). Similar behaviour may occur in pit-lake systems affected by seepage inputs, groundwater exchange, and ongoing geochemical reactions.

3.7 Integrated Closure Assessment

As illustrated in Fig. 2, pit-lake evolution should be evaluated as an integrated hydrogeological system rather than as isolated groundwater, climate, or water-quality processes.

The assessment framework adopted in this study emphasises the importance of integrating:

- groundwater flow;
- climate forcing;
- surface-water interaction;
- contaminant transport;
- geochemistry; and
- long-term closure objectives.

Integrated approaches provide a more realistic representation of pit-lake evolution because they account for interactions among processes that are often evaluated independently. Recent closure studies similarly emphasise the importance of long-term monitoring and integrated assessment throughout pit-lake planning, filling, closure, and post-closure management (Schultze et al., 2024).

As regulatory expectations increasingly focus on long-term environmental performance, adaptive management, and closure resilience, integrated assessments provide a stronger basis for evaluating future pit-lake behaviour, groundwater protection, and closure stability than single-discipline approaches alone.

Figure 2. Integrated conceptual framework linking climate forcing, groundwater recovery, hydrological-state transitions, water-balance processes, groundwater-surface water interaction, geochemical evolution, and closure performance. The framework illustrates how pit-lake behaviour evolves through time as interactions between groundwater systems, climate variability, and geochemical processes influence long-term hydrological and environmental outcomes.

4. Results and Findings

4.1 Groundwater Sink Behaviour

During the initial stages of closure, pit lakes commonly function as groundwater sinks because historical mine dewatering has created depressed groundwater levels relative to surrounding aquifers. Under these conditions, groundwater gradients are directed toward the pit lake, resulting in net inflow from the surrounding groundwater system.

Sink behaviour generally promotes hydraulic containment of seepage originating from adjacent mine facilities and may reduce the potential for off-site contaminant migration. However, sustained inward

groundwater flow may also increase residence times within the pit lake and contribute to the accumulation of dissolved constituents. As a result, water-quality deterioration can occur despite apparently favourable hydraulic containment conditions (McCullough et al., 2020; Nordstrom & Blowes, 2020).

The sink phase often represents the dominant hydrological state during early closure and may persist for many decades depending on aquifer recovery rates, recharge conditions, and pit geometry.

4.2 Groundwater Source Behaviour

As groundwater recovery continues and pit-lake water levels increase, hydraulic gradients may eventually reverse. Under these circumstances, pit lakes can transition from groundwater sinks to groundwater sources, where groundwater movement occurs away from the lake and into surrounding aquifers.

Source behaviour is particularly important from a closure perspective because it may create pathways for the outward migration of dissolved constituents accumulated during earlier phases of pit-lake evolution. The timing of this transition is site-specific and depends upon regional hydrogeology, climatic conditions, groundwater recharge, and lake-water balance.

Failure to evaluate potential source conditions may result in underestimation of long-term groundwater impacts and receptor exposure pathways. Consequently, closure assessments should explicitly evaluate the potential for future hydraulic reversals and associated groundwater-quality risks (Castendyk & Eary, 2020; Zhou et al., 2021).

4.3 Through-Flow Behaviour

Between sink and source conditions, pit lakes may function as groundwater through-flow systems. Under this scenario, groundwater enters one portion of the lake while simultaneously exiting another.

Through-flow behaviour is commonly associated with:

- regional groundwater gradients;
- fault-controlled pathways;
- structural discontinuities;
- palaeochannels;
- heterogeneous hydrostratigraphy; and
- anisotropic hydraulic conductivity distributions.

Because inflows and outflows occur concurrently, through-flow systems may establish direct hydraulic connections between mine facilities and environmental receptors. These conditions may be particularly important where groundwater-dependent ecosystems, rivers, wetlands, or water-supply receptors occur downgradient of the pit lake.

Through-flow systems frequently emerge gradually and may remain undetected in short-duration closure assessments. As a result, long-term simulation periods are often necessary to identify the timing and significance of these hydraulic transitions (McCullough et al., 2020; Zhou et al., 2021).

4.4 Multi-Century Hydrological Evolution

The hydrological evolution of pit lakes generally does not occur as a single step-change but as a progressive sequence of responses influenced by groundwater recovery, climatic variability, and changing hydraulic gradients.

A conceptual sequence may include:

1. Early closure sink conditions.
2. Progressive groundwater recovery.
3. Development of through-flow pathways.
4. Transition toward source behaviour.
5. Long-term hydrological equilibrium.

The duration of each phase varies considerably between sites and may extend over decades or centuries. Consequently, assessments limited to short post-closure periods may fail to identify later-stage transitions that influence groundwater protection and closure performance. Recent post-mining investigations demonstrate that groundwater rebound may continue altering land-surface conditions, hydrological connectivity, and environmental behaviour long after closure activities have ceased (Guzy, 2025).

The conceptual progression through these hydrological states is illustrated in Fig. 1 and forms the basis for understanding long-term pit-lake behaviour.

4.5 Long-Term Water-Quality Evolution

Water-quality evolution often continues after major hydraulic adjustments have occurred. While pit-lake water levels may approach equilibrium relatively early, geochemical processes commonly continue over much longer periods.

Factors influencing long-term pit-lake chemistry include:

- groundwater inflows;
- pit-wall weathering;
- oxidation and reduction reactions;

- seepage from waste-rock and tailings facilities;
- climatic variability;
- lake stratification; and
- hydraulic residence times.

Potential long-term water-quality concerns include:

- increasing salinity;
- sulphate accumulation;
- dissolved metal mobilisation;
- acidity generation;
- stratification-related water-quality changes.

These processes may evolve independently of water-level responses and therefore require separate evaluation during closure planning. Investigations of groundwater-connected lakes similarly demonstrate that water and solute balances may continue evolving after hydraulic responses have stabilised, highlighting the need for integrated hydrological and geochemical assessments (Yihdego et al., 2016).

4.6 Climate Influence on Long-Term Behaviour

Climate variability exerts a strong influence on both pit-lake hydrology and water-quality evolution. Changes in recharge, evaporation, rainfall intensity, and drought frequency can alter groundwater recovery rates, lake-water balances, and hydraulic-state transitions.

Potential climate-related impacts include:

- delayed groundwater recovery;
- accelerated lake filling;
- changes in groundwater recharge;
- extended drought-related concentration effects;
- altered groundwater gradients;
- modified contaminant transport pathways.

Recent groundwater and climate studies indicate that these processes may operate over multi-decadal to centennial timescales and therefore contribute significant uncertainty to long-term closure predictions (Cuthbert et al., 2020; Taylor et al., 2022).

For this reason, pit-lake assessments should evaluate multiple climate scenarios and future hydrological conditions rather than relying solely on historical observations.

4.7 Implications for Closure Stability

The results indicate that pit-lake stability cannot be assessed solely on the basis of water-level recovery. Long-term closure performance depends on the interaction between hydrological recovery, groundwater connectivity, climatic variability, and water-quality evolution.

Assessments that focus exclusively on hydraulic equilibrium may overlook:

- future sink-source transitions;
- delayed groundwater impacts;
- contaminant migration pathways;
- climate-driven system responses;
- long-term water-quality deterioration.

Accordingly, closure planning should adopt integrated assessment frameworks that explicitly consider both hydrological and geochemical evolution over extended timescales.

The combined results support the need for multi-century evaluation of pit-lake systems to improve confidence in closure predictions, groundwater protection, environmental stewardship, and long-term regulatory compliance.

5. Discussion

Pit lakes should not be viewed as static post-mining landforms. Rather, they represent evolving hydrogeological systems whose behaviour changes in response to groundwater recovery, climatic variability, geological controls, and ongoing geochemical processes. The results presented in this study indicate that long-term closure stability depends not only on the attainment of a stable water level but also on the evolution of groundwater interactions and water quality over extended timescales.

A key finding is that pit lakes may transition through multiple hydrological states during closure. As illustrated conceptually in Fig. 1, early sink conditions may gradually evolve into through-flow and source conditions as groundwater systems recover. These transitions have important implications for groundwater protection because pathways that are hydraulically contained during early closure may

become active migration pathways many decades later. Consequently, closure assessments based solely on short post-closure simulation periods may underestimate future environmental risks.

The findings also highlight the importance of considering groundwater recovery as a long-term regional process rather than a site-specific closure outcome. Recovery rates are influenced by aquifer properties, recharge patterns, geological structures, residual dewatering impacts, and climate variability. As these factors evolve through time, hydraulic gradients may shift substantially, influencing groundwater connectivity, contaminant transport pathways, and receptor exposure. Similar observations have been reported in long-term groundwater and lake-system investigations where delayed hydrological responses significantly influenced environmental outcomes (Yihdego et al., 2015; Yihdego et al., 2016).

Climate uncertainty represents a further challenge for pit-lake prediction. Recent studies indicate that future groundwater recharge and evaporation patterns may differ significantly from historical conditions, introducing uncertainty into long-term closure forecasts (Cuthbert et al., 2020; Taylor et al., 2022). The influence of climate variability extends beyond water levels and includes impacts on groundwater recovery rates, pit-lake residence times, water-quality evolution, and contaminant mobilisation. Accordingly, pit-lake assessments should incorporate multiple climate scenarios and adaptive management strategies rather than relying on a single deterministic prediction.

The study further demonstrates that hydrological equilibrium should not be interpreted as evidence of long-term environmental stability. Water-quality evolution frequently continues beyond the period during which groundwater levels stabilise. Geochemical reactions, groundwater inflows, pit-wall weathering, seepage contributions, and stratification processes may continue influencing pit-lake chemistry long after hydraulic conditions appear stable. Consequently, successful closure planning requires integration of water-balance assessments with geochemical evaluation and long-term water-quality prediction.

An important implication for mine closure practice is the need for integrated assessment frameworks. Historically, groundwater modelling, pit-lake water balances, climate assessment, and geochemical analysis have often been undertaken independently. However, the interactions among these processes ultimately determine closure outcomes. As illustrated conceptually in Fig. 2, integrated approaches provide a more realistic basis for evaluating long-term closure performance because they explicitly account for process interactions and evolving system behaviour. Similar conclusions have been reached in closure-planning studies where groundwater behaviour, geomechanics, and long-term water-management outcomes were assessed as an integrated system (Meikle et al., 2023)

The findings are also relevant to emerging regulatory expectations surrounding closure relinquishment and long-term environmental stewardship. Regulators increasingly require evidence that post-mining landforms will remain stable under a range of future environmental conditions. Multi-century assessment frameworks improve confidence in closure predictions by identifying delayed system responses that may not be apparent within conventional monitoring periods. Such approaches support more robust risk assessment, improved groundwater protection, and greater confidence in long-term closure outcomes.

Ultimately, the most important lesson from pit-lake evolution studies is that closure should be viewed as the beginning of a new hydrogeological phase rather than the end of mining. Long-term pit-lake behaviour is governed by continuing interactions among groundwater systems, climate forcing, and geochemical processes. Understanding these interactions is essential for achieving closure stability, protecting environmental values, and supporting sustainable stewardship of post-mining landscapes.

6. Illustrative Mine-Site Observation

Observations from a mine-closure assessment demonstrated how pit-lake behaviour may evolve over extended post-closure periods as groundwater systems recover and hydraulic conditions change. During the early stages of closure, the pit lake functioned primarily as a groundwater sink, receiving inflow from the surrounding aquifer system. Under these conditions, solute migration remained largely contained within the pit-lake environment.

As groundwater recovery progressed, regional hydraulic gradients gradually changed and previously minor flow pathways became increasingly important. The pit lake subsequently exhibited characteristics consistent with a through-flow system, where groundwater entered and exited the lake through different portions of the surrounding hydrogeological system. This transition altered groundwater-flow patterns and increased the importance of evaluating potential downgradient receptors.

The observation highlights the value of long-term closure assessment because the evolving hydraulic behaviour would not have been evident from short-term post-closure evaluations alone. It also demonstrates the importance of integrating groundwater recovery, climate variability, geological controls, and water-quality considerations within a unified closure framework.

While the timing and magnitude of such transitions vary between sites, the example illustrates a broader principle applicable to many pit-lake systems: hydrological behaviour may continue to evolve long after active mining has ceased, and closure assessments should therefore consider multiple future system states rather than a single equilibrium condition.

This example reinforces the conceptual evolution framework illustrated in Fig. 1 and supports the need for integrated, long-term approaches to pit-lake management, groundwater protection, and closure planning.

7. Conclusion

Pit lakes should not be regarded as static post-mining landforms or passive repositories of water. Instead, they are evolving hydrogeological systems whose behaviour is controlled by interactions among groundwater recovery, climate forcing, geological structures, water-balance processes, and long-term geochemical evolution. As these processes continue to operate after mine closure, pit lakes may undergo substantial hydrological and environmental change over extended timescales.

This study highlights the importance of evaluating pit-lake evolution beyond conventional closure assessment horizons. The conceptual framework presented demonstrates that pit lakes may transition through multiple hydrological states, including groundwater sink, through-flow, and source conditions, as groundwater systems progressively recover. These transitions can significantly influence groundwater gradients, contaminant migration pathways, receptor exposure, and long-term closure performance.

The findings also reinforce the importance of integrating climate variability into pit-lake assessments. Future changes in recharge, evaporation, drought frequency, and extreme rainfall events may alter groundwater recovery trajectories and pit-lake behaviour, introducing additional uncertainty into long-term closure predictions. Consequently, closure strategies should incorporate multiple climatic scenarios and adaptive management approaches rather than relying solely on historical conditions.

Equally important is the recognition that hydraulic equilibrium does not necessarily imply environmental stability. Water-quality evolution may continue long after groundwater levels stabilise, driven by groundwater inflows, geochemical reactions, seepage inputs, and lake stratification processes. Long-term closure assessments should therefore integrate hydrological and geochemical evaluations to provide a more reliable basis for risk assessment and environmental stewardship.

The study further demonstrates that integrated frameworks combining groundwater flow, groundwater-surface water interaction, climate forcing, water-balance assessment, geochemistry, and contaminant transport provide the strongest basis for evaluating future pit-lake behaviour. Such approaches improve confidence in closure predictions by recognising the interconnected nature of the processes governing pit-lake evolution.

From a mine-closure perspective, understanding long-term pit-lake behaviour is essential for groundwater protection, environmental management, closure relinquishment, regulatory compliance, and post-mining land-use planning. Assessments that fail to consider delayed hydrological responses and long-term water-quality evolution may underestimate future environmental risks and compromise closure outcomes. Such assessments also contribute to broader groundwater-sustainability objectives and long-term management of groundwater resources in post-mining landscapes (Karandish et al., 2025).

Ultimately, successful pit-lake closure depends not only on achieving short-term hydraulic stability but also on understanding how groundwater systems, climatic conditions, and geochemical processes interact through time. Adopting a multi-century perspective provides a more realistic basis for evaluating closure stability, supporting informed decision-making, and promoting sustainable stewardship of post-mining landscapes.

Declarations

Declarations

Competing Interests:

The author declares no competing interests.

Ethics Approval and Consent to Participate:

Not applicable.

Consent for Publication:

Not applicable.

Funding:

No specific funding was received for this research.

Author Contribution

Y.Y. conceptualized the study, developed the methodology, conducted the analysis, interpreted the results, prepared figures and tables, wrote and revised the manuscript, and approved the final version.

Data Availability

The datasets generated and/or analysed during the current study are not publicly available due to commercial confidentiality and project-specific restrictions but are available from the corresponding author on reasonable request, subject to approval by the data owner.

References

1. Castendyk DN, Eary LE. Pit lakes: Their characteristics and future. *Mine Water Environ.* 2020;39:1–20.
2. Crosbie RS, Pickett T, Mpelasoka F, Hodgson G, Charles SP, Barron O. Climate impacts on groundwater recharge in Australia. *Hydrogeol J.* 2021;29(2):567–84.
3. Cuthbert MO, Gleeson T, Moosdorf N, Befus KM, Schneider A, Hartmann J, Lehner B. Global patterns and dynamics of climate-groundwater interactions. *Nat Clim Change.* 2020;10:663–9.
4. Dold B. Evolution of acid mine drainage formation in sulphidic mine tailings. *Minerals.* 2014;4(3):621–41.
5. Döll P, Scanlon BR, Reinecke R, Schmied HM, Wada Y. Global-scale groundwater modelling under climate change. *Environ Res Lett.* 2022;17:034021.

6. Guzy A. Environmental Impacts of Post-Closure Mine Flooding: An Integrated Remote Sensing and Geospatial Analysis of the Olkusz–Pomorzany Mine, Poland. *Water*. 2025;17(23):3337.
7. IPCC. *Climate Change 2021: The Physical Science Basis*. Cambridge, United Kingdom: Cambridge University Press; 2021.
8. Karandish F, Liu S, de Graaf I. Global groundwater sustainability: A critical review of strategies and future pathways. *J Hydrol*. 2025;657:133060.
9. Kløve B, Ala-Aho P, Bertrand G, Boukalova Z, Ertürk A, Goldscheider N, Ilmonen J, Karakaya N, Kupfersberger H, Kværner J, Lundberg A, Mileusnić M, Moszczynska A, Muotka T, Preda E, Rossi P, Siergieiev D, Šimek J, Wachniew P, Angheluta V, Widerlund A. Climate change impacts on groundwater and dependent ecosystems. *Water*. 2020;12:678.
10. McCullough CD, Lund MA, Wyse L. Sustainable pit lake closure and post-mining landscapes. *Mine Water Environ*. 2020;39:617–30.
11. Meikle CD, Skorulis A, Cupitt P. (2023). Closure Concepts for Sustainable Groundwater Management: A Case Study. In *Proceedings of Mine Closure 2023*. Australian Centre for Geomechanics. *Proceedings of the 16th International Conference on Mine Closure*. Australian Centre for Geomechanics, Perth.
12. Nordstrom DK, Blowes DW. Mine drainage: The science and the practice. *Elements*. 2020;16(6):395–400.
13. Rudakov D, Sharifi S, Westermann S. An Empirical–Analytical Model of Mine Water Level Rebound. *Mining*. 2025;5(4):59.
14. Schultze M, Vandenberg J, Castendyk D, Schleußner H-P, McCullough CD. (2024). Monitoring for pit lake planning, filling and use: Why? When? What? In A. B. Fourie, M. Tibbett, & G. Boggs, editors, *Mine Closure 2024: Proceedings of the 17th International Conference on Mine Closure* (pp. 1049–1062). Australian Centre for Geomechanics, Perth.
15. Taylor RG, Alley WM, Scanlon BR, Döll P, Rodell M, van Beek R. Groundwater recharge under climate variability and change. *Nat Clim Change*. 2022;12:123–31.
16. Yihdego Y, Webb JA. Modeling of bore hydrograph to determine the impact of climate and land use change in a temperate subhumid region of south-eastern Australia. *Hydrogeol J*. 2011;19(4):877–87.
17. Yihdego Y, Webb JA, Leahy P. Modelling of lake level under climate change conditions: Lake Purumbete in south-eastern Australia. *Environ Earth Sci*. 2015;73:3855–72.
18. Yihdego Y, Webb JA, Leahy P. Modelling of water and salt balances in a deep groundwater-throughflow lake: Lake Purumbete, southeastern Australia. *Hydrol Sci J*. 2016;61(1):186–99.
19. Zhou Y, Li W, Zhang Y. Prediction strategies for large-scale groundwater models. *Hydrogeol J*. 2021;29:1141–58.

Figures

EARLY CLOSURE



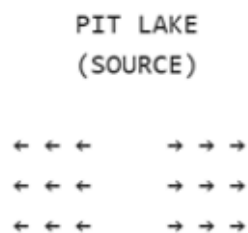
Groundwater flows toward the pit

MID CLOSURE



Water enters one side and exits another

LONG TERM



Water discharges outward

Figure 1

Conceptual long-term pit-lake water-level evolution showing groundwater recovery, pit-lake filling, hydrological-state transitions, and gradual approach to equilibrium over extended post-closure timescales.

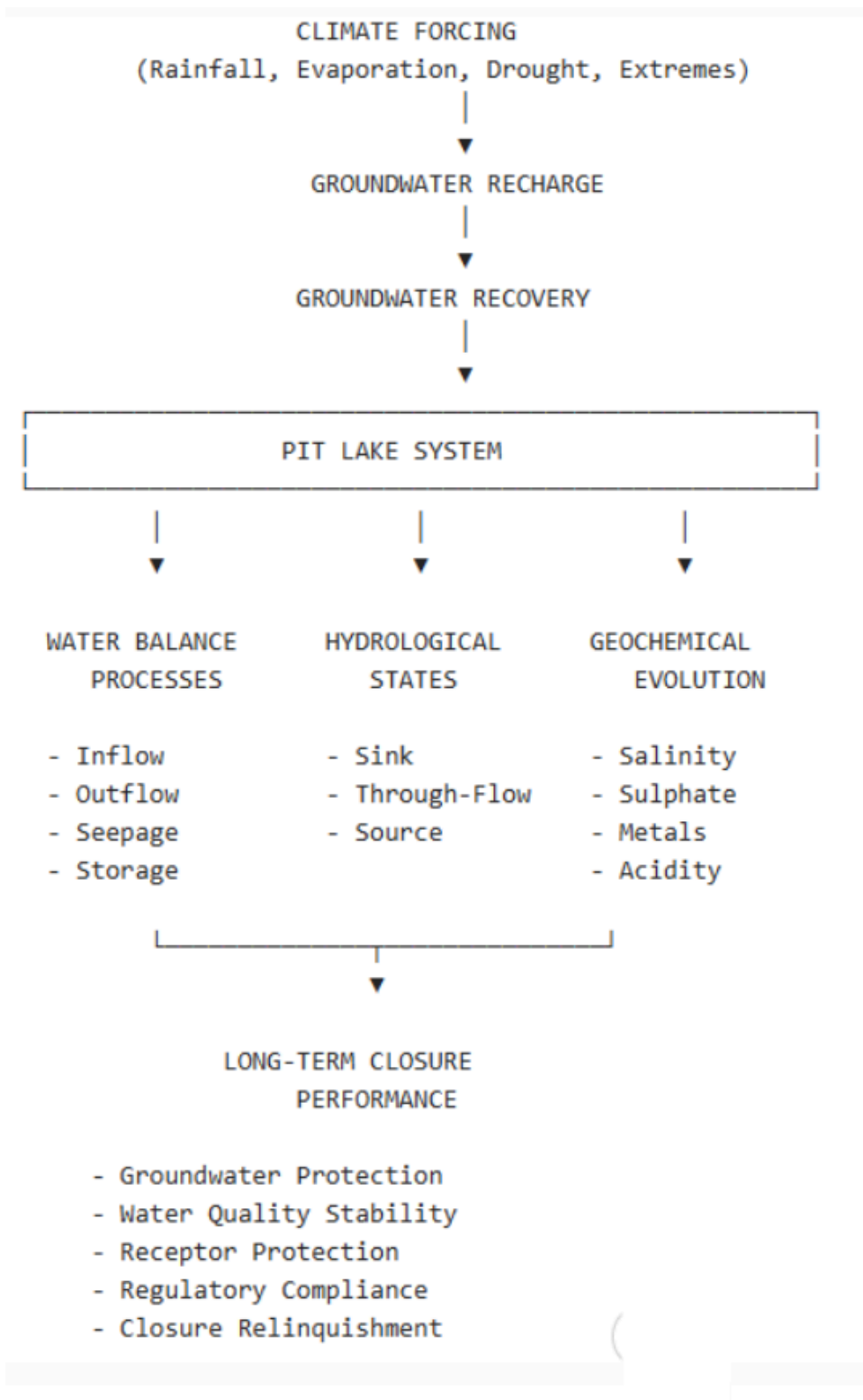


Figure 2

Integrated conceptual framework linking climate forcing, groundwater recovery, hydrological-state transitions, water-balance processes, groundwater-surface water interaction, geochemical evolution, and closure performance. The framework illustrates how pit-lake behaviour evolves through time as interactions between groundwater systems, climate variability, and geochemical processes influence long-term hydrological and environmental outcomes.

