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A mine water system framework: designing with the end in mind for monitoring that works across and beyond mine life

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Abstract

Mine water monitoring programs are often designed with limited reference to how water interacts across a site. Geology, landforms and materials shape water movement, active processes and system response over time. Yet monitoring locations are typically defined by compliance spacing, infrastructure layout or stability concerns. Closure monitoring, by contrast, must characterise how the site functions as a system – how water interacts with landscape features, what risks or opportunities may arise and what stable performance looks like beyond operations.

Water moves according to geology and landscape, not compliance maps. In geology we say, "there is a reason for every feature in the landscape". The same is true for water, though in reverse: water reasons with every feature in the landscape. As landforms evolve, so do the interactions with water, the responses of systems and the models used to explain them.

Establishing long-term and future-focused monitoring earlier in the mine life improves the ability to anticipate and respond to these challenges. At closure, unresolved or slow-developing issues – previously managed through reporting cycles – require resolution. If monitoring networks are not structured with closure in mind, gaps in understanding can lead to misrepresented risks, increased costs, asset impairments or prolonged regulatory review.

This paper presents the Mine Water System Monitoring Framework – a method for addressing complex water issues through the design of a monitoring network tailored to how water interacts with the geology, landscape and mining landforms. Drawing from examples in waste rock, heap leach, tailings and pit lakes, the framework is grounded in practice and focused on landform function and system behaviour. Case studies from legacy, active and planned operations demonstrate how monitoring aligned with geology, landform evolution and system logic improves effectiveness, reduces closure uncertainty and supports more confident decisions.

Successful monitoring is not about collecting more data or building larger models. It's about designing representative networks that reflect how the site works – providing the foundation for shared understanding across operations, transition and closure.

Keywords: *mine closure, mine water, monitoring framework, landform evolution, representative monitoring, geology and environment, holistic water management, water strategy, complex problems*

1 Introduction

At the start of a project, we describe how the site is expected to behave. A permit is issued based on expectations derived from limited characterisation of background conditions, and monitoring becomes a compliance activity rather than a tool for understanding. However, monitoring is how we determine what is happening in reality and provide feedback regarding our expectations. It tests and challenges assumptions based on evidence, providing the foundation for environmental performance during operations and

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throughout closure. Too often, however, it is treated as a separate operational task, developed to meet regulatory requirements long after the site has undergone changes, and system understanding is sought long after the site has been altered.

Mine landscapes evolve, and mining is a form of terraforming. It creates new landforms, material assemblages and hydraulic conditions. Potentiometric surfaces change, pit lakes form, catchments adjust, and confined systems re-equilibrate. These pit lake systems present unique challenges for long-term water management and require specialised monitoring approaches (McCullough & Lund 2006; McCullough et al. 2013; McCullough et al. 2024). Landforms influence how water moves, and water, in turn, influences how systems respond. It flows through tailings, dumps, pit walls, haul roads and natural creeks – its path governed by geology, rainfall, containment and dewatering. Understanding that behaviour takes time and depends on the context of geology, landform development, water systems and their interactions. But most compliance-based networks are not designed to track how the system behaves.

Sites are geologically diverse. Mineralised and non-mineralised domains often have very different hydrochemical behaviour, shaped by host rock mineralogy and oxidation pathways (Younger 2004). Surface water moves across these zones, linking creeks, storages and operational areas. But background conditions are often poorly defined, making it difficult to distinguish natural variability from site effects (Lacy & Barnett 2015). Monitoring needs to reflect both ambient conditions and system function.

Much of a site's water behaviour is shaped early in a project's life by infrastructure placement, material segregation and landform design. These decisions, often made at the pre-feasibility stage, embed risks and define what monitoring can reveal later. When done well, monitoring design can support approvals, reduce uncertainty and facilitate closure. Monitoring can – and should – be how we understand what a site becomes and how the system responds. It should reflect both the original setting and how that setting changes in response to mining. Without this foundation, risk is poorly defined or understood and closure and transition planning can be undermined, delayed or incur greater costs.

As a result, monitoring is a strategic and future-focused process that matures over time to track system responses and build confidence. When aligned with landform processes and geological context it becomes an integral part of site understanding, from concept through to relinquishment.

This paper presents a practical framework for monitoring mine water systems. It shifts the focus from compliance-based layouts to system-based understanding. By aligning monitoring with geological setting, landform evolution and hydrological behaviour, the framework enables better decisions through operations and into closure. Real-world examples show how monitoring grounded in system thinking can uncover misdiagnosed trends, reduce uncertainty and support more confident closure outcomes.

2 Context and design challenge

Monitoring networks often reflect how a site was constructed rather than how it behaves. In many projects, technical understanding develops in patches, driven by short-term needs rather than a comprehensive understanding of the system. Over time this disconnect can create barriers to interpretation, especially during closure. The challenge is often structural: monitoring grows incrementally or by inheritance, without realignment to site behaviour or landform function (Department of Industry, Innovation and Science 2016).

Figure 1 shows two potential trajectories for knowledge development across a project's life. The progressive trajectory builds water system understanding incrementally, with monitoring networks evolving to reflect changing conditions and deepening insights into landform behaviour. This approach supports confident closure decisions based on robust, long-term datasets that capture system evolution. The fragmented trajectory, by contrast, sees knowledge stagnate or fragment as the effort of early monitoring and characterisation conducted during approvals rarely carries through into operations. Networks and programs are often built for minimum compliance or grafted from engineering monitoring, reflecting tactical thinking that responds to immediate needs rather than building systematic understanding.

Early monitoring is often conducted during approvals or impact assessments but rarely carried through into operations. Networks tend to be built around compliance or embankment monitoring, especially for slope stability. These bores are typically shallow and located near structures, not necessarily where long-term system performance can be observed. As a result, seepage detection may be mistaken for groundwater monitoring and networks may fail to represent how the system works at scale (Lacy & Barnett 2015).

Construction quality also affects confidence. Bores may be installed using any available equipment, without adhering to minimum standards. Screens may follow drill depth, not aquifer zones. Surface monitoring sites may be placed for convenience, not catchment logic. Without good construction records, interpretation becomes uncertain, especially when long-term patterns matter more than spot concentrations.

Many networks are inherited or assembled incrementally. Over time they may become disconnected from landform evolution or system processes. This is often structural. Key design decisions – such as infrastructure siting or landform geometry – are locked in early. These decisions shape hydraulic behaviour, influence data interpretation and constrain future adaptation. Uncertainty around water systems is often carried forward. Unless deliberately revisited, early assumptions or tolerance of risk may harden into design decisions. Where monitoring doesn't reflect how the system evolves it cannot explain why conditions differ at closure. The effort needed to realign networks late in the mine life increases the cost, complexity and regulatory risk.

Effective monitoring builds from a conceptual model: a site-specific understanding of how water moves through materials, landforms and infrastructure. Monitoring makes this measurable through levels, flows and chemistry. Over time, data refines or challenges the model. If networks are misaligned, approvals may be delayed and closure risks overstated.

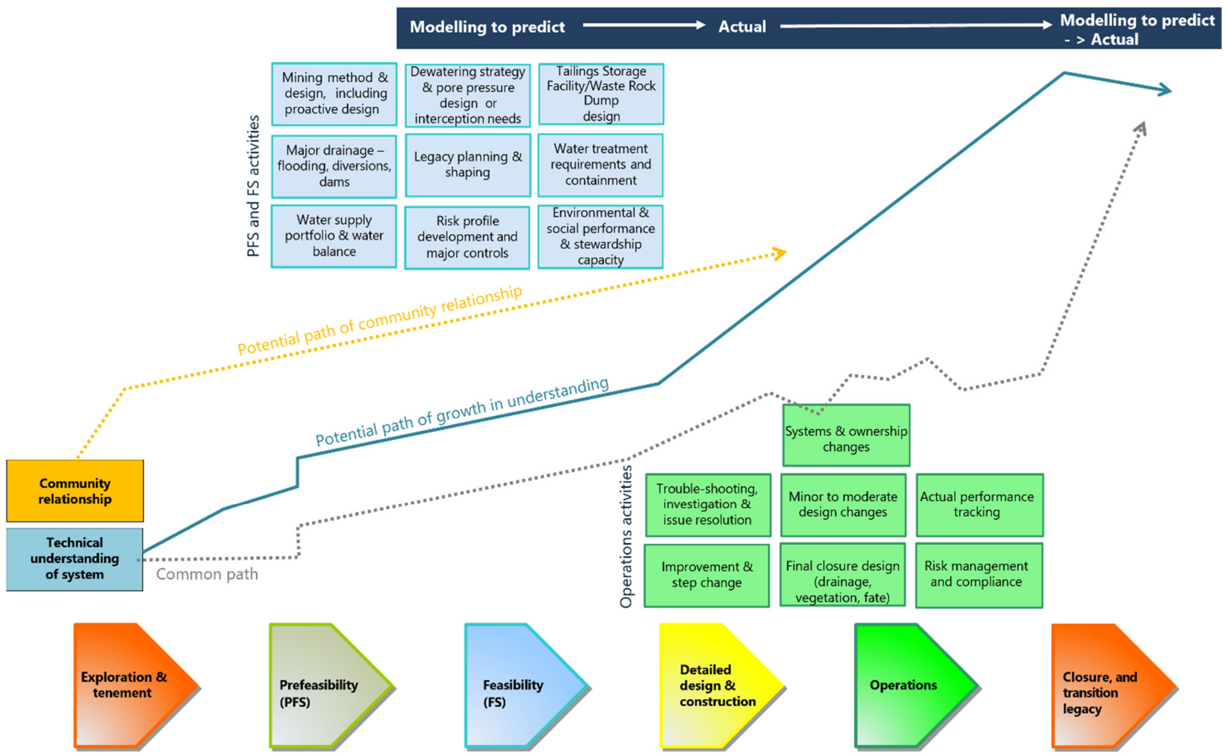

Figure 1 How knowledge grows over the life of a project

3 Principles for an effective mine water system monitoring framework

Monitoring is often treated as a compliance issue but its foundations are laid earlier, typically at the feasibility or permitting stages. These early choices shape what can be known for years, echoing through time. Poor alignment creates knowledge gaps and misunderstandings, while system-based monitoring reveals how landforms and water interact over time.

The Mine Water System Monitoring Framework presented provides practical principles for aligning monitoring with evolving site conditions. It addresses common issues observed across multiple operations, including fragmented networks, poor bore construction and limited spatial coverage. The goal is not to collect more data but to ensure monitoring captures what matters, where and when.

These principles support confident decisions across the project life – from approvals to closure. Grounded in real-world practice, they help structure monitoring around evolving landforms and water systems using representative placement and site-specific design.

3.1 Framework principles

The Mine Water System Monitoring Framework is structured around how sites behave, not just how they're built. Monitoring must reflect landform evolution, geological context and changing water dynamics over time. This framework groups principles into three tiers named:

- technical foundation, which captures how water moves, interacts and changes
- strategic alignment, which ensures monitoring evolves as the project requires
- decision-supported outcome, which provides confidence throughout a mine's project life.

Each tier builds on the last, moving from system understanding to long-term confidence. Figure 2 shows a diagram of the working Mine Water System Monitoring Framework.

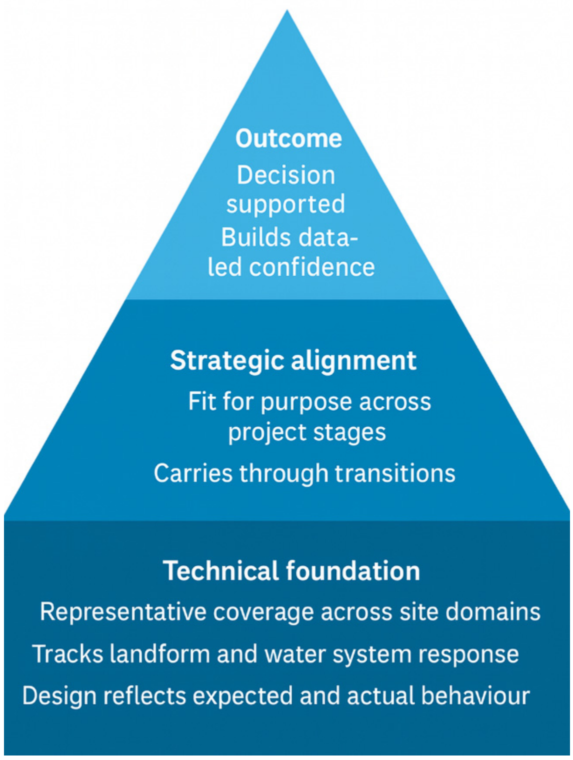

Figure 2 A mine water system monitoring framework to address common closure issues for water

3.1.1 Technical foundation

Representative coverage across site domains: networks need to span mineralised and non-mineralised zones, constructed and natural landforms, shallow and deep systems, and upgradient to downgradient areas. Representativeness applies to both spatial coverage and sample integrity.

Design reflects expected and actual behaviour: monitoring must reflect how the site plausibly behaves based on hydrology, geochemistry and structural setting. Placement should be driven by gradients, recharge zones, flow paths, materials and infrastructure levels, not just asset locations.

Tracks landform and water system response: Constructed landforms evolve, and monitoring needs to shift or account for potential changes. Static layouts miss key transitions in system behaviour.

3.1.2 Strategic alignment

Fit for purpose across project stages: monitoring should support approvals, operations, closure and post-mining or land use phases. Each stage offers different insights. Without staged design, networks often require costly rebuilds and cannot support long-term interpretation.

Carries through transitions: closure is not an end point – it's a shift in activity, responsibility and land use as the land endures. Monitoring must remain relevant as the site transitions.

3.1.3 Decision-supported outcomes

Builds data-led confidence: monitoring must show whether systems are stable, improving or deteriorating. Long-term decisions require evidence, not just assumptions or models. This informs confidence-based regulatory or investment decisions.

3.2 Application in practice

Table 1 shows how each principle can be applied in practice, using common mine settings to explain where monitoring makes a difference, and how design decisions translate to field and site outcomes.

Table 1 Application of mine water system monitoring framework principles in practice

Principle	What this looks like in practice	Why it matters
Representative coverage of key domains	Bores and surface water points capture variability across mineralised and non-mineralised zones, constructed and natural landforms, and shallow to deep systems	It supports clearer interpretation of impacts and background conditions, enabling robust assessment of compliance and system response
Tracks landform and system responses	Monitoring captures changes resulting from landform settlement, material weathering and evolving flow directions, particularly over longer time frames	Ensures that system changes are tracked, not assumed; helps demonstrate stability or adaptive response as part of the closure evaluation
Design reflects expected and actual behaviour	Monitoring points are positioned along known or expected flow paths, aligned with recharge zones, infrastructure elevations or material interfaces	Improves the ability to detect risk or performance issues early; avoids misinterpretation due to poorly placed monitoring points
Fit for purpose across project stages	Monitoring is designed to support permitting, operations and closure, starting with early characterisation and progressing to post-surrender verification	Reduces the need to replace or duplicate networks later; builds trust and continuity across project stages
Carries through transitions	Monitoring remains in place as mining activity decreases; trends continue to be interpreted to support land use change, governance handover or reduced intervention	Supports long-term stewardship, ensuring compliance with regulations, the interests of landholders and the needs of future site users
Builds data-led confidence and interpretation	Long-term datasets support performance assessments and relinquishment arguments; monitoring becomes the evidence base, not just a reporting tool	Increases confidence in decisions; reduces reliance on untested models or assumptions at key regulatory stages

3.3 Fit against other published frameworks

Table 2 summarises several widely used industry and regulatory frameworks relevant to closure and monitoring. While each provides useful guidance, most are structured around reporting requirements, landform safety or revegetation outcomes; few address the need for holistic water system understanding.

Water and water monitoring often span multiple domains, including compliance, environment and geotechnical risk; however, given its significance, it requires a unified and whole-of-site approach across the transition from approvals to operations and through to relinquishment, particularly where water systems evolve. The Mine Water System Monitoring Framework addresses this gap by focusing on how water interacts with geology, landforms and materials throughout the site's life. It is characterised by:

- coverage across both natural and constructed domains
- responsiveness to evolving landforms and site conditions
- integration across the site and full project life cycle – from approvals through to post-mining
- emphasis on direct observation and system logic to inform decision-making.

The design of a monitoring network fundamentally shapes how well a site can be understood during operations, through transition and into closure. Across the examples presented, monitoring gaps often led to overstated risks, difficulty in interpreting system behaviour and costly remedial work late in the project. A lack of data did not cause these issues, but networks that did not reflect landform function, system variability or project stage did. The case studies highlight a systemic pattern: networks often mirrored infrastructure layout rather than hydrological function. Data were collected without representing system processes, and landform changes were not tracked. These are not isolated issues but rather reflect a broader approach to monitoring as a compliance exercise rather than a tool for understanding. Frameworks that focus on thresholds or operational flows often fail to support long-term understanding. Mines do not create static conditions; they generate new landforms and drainage systems that evolve beyond the construction phase. Monitoring must be able to track these changes.

Most published frameworks outline what monitoring should achieve – thresholds, closure criteria or reporting milestones – but few provide a structure for designing networks that reflect how mining landscapes behave. Mining reshapes gradients, alters drainage and exposes or buries geological materials. These are not incidental changes. They reconfigure water systems, yet monitoring is often applied as an overlay without consideration of how the landscape itself has changed.

The Mine Water System Monitoring Framework offers a structure for aligning monitoring design with geological setting, landform evolution and site-scale hydrology. Its goal is not to add complexity but to improve visibility on how mine systems behave, and how understanding supports better decisions over time.

Table 2 Alignment of published frameworks with system-based monitoring principles of the Mine Water System Monitoring Framework

(⚠ =partial alignment, ✅ = present, ❌ = not addressed)

Framework/source	1 Representative domain coverage	2 Tracks landform and system responses	3 Design reflects expected behaviour	4 Fit for purpose across project stages	5 Carries through transitions	6 Builds data-led confidence
International Council on Mining and Metals (ICMM) Integrated Mine Closure: Good Practice Guide (ICMM 2019)	⚠ Covers water and environment broadly, not design-specific	❌ Landscape processes are not a focus	⚠ Encourages site-specific approaches, limited to system detail	✅ Promotes life cycle planning and closure integration	⚠ Addresses transitions conceptually, not via monitoring design	✅ Advocates for evidence-based closure decisions
GISTM (ICMM 2020) *Global standard for tailings risk management*	⚠ Facility zone monitoring	⚠ Facility-centric	⚠ Risk-driven design considerations	✅ Standards extend through project stages	❌ Not focused on transition	⚠ Compliance-driven monitoring
Minerals Council of Australia (MCA) Water Accounting Framework (MCA 2014) *Tracks operational water flows and reports*	⚠ Tracks inputs/outputs, not representativeness	❌ Does not assess landscape response	⚠ Focus on flows, not system behaviour	✅ Aligned with project life cycle reporting	⚠ Limited to operational handover	✅ Emphasises consistent, quantitative data
Department of Mines, Industry Regulation and Safety & Western Australian Biodiversity Science Institute (DMIRS & WABSI) Completion Criteria Framework (DMIRS & WABSI 2022) *Supports outcome-based closure and rehabilitation validation*	⚠ Reference areas compared to disturbed zones	⚠ Treats landforms as static end points	⚠ Driven by land-use objectives	✅ Focus on closure criteria throughout planning stages	⚠ Emphasises closure milestones	✅ Uses field evidence for closure sign-off
Qld Progressive Rehabilitation & Closure Plan Framework (Department of Environment and Science 2020) *Mandates staged rehabilitation and residual risk reporting*	⚠ Monitoring tied to disturbance areas	⚠ Encourages stable forms, less focus on dynamic response	⚠ Linked to milestones, less site-behaviour focused	✅ Staged rehabilitation with monitoring milestones	✅ Residual risk reporting and post-surrender monitoring	✅ Monitoring is required to reduce liability
National Leading Practice Sustainable Development Program (LPSDP) Mine Rehabilitation Handbook (Department of Industry, Innovation and Science 2016) *Promotes adaptive, stakeholder-informed rehabilitation and monitoring*	⚠ Examples reference rehabilitation zones	❌ Does not emphasise landscape processes	⚠ Partial alignment with environmental conditions	✅ Emphasises adaptive monitoring over the life cycle	✅ Encourages adaptive monitoring to support transitions	⚠ Acknowledges the importance of observational data
Closure Groundwater (Gemson et al. 2019) *Applies source–pathway–receptor logic to closure monitoring*	✅ Incorporates various domains	⚠ Includes evolving landscape features	✅ Groundwater behaviour-driven	✅ Life cycle phases are built into guidance	✅ Incorporates long-term planning	⚠ Supports data-based decision-making
Groundwater Monitoring Design (Lacy & Barnett 2015) *Explores design implications for performance interpretation*	✅ Spatially representative networks	⚠ Limited discussion of landform evolution	✅ Emphasis on system understanding	✅ Considers life cycle and approvals context	⚠ Closure transition is not a primary focus	✅ Supports data-led risk interpretation
Environmental Monitoring (Wiersma 2004) *Covers system-level environmental monitoring examples*	✅ Inclusive across media	⚠ Includes landscape-level monitoring case studies	✅ Provides case studies reflecting site-specific monitoring	⚠ Discusses monitoring programs, limited life cycle context	⚠ Adaptability, but limited focus on post-closure transitions	✅ Emphasises high-quality, observational data

4 Examples from practice

4.1 Example 1: revealing surface and groundwater dynamics around a tailings facility

A copper-gold operation in northwest Queensland faced regulatory concern due to water quality exceedances and persistent ponding near the tailings storage facility (TSF). The facility operated within design limits, with no embankment stability issues. However, the water system had not been well characterised during design or permitting. While the TSF operated within design limits and showed no stability issues, the water system had not been well characterised from a design and permitting perspective, particularly in terms of landscape and geology.

A site-scale review was undertaken to understand water movement through and around the TSF. This included reinterpreting groundwater levels and chemistry, analysing satellite imagery and rainfall response, and reviewing bore construction. The geology was reassessed for its influence on flow and geochemistry. Figure 3 shows the interpreted cross-section used to evaluate drainage patterns and bore positions with geology and landform features.

Key findings included:

- The TSF sits within a low-relief catchment where surface water accumulates northwest of the facility due to undiverted upstream flow. Constructed landforms – including the TSF – had reshaped catchment flow and caused prolonged surface retention.
- Mounding near the embankment was linked to shallow saturation in weathered colluvium which could not drain, not to a TSF leakage.
- Geochemical signatures reflected natural background conditions shaped by the naturally occurring geology and mineralogy (e.g. sulphate from evaporites, strontium, chloride, bromide, copper).
- Several monitoring bores were too close to infrastructure such as wall toe monitoring bores, had lost integrity or were not representative. The bore network was updated to establish a long-term network for levels and quality.

Issue-based reflections included:

- Monitoring was not designed to reflect how the water system behaved. Early characterisation was shallow and incomplete, and gaps were carried forward into operations. In this case, the monitoring results at the site indicated a problem that did not exist as it was not representative of groundwater.
- The influence of geology on water quality was not accounted for in the network design, particularly differences between mineralised and non-mineralised zones.
- Changes to landform and catchment structure were not tracked, even though they altered drainage and water accumulation patterns around the facility.
- Bore construction and placement focused on proximity to infrastructure rather than representativeness or system-scale understanding.

The systems and strategic approach led to outcomes of:

- established a monitoring network able to track landform behaviour from operations through to closure, providing the basis for updating trigger and compliance limits to reflect actual site conditions
- delivered a step change in water management and environmental performance by aligning monitoring with how the system worked
- materially reduced regulatory risk and site exposure by resolving uncertainty around observed conditions

- shifted site understanding from local exceedance concerns to system-scale behaviour, supporting more effective and proportionate responses.

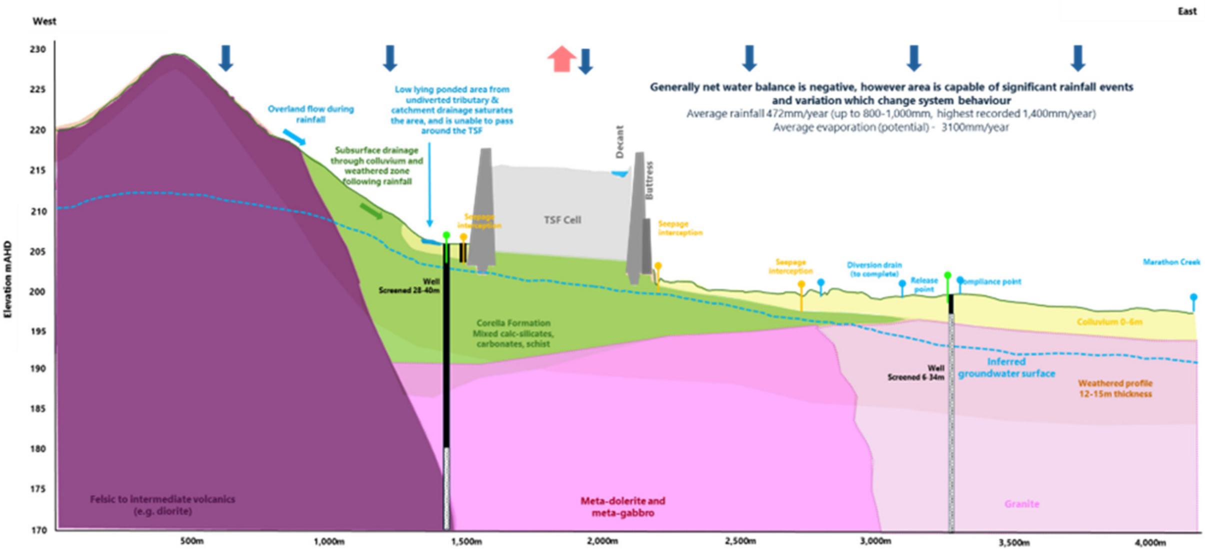

Figure 3 Example 1: tailings storage facility TSF water system conceptual model with initial monitoring

4.2 Example 2: redesigning a monitoring network for closure planning of a legacy mine with future potential

A legacy gold site in central Queensland with ongoing production potential entered formal closure planning under transitional rehabilitation provisions after decades of limited activity. The site included two pit voids, a TSF, a heap leach pad and several historical groundwater bores. Regulators raised concerns about water-related risks based on monitoring results from the existing network. Early interpretations flagged elevated risks but were based on sparse and non-representative data.

A site-wide groundwater review was undertaken to develop a conceptual model and assess whether the network could support closure. Bore construction and chemistry were reviewed alongside the site's geology, which includes a fault separating mineralised volcanics from low-permeability metamorphic units. These contrasting domains strongly influence groundwater occurrence and chemistry; however, the original network did not identify or characterise them. New bores were installed across key zones, including mineralised areas that had not previously been sampled. Surface storages were also fitted with loggers to assess rainfall response and the potential connection to groundwater. Figure 4 illustrates the conceptual cross-section of the pit lake system, showing the inferred groundwater surface, pit lake water cover and surrounding geological units. Key findings included:

- Many historical bores were located near the TSF or within disturbed zones. These showed elevated salinity and metals, but were not representative of the broader system.
- The absence of background data in mineralised areas made it difficult to distinguish natural variability (variable natural background) from site effects, resulting in overstated risks and delays.
- Fault zones and geological boundaries defined distinct groundwater domains.
- Without geological context, interpreted risks appeared widespread when they were spatially constrained.

Issue-based reflections included:

- The monitoring network lacked geological breadth and spatial coverage, leading to uncertainty around baseline conditions and risk attribution.
- Mineralised zones had not been characterised, despite their influence on natural chemistry.

- The original network design did not reflect key geological structures or hydrogeological boundaries, masking natural zonation and flow behaviour.

The systems and strategic approach led to outcomes of:

- mapped distinct hydrogeological zones linking geology to water quality variability. This supported a redesigned monitoring network and updated site-specific criteria suitable for closure, care and maintenance or restart, and reduced the overall monitoring effort.
- identified potential surface–groundwater interactions and installed targeted monitoring.
- enabled successful closure progression by revisiting and correcting earlier interpretations and risk pathways when facing prolonged closure planning timelines and work programs.
- contributed to a materially lower site risk classification and reduced financial provisioning across TSF, heap leach and pit landforms.

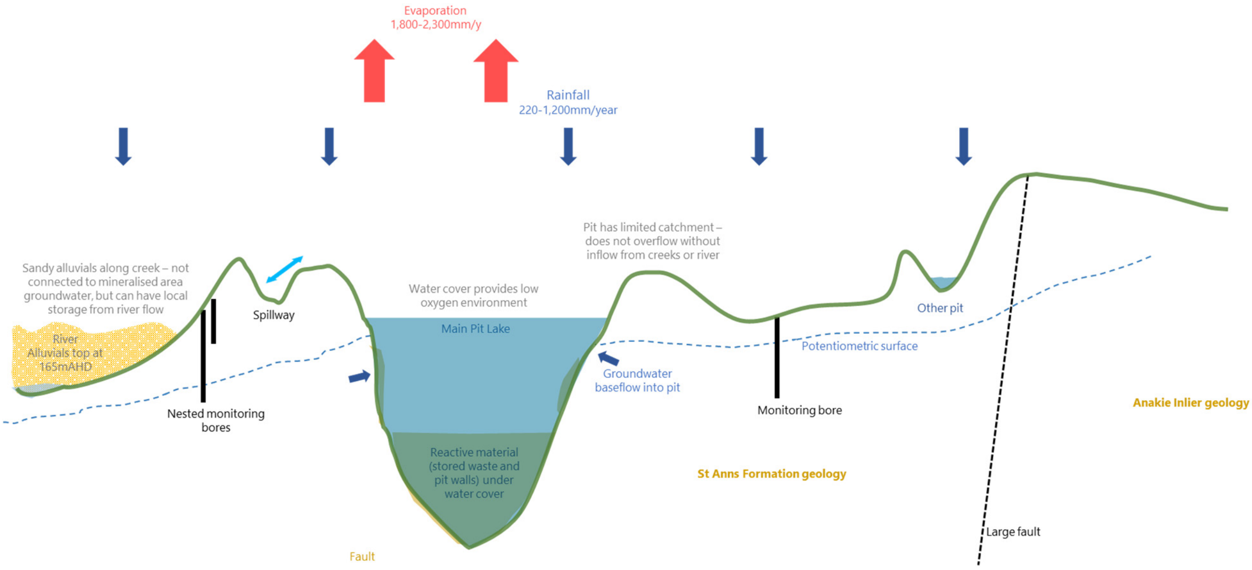

Figure 4 Example 2: pit lake water system with hypersaline groundwater as the natural background with structural and geological controls

4.3 Example 3: revisiting water balances and geology in an operational water system

A long-running copper–gold mine in Western Australia relied on groundwater extraction, tailings return, and recirculation to meet operational water needs. The site included multiple aquifer systems within Proterozoic sedimentary rocks, limestones and dolerite intrusions. Monitoring had evolved to support water supply and dewatering but lacked a cohesive conceptual model. A site-wide review was initiated as borefields experienced yield losses and water demand appeared to increase, while unexpected mounding occurred beneath the TSF. Unresolved mass balance gaps raised concerns about system behaviour.

A system-wide review was undertaken to reassess how water moved through the site. Bore construction and placement were analysed to screened geology, including the distribution of fractured limestone, weathered mudstone and structural features that influence connectivity. Underdrain flows, water level responses and mass balance discrepancies were examined, as well as potential interactions with pit dewatering and structural connections. Key findings included:

- Mounding beneath the TSF in mudstone areas was related directly to geology, given lower conductivity in mudstones compared to fractured limestone.
- Mass balance confirmed the magnitude of water losses and the connection of water from the TSF to nearby production bores, indicating unmonitored seepage pathways.

- Pit dewatering was affecting aquifers connected to the potable borefield – an interaction not previously recognised.

Issue-based reflections were:

- Siloed monitoring efforts focused separately on TSF, water supply and dewatering, failing to explain cumulative site responses.
- Monitoring coverage did not focus on whole-of-site management implications.

The systems and strategic approach led to outcomes of:

- clarified causes of groundwater mounding beneath the TSF, shifting interpretation from assumed leakage to a system response driven by geology
- identified water supply optimisation options without developing new borefields
- enabled integration of dewatering, TSF performance and borefield operation into a cohesive water management approach.

5 Discussion

5.1 How the framework principles played out in real-world cases

The principles outlined in the Mine Water System Monitoring Framework were developed directly from practice. Across the sites presented in this paper – spanning legacy, operational and transitional phases – are similar types of monitoring challenges, despite differences in geology, landforms and regulatory context.

5.1.1 Technical foundation

Representative coverage of key domains: spatial and geological coverage was a consistent limitation. Networks were often concentrated near infrastructure, while background areas – particularly undisturbed or mineralised zones – were under-represented. This limited the ability to distinguish site impacts from natural ambient conditions or variability, i.e. salinity exceedances near a TSF could not be contextualised due to the lack of background data, and the absence of downgradient or deeper bores limited interpretation of the system-wide influence. Networks that span natural and constructed domains across depth and materials provide clear evidence for trends and boundaries.

Tracks landform and water system responses: constructed landforms significantly influenced water movement over time yet monitoring networks were rarely updated to reflect those changes. Persistent ponding linked to catchment reshaping was initially misinterpreted as seepage. Elsewhere, pit lake development created new hydrochemical dynamics and groundwater connections that were unknown until later. Monitoring must reflect settlement, drainage realignment, rebound and geochemical transitions, especially for closure outcomes.

Design reflects expected and actual behaviour: in several examples, monitoring layouts did not reflect how systems were behaving. At one site, mounding near a TSF was misdiagnosed until catchment dynamics and aquitard conditions were reconsidered. In another, borefield decline was only linked to pit dewatering after broader hydrogeological review. Despite adequate bore coverage, the lack of system-based interpretation obscured cause. Monitoring must support understanding of system function – not just satisfy spacing requirements.

5.1.2 Strategic alignment

Fit for purpose across project stages: many networks were developed for early approvals or operational needs and were not revisited until closure. Shallow bores near infrastructure were later used to assess long-term behaviour, despite being poorly located or screened. In one case a historical network lacked the coverage or quality needed for closure submissions and required new bores under pressure. In contrast, networks progressively updated to reflect long-term needs required fewer changes and supported clearer decisions.

Carries through transitions: transitions between phases or owners, or into closure, require networks to remain interpretable. Where networks were narrow or compliance-driven, they failed to explain site behaviour once mining ceased. In one case rebound and drainage changes were only detected after new bores were added. Where networks were aligned to system-scale domains, data remained usable across phases, supporting continuity and reducing reworking.

5.1.3 Decision-supported outcomes

Build data-led confidence: confidence depends not just on data volume but on whether it reflects system behaviour. In several examples, bore construction issues, poor placement or misaligned design led to misinterpreted exceedances, ambiguous trends or regulatory concerns. One site triggered exceedances in areas without background characterisation, delaying closure. Where networks were well-structured and representative, data supported clarity and reduced uncertainty.

5.2 Strategic and business value of monitoring

Monitoring that reflects how a site behaves is more than a technical requirement – it's a strategic asset. It supports faster and easier permitting, improves trust with regulators and communities, and reduces water-related risk and compliance disputes. Lower environmental risk protects and enhances asset values through reduced liability. Monitoring helps detect emerging issues early, supports investigations or emergency response, and enables cost savings and responsive water management.

Towards closure, representative data are critical for demonstrating landform function, assessing system stability and reducing uncertainty in relinquishment. These benefits are clearest when monitoring reflects the distinct hydrological behaviours of mine landforms. TSFs, pit voids, dumps and reshaped catchments interact with water in different ways, and these interactions vary depending on the geology and landscape setting.

Mining reshapes catchments, alters gradients and reconfigures materials within geology: engineered landforms for a set purpose, but potentially with other hydrological consequences. Broader environmental literature (e.g. Wiersma 2004) recognises the value of broader monitoring, but this is rarely linked explicitly to landform-scale processes or evolving mining systems. Table 3 sets out how different landforms give rise to specific monitoring priorities across the mine life, key questions and typical types of monitoring.

Table 3 Mining landform and setting monitoring through a project's mine life

Landform or setting type	Key water questions	Monitoring needs	Feasibility focus	Operations focus	Closure focus
Site-wide domains (mineralised, non-mineralised, natural systems)	What are natural conditions and background variability? How do constructed landforms work?	Background bores, domain sampling, geochemical characterisation, rainfall and run-off	Establish natural variability and baseline system	Track influence zones and distinguish between natural and site effects	Demonstrate stabilisation relative to natural systems and landscape
Tailings storage facility (TSF)	Is water being lost? Is containment effective? Is seepage or leakage occurring? What metals are being mobilised?	Seepage detection, groundwater bores, underdrain flow, piezometers, water balance monitoring	Predict water balance needs; landform controls	Track water recovery; adjust TSF management	Demonstrate long-term containment and performance

Landform or setting type	Key water questions	Monitoring needs	Feasibility focus	Operations focus	Closure focus
Underground workings	Is there groundwater inflow? Are faults conduits or barriers? Are there other connections?	Dewatering flows, pressure heads, inflow chemistry, drawdown and rebound	Define expected inflows; dewatering system design	Monitor inflows and water levels; manage take volumes	Track rebound and water chemistry stability
Waste rock dump/heap leach	Are materials generating poor quality drainage? Is there infiltration into the groundwater?	Surface and basal leachate, pore water sampling, groundwater bores, lysimeters	Assess material properties and drainage risk	Monitor geochemical conditions and run-off behaviour	Evaluate drainage quality and system connection
Open pit – voids and/or pit lakes	Is the pit a sink or a source? During operation and closure?	Water levels, chemistry profiles and pit lake monitoring	Model rebound and future pit lake behaviour	Groundwater inflow, wall flows and dewatering response	Assess pit lake stability and offsite connectivity
Surface subsidence zone(s)	Has subsidence affected drainage or altered groundwater gradients?	Surface flow mapping, piezometers, groundwater levels pre-/post-subsidence	Baseline gradients and potential drainage changes	Observe real-time change from mining movement	Determine long-term change to gradients and land use impacts
Water features on or near site	Are flows, levels or quality being altered by mining? Are interactions with groundwater changing?	Stream gauges, surface water quality, connectivity bores, flow event sampling	Baseline flow and water quality; assess interaction potential	Detect change in flow or quality; identify impact zones	Confirm system recovery or adjustment; validate model assumptions

5.3 What monitoring design reveals about mining practice

The monitoring challenges observed across case studies reflect systemic patterns in how mine systems are conceptualised and managed. In each example, limitations in monitoring were not isolated technical issues but rather indicators of how water had been positioned, often as a constraint or compliance task rather than as a system to be understood. Monitoring networks reveal the legacy of early decisions: where infrastructure was placed, how materials were handled and what assumptions shaped design. Where water pathways or gradients were not considered, monitoring struggled to explain site behaviour. When landform evolution was not anticipated, networks became outdated as conditions changed. These are not just data gaps – they show deeper misalignment between mine design and system function.

A consistent issue was fragmentation between water systems, landscape processes and monitoring logic. Different aspects of the water system were managed and monitored in isolation from each other. This compartmentalisation reduced the ability to interpret trends or demonstrate performance.

Often, there were no clear questions guiding monitoring. Networks inherited from earlier phases were used without verifying whether they accurately reflected current flow paths or material domains. Without guiding logic, data could not explain change or support closure decisions.

In the broader context, monitoring failures often reflect failures in project framing. They stem from a narrow view of water as a variable to control, rather than a defining part of how mine systems function. The Mine Water System Monitoring Framework addresses this limitation, providing a structure that links monitoring with landform behaviour, system evolution, and decisions that shape a mine's future.

6 Conclusion

The Mine Water System Monitoring Framework presented in this paper addresses a critical gap. It is structured around principles that support long-term understanding of how water moves across a site, aligning monitoring with landform function, water system evolution and the level of confidence needed for decision-making. It builds on existing guidance, providing clearer visibility into the role of geology, landform influence and spatial context in shaping monitoring needs.

Each site is geologically and situationally unique. Mining reshapes gradients, reconfigures materials and forms new landforms that fundamentally alter the movement of water. These are not temporary changes; they create new landscapes with their hydrological systems and behaviours. Monitoring must reflect this reality rather than operating in isolation from it.

Monitoring involves observing and interpreting the landscapes created by mining, as well as assessing their stability over time. It must be specific to place: designed to capture how the system behaves in that setting, and to communicate what is happening there. For any mine, the challenge is not just understanding what water does now but anticipating what it is likely to do next, whether the system is built to see or track that coming, and how much it will cost in time, value or quality to address.

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