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Proactive risk management for aligning mine operations with closure objectives

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Abstract

Mine sites commonly rely on international standards and best practices to develop closure plans that meet corporate policies and jurisdictional requirements. Despite this structured guidance, gaps and misalignments frequently occur between closure planning, ongoing operations and long-term strategic decision-making. These disconnects can introduce environmental, technical and financial risks to the closure plan and the post-closure period. One area where this can be evident is mine water management, including both water quality and water quantity; particularly where operational practices do not fully account for long-term environmental performance and the protection of water resources following cessation of mining activities.

Risk assessments provide a systematic framework to identify and evaluate these misalignments. By characterising risk sources, pathways and consequences, risk-based methodologies enable the identification of mitigation measures and operational controls to reduce long-term liabilities.

This study evaluates mine closure through a risk-based lens, focusing on risks that emerge during active operations and the transition to closure. Emphasis is placed on identifying gaps between operational practices and the defined closure objectives, as well as assessing how these gaps may compromise closure criteria. The analysis highlights the importance of integrating closure strategies into operational decision-making through structured risk assessment processes.

The findings underscore the need for early and continuous integration of operations strategies and closure planning, supported by risk management systems and cross-disciplinary collaboration, to proactively manage uncertainty and reduce long-term closure risks.

Keywords: *mine closure, risk assessment, criteria, objectives, gaps, integration*

1 Introduction

Mine closure planning is typically guided by international standards and best practices to develop closure plans that meet corporate policies and jurisdictional requirements. Closure objectives define the intended post-closure outcomes for a site, while closure criteria provide measurable conditions for evaluating whether those objectives have been achieved. Closure strategies describe the overall approaches selected to meet the objectives and criteria, and closure plans document the actions, designs, schedules, monitoring requirements and costs required to implement those strategies.

Initial closure plans are often developed during the early stages of mine life, such as during the pre-feasibility or feasibility engineering and design stages. At this time a closure plan is generally conceptual and based on available understanding of the orebody, waste characteristics, environmental baseline conditions, stakeholder expectations and regulatory requirements for the projected life of mine. As mining progresses, conditions can change and additional information become available including geological models, Geochemical datasets expand, and water quality predictions and operations can change, which may materially affect the assumptions that supported the original closure plan. When closure plans are not

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reviewed and updated in concert with these changes, misalignments can develop between the operational practices and the closure strategy. These misalignments can increase the risk that the closure objectives and criteria may not be achieved. Furthermore, it has been established there is a relationship between risks and the costs to effectively implement a closure plan to meet the closure objectives and criteria (Byrne 2024; Sanders et al. 2018).

Risks can be defined in different ways and for specific situations. In the context of risks to a closure plan, the following seems to be appropriate:

> *'Risk is the effect of uncertainty on objectives – the deviation from the expected, due to our ignorance, on objectives. Based on our "lack of knowledge, understanding on how things will turn out. Events will happen, just do not know when, how, or which ones.'* (International Council for Mining and Metals [ICMM] 2025)

Despite this structured guidance, gaps and misalignments frequently occur between closure planning, ongoing operations and long-term strategic decision-making. Disconnects can arise when a closure strategy is misinterpreted as a closure plan: a strategy is a general blueprint, or design, that spells out the goal to be achieved during and post mine closure, whereas the closure plan gives clear, organised steps that provide a structured plan on how the goals are to be achieved.

A closure risk assessment evaluates potential events, their causes, pathways, consequences, likelihoods and controls. The process can be used to identify knowledge gaps, test whether the closure strategy remains valid and prioritise mitigation measures or additional studies.

This paper discusses the use of closure risk assessment as a practical tool for integrating operational decision-making with long-term closure objectives and criteria. A case study is used to illustrate common closure risk scenarios, including outdated closure plans, operational changes that affect closure performance, external drivers such as regulatory and climate change, and misalignment between technical closure criteria and stakeholder expectations.

2 Typical closure plan development

Mine closure planning commonly begins at the pre-feasibility or feasibility stage, when the initial closure strategy is developed to support permitting, engineering design and cost estimation. At this stage, waste and water management concepts are designed to reflect regulatory requirements, corporate closure commitments, anticipated closure costs and long-term environmental performance. Closure plans are generally conceptual, and based on information available at the time and the level of exploration conducted, including:

- mineral deposit estimates (resource, reserve, potential and probable)
- current and future near-term market conditions
- geochemical assessment of the ore and waste materials
- environmental baseline studies
- stakeholder and Indigenous engagement outcomes
- identified risk and opportunities
- preliminary economic analysis.

During mine operations, information gathering continues to build on the initial dataset, which can significantly impact the trajectory of the mine. This new information may affect the closure design basis and should trigger review of the closure strategy and closure plan. Some examples of areas that often change during the operations include:

- geological and geochemical data

- exploration of other potential nearby orebodies
- existing and projected water quality both onsite and in receivers
- quantities of waste rock or tailings
- waste materials handling practices
- water management operations
- water treatment requirements and operations
- senior management and/or company ownership
- best practices
- regulatory requirements.

Some changes are within the control of the operator while others are external. Regulatory changes, for example, may alter closure criteria or financial assurance requirements. Similarly, updated climate projections may affect water balance assumptions, infrastructure design criteria or long-term water treatment requirements.

If these changes are not evaluated against the closure strategy, objectives and criteria, the closure plan may quickly become outdated. The result can be increased closure liability, reduced confidence in achieving closure objectives and criteria, or the need for substantial redesign late in the mine's life. The risk is particularly high if a site enters sudden closure or care and maintenance while the closure plan remains conceptual.

Conducting periodic risk assessments provides a practical tool for identifying whether or not these changes affect the ability to achieve the closure plan, or if the closure plan or closure strategy requires updating.

3 Risk assessment

Risk assessments provide a systematic framework to identify and evaluate potential misalignments between current or planned operational process/changes and the closure plan. By characterising risk sources, pathways and consequences, risk-based methodologies enable the identification of mitigation measures and operational controls to reduce long-term liabilities (ICMM 2025; Sullivan & Sanders 2025; Sanders et al. 2018).

Risk assessments provide a structured process for identifying, evaluating, prioritising and managing uncertainty that may affect closure outcomes. In the context of mine closure, a risk assessment evaluates whether current or proposed operational conditions could compromise the ability of the site to meet its closure objectives and criteria.

Risk assessments can be conducted under different levels of detail. A high-level assessment may be used to review whether the closure strategy remains appropriate, identify key vulnerabilities and prioritise areas requiring additional work. This can be as simple as a risk assessment for a potential change to the site; new ore development, scouting a location for a new waste stockpile or establishing a new tailings facility; with an appropriate group of multidisciplinary stakeholders convening to workshop the high-level criteria and identify how the potential change may impact the closure strategy, objectives and criteria.

The outcomes of this high-level assessment can then inform whether a more detailed, quantitative risk assessment is required. In cases where significant risks or uncertainties are identified, further analysis may be undertaken to better understand the likelihood and consequences of potential failure modes, evaluate mitigation measures and refine closure planning. This tiered approach ensures that effort is proportionate to the level of risk while still maintaining a proactive and systematic evaluation process that supports effective decision-making and long-term closure outcomes.

In contrast, a more detailed risk assessment may focus on a specific facility, system or process, such as a tailings storage facility, waste rock storage area, water management system or water treatment plant.

A detailed risk assessment process generally includes the following steps:

1. define the context
   - Establish the closure objectives, criteria and strategy, site conditions and decision being assessed
2. identify risk sources and events
   - Identify operational conditions, design assumptions, knowledge gaps or external factors that could affect closure performance
3. evaluate pathways and consequences
   - Assess how each risk event could affect environmental performance, technical feasibility, stakeholder confidence, closure cost or relinquishment potential
4. assess likelihood and consequence
   - Use a defined risk matrix or company risk framework to assign likelihood and consequence ratings that will result in a risk rating
5. identify controls and mitigation measures
   - Document existing controls and identify additional measures required to reduce risk
6. identify knowledge gaps and actions
   - Define studies, monitoring, design updates or operational changes needed to improve confidence in closure outcomes
7. document residual risk
   - Evaluate whether the remaining risk is acceptable and whether further action is required.

From this process, attention can be focused on higher-risk items to identify opportunities for mitigation, reduce overall risk ratings and define any residual risks. The potential effects of the mitigation measures can be assessed by evaluating how the likelihood or consequence rating would change and thereby lower the overall risk rating.

Knowledge gaps are often identified during this process. From these, recommendations can be established to address the gaps and implement mitigation plans to get back on track with the ability to meet closure objectives and criteria.

Risk assessments are more effective and better received when conducted through multidisciplinary workshops that promote stakeholder buy-in to develop and support mitigation measures. Participants should include representatives from operations, closure planning, water management, geochemistry, geotechnical engineering, environment, permitting, community relations, finance and corporate governance. This approach improves communication between disciplines and supports more defensible decision-making.

3.1 Implementation and timing of risk assessments

Closure risk assessments should be conducted periodically and when specific triggers occur. Routine assessments provide a structured opportunity to confirm whether the closure plan remains aligned with current site conditions and whether the closure strategy remains capable of meeting closure objectives and criteria. The ICMM (2020) closure maturity assessment provides some guidance on closure plan development and the triggers for revisions (conceptual to executable and post-closure monitoring) over the life of mine that reflect the expected levels of the knowledge base or gaps and represent some key periods for conducting risk assessments (Sullivan & Sanders 2025). These are also beneficial times to conduct risk assessments on the current site operations against the closure plan to see if it remains aligned to meet the closure objectives and criteria, and identify areas at risk of not being able to meet the closure objectives and criteria.

Potential triggers for closure risk assessments include:

- scheduled closure plan updates
- material changes to the operations, mine plan or life of mine such as
  - new ore development (underground or pit)
  - new tailings storage facility (TSF) or waste dump requirements
- changes in the geochemical characteristics of waste rock or tailings
- changes in water quality predictions
- changes in water management or treatment requirements
- changes in regulatory requirements
- change in ownership and corporate closure policies
- progression from conceptual to preliminary or detailed closure design
- transition into care and maintenance
- being between 10 and 5 years of the end of mine life.

4 Case study: Operationally driven closure risks

The site is an open pit mine operation located in northern, permafrost-affected environment and comprises 3 orebody geologies with 2 principal waste rock types. Type 1 is classified as non-potentially acid generating (non-PAG) and has low metal leaching (ML) characteristics, and type 2 is classified as high sulphide (high-S) and acid rock drainage (ARD) generating with ML characteristics. The waste rock management plan implemented at the site stipulates which materials can be utilised as construction material for roads, dams and, potentially, cover material for closure based on the waste's geochemical classification.

The closure strategy includes the subaqueous placement of the type 2 high-S waste rock in an open pit with a water cover to mitigate the long-term oxidation potential. The TSF will have a combination of water cover and a high-density polyethylene (HDPE) liner cover system on the slopes and surface above the water cover. The overall closure objective is to reduce the long-term environmental risks and limit the post-closure period requiring active water treatment.

The site contact water is collected and treated in a high-density lime water treatment system and is expected to operate through the transition to approximately 25 years post-closure, when steady-state conditions were predicted to be met. The generation of treatment sludge collected in the clarifier will be deposited in the same pit as the high-S waste rock. A second small pit developed during operations will remain in place post closure to be used as part of the site water management system.

As the site was approaching the end of life (within 5 years), 2 risk assessments, water and closure, were conducted to evaluate if the current site conditions, operational decisions and external drivers remained aligned with the closure strategy and the mining company's ability to meet the closure objectives and criteria. The following illustrates how the risk assessments identified several operational scenarios, and highlights the interactions and ripple effect that started with an outdated closure plan and deviation from the site's operational water and waste management plans.

4.1 Scenario 1: Outdated closure plan

Typically, mine sites will have a conceptual level closure plan that was developed as part of the feasibility design and engineering of a site or early operations. While these plans are periodically reviewed, many can be 10 to 15 years old and hence do not reflect the current site conditions. As a result, the original closure strategy may become outdated or no longer viable.

At the time of development, the closure strategy is generally based on the best science and industry practices. The closure plan outlines the path to meet closure objectives and criteria. However, these plans are not always adequately updated to reflect evolving site conditions, operational changes or new regulatory requirements.

This gap was highlighted during the initial water risk assessment, which identified that the existing water treatment system would likely be unable to meet the anticipated changes to regulatory effluent discharge criteria under evaluation at the time. This finding indicated that either the existing water treatment system would need to be upgraded or a secondary treatment system would need to be implemented. Additionally, it was identified that climate change has influenced site hydrological and hydrogeological conditions, altering water quantities, quality and flow regimes.

Both options would require updates to the closure plan to incorporate significant changes in the long-term water management and treatment requirements, as well as the associated financial assurance (FA) obligations. These changes may result in a revised closure strategy to align the design with closure objectives and criteria, and establish a new path for the closure plan.

4.2 Scenario 2: Operational decisions made without considering closure

4.2.1 Extension of mine operations – waste management

During operations, decisions are commonly driven by the need to maintain ore production and generate revenue. Consequently, when operational changes are proposed, closure implications are not always considered as closure may be perceived as a future issue that distracts from operational priorities. As a result, capital and operational budgets are typically directed to operations rather closure planning. However, deferring consideration of closure implications can introduce significant risk. Operational decisions made without adequate evaluation of closure impacts may affect the site's ability to meet closure objectives and criteria, compromise the integrity of the closure strategy and reduce confidence in the successful implementation of the closure plan (Sanders et al. 2018).

The case study site did not fully consider the closure impact of extending ore extraction and development of a new orebody. During the closure risk assessment it was identified that doing so would generate volumes of type 2 high-S waste such that subaqueous deposition was no longer feasible given inadequate storage capacity. This constraint introduces substantial challenges for the long-term management of PAG materials and increases the overall risk to closure.

While the waste management and closure plans considered the more reactive materials, the challenge presented was that the quantities of materials were more than what was planned for, leading to insufficient storage capacity for the type 2 high-S waste. With the limited time frame (i.e. the mine was reaching end of mine life), alteration to the waste management plans was not an option and the site had to pivot to other considerations such as where to store the waste rock operations with limited area on the surface for storage, potential double handling of the material at closure and subaerial deposition that would require an engineered cover design using a low permeable HDPE liner.

4.2.2 Extension of mine operations – the ripple effect

Exploration activities often continue during mine operations to evaluate the potential for resource expansion and identify new development opportunities. Decisions regarding mine expansion need to be carefully integrated into the closure strategy. For example, the development of new orebodies with type 2 high-S waste, combined with limited to no capacity for subaqueous deposition, can increase the long-term oxidation potential of waste materials. This can create a ripple effect on the water management and treatment systems.

Changes in the waste management practices, especially under constrained storage capacity, can lead to a change in the water management system. These may include additional collection systems for the new waste rock stockpiles, expanding pumping systems and increased volumes of water requiring treatment.

The high-density lime water treatment system produces treatment sludge that needs to be actively managed and disposed of to maintain the clarifier performance. As water treatment volumes increase, sludge produced also increases, creating additional operational and closure challenges. Increased sludge volumes to be deposited in the open pit may reduce the storage capacity for waste rock or vice versa. This may introduce competing demands on available storage capacity and complicates long-term closure planning.

The risk assessment also identified the high likelihood that the water management and treatment systems will probably need to remain for 50 years or more post closure. This extended time frame has significant implications for long-term closure planning, design considerations and FA requirements, particularly with respect to long-term operation, maintenance and liabilities.

Under a long-standing agreement with local communities, portions of the mine infrastructure are intended to remain in place post closure for community use, with closure-related costs shared between the community and mining company. However, the potential extension of post-closure operations and maintenance, particularly related to water management and treatment, introduces additional uncertainty and challenges. These may result in significant unexpected costs shared between the company and the community.

Furthermore, this development may raise concerns with the regulators regarding the adequacy of closure planning and the site’s ability to meet long-term obligations. This could, in turn, affect the site’s reputation and relationships with stakeholders and Indigenous communities, particularly if expectations around closure outcomes and long-term liabilities are not clearly aligned.

4.3 Scenario 3: Impact of climate change

Even with frequent reviews and updates of the closure strategy and closure plan, risks to meeting closure criteria and objectives can also arise from factors outside the control of the site. The water risk assessment identified that, despite updates to the water balance model incorporating multiple climate change scenarios, the associated impacts of climate change have not been fully integrated into the site water management system. This gap may result in the inability to effectively manage large or frequent storm events, increased potential for damage to mine infrastructure and long-term changes in precipitation patterns that can compromise the integrity of waste containment structures (Clarke 2025; Stratos Inc. & Brodie Consulting Ltd. 2011). Understanding future climate conditions at a mine site is complex and is often addressed through detailed modelling of multiple climate change projections (Erasmus & Coetzer 2024).

Long-term projections of net positive or net negative water conditions can significantly influence closure strategies and plans. Sites experiencing net water positive (excess) conditions may encounter challenges with water conveyance and storage capacity, while mines that are net negative (deficit) may experience challenges with water storage such as maintaining a water cover over reactive waste material increasing the impacts of ML/ARD (Stratos Inc. & Brodie Consulting Ltd. 2011). Increased ML/ARD risks can lead to poor seepage and run-off water quality, resulting in increased treatment requirements to meet the environmental and effluent criteria.

In Arctic environments, permafrost degradation can introduce unique challenges at both local and regional scales. Permafrost degradation can lead to complex and sometimes unintuitive changes in groundwater and surface water flow patterns due to the interconnection of physical, chemical and biogeochemical processes (Walvoord & Kurylyk 2016). At remote mine sites, the impact of permafrost thawing can introduce risks to water management infrastructure and planning assumptions while also increasing uncertainty in achieving closure water treatment criteria.

The water risk assessment identified that the climate change modelling indicated the potential for an increased frequency and intensity of precipitation events, degradation of permafrost, changes in groundwater quality (from permafrost degradation), increased groundwater flow volumes into reservoirs and changes to groundwater flow patterns. Notably, even the ‘dry year’ modelling scenarios projected an overall increase in water volumes requiring management. Additional risks were identified related to limited water storage capacity in the open pits and TSF that could lead to either the release of untreated water or water that does not meet effluent criteria, especially during upset or storm events. As a result, the risk assessment concluded that a detailed review of the water management system is required, with potential redesign measures needed to accommodate increased water volumes (e.g. consideration of additional water storage ponds).

Climate change impacts also contribute to the ripple effects discussed in Section 4.2.2. The site was already operating at the maximum flow limits of the water treatment plant due to the current stage of mining and operational decisions to date (e.g. increased contaminant loads in the contact water due to larger material quantities from extending mine life). Any increased precipitation, or other influent sources, would result in higher volumes of water requiring treatment.

Additionally, there is the potential for increased volumes of non-contact water (e.g. run-off) directed into the system. This may dilute the influent water quality, potentially reducing the efficiency and effectiveness of the treatment process.

This situation could create a self-reinforcing cycle where increased water volumes require greater treatment, leading to higher sludge production. The additional sludge would require storage, thereby reducing the available water storage capacity and further increasing the volumes of water requiring treatment. This feedback loop has the potential to significantly exacerbate long-term water management and closure challenges.

4.4 Scenario 4: Misalignment with closure objectives and criteria

Closure objectives and criteria are often developed to establish clear end points for decision-making, with closure criteria serving as measurable indicators of whether objectives have been achieved. However, meeting these technical end points is sometimes undertaken in isolation, without sufficient engagement with stakeholders and affected communities. As a result, regulators and/or proponents may view closure as a technical or procedural milestone while other stakeholders, such as affected communities, Indigenous groups or long-term land stewards, may continue to face uncertainty, residual risks or unresolved concerns.

Consequently, achieving established closure criteria does not necessarily equate to social acceptance or stakeholder confidence. This highlights the importance of recognising that closure is not solely a technical or regulatory determination but also a matter of perspective shaped by broader social, cultural and long-term considerations. These differing perspectives are often reflected in the residual risks identified through closure risk assessments.

At this site the closure risk assessment identified that some of the existing closure criteria fell under this scenario. In particular, the end land use had not been clearly defined, especially in consultation with local communities. With closure anticipated within 5 years, this resulted in the need for targeted engagement with communities to establish agreement on appropriate end land use. Without clarity, there is a high risk of misalignment between the closure strategy, the desired end land use and the ability to achieve desired criteria.

Additionally, several of the ‘defined’ closure criteria were more in line with high-level objectives and lacked measurable end points to evaluate success. For example, one objective was to minimise monitoring and maintenance requirements during closure and post closure to align with eventual end land use. However, the end land use of the site was not defined. This objective cannot be effectively translated to measurable criteria. The lack of clarity results in a high risk of strategic misalignment and weakens the closure strategy.

Furthermore, the assessment identified the requirement for long-term water treatment, which reduces the potential for walk away closure strategy and is a misalignment in the corporate closure policy. Collectively, these gaps highlight the need to better define closure criteria, align them with a clearly established end land use and integrate stakeholders’ expectations into closure planning.

5 Conclusion

Risk assessments provide a structured process for evaluating closure risks and supporting decision-making, serving as an effective communication tool across multidisciplinary teams. The process establishes a common forum for discussing assumptions, identifying information gaps, defining responsibilities, and developing a shared understanding of closure risks, controls and required actions.

A key strength of the risk assessments process is the development of a shared vocabulary among disciplines. Clearly defining concepts such as closure objectives, criteria, strategy, measures and controls, and residual risk, reduces misunderstandings and misalignment; ensuring a consistent interpretation of closure goals and performance expectations (Whitbread-Abrutat 2025).

Risk ranking further strengthens this approach by providing a transparent and systematic basis for prioritisation while supporting engagement by both technical and non-technical stakeholders through a visual representation of relative risk levels. When combined with the identification of knowledge gaps, risk ranking provides a basis for prioritising what additional data collection, monitoring or studies are needed to reduce uncertainty. The resulting gap analysis also provides a documented record of the information reviewed and establishes a clear path forward through defined actions and workplans.

Integrating closure considerations into operational management of change processes creates an opportunity to identify potential closure implications early. Operational decisions that provide short-term benefits, such as waste management practices, the use of reactive materials in construction, increases in contact water volumes or revised water treatment assumptions, can significantly increase long-term closure risk if they are not evaluated against the closure strategy and criteria. By embedding closure risk assessment into operational decision-making, sites can identify misalignments early, implement corrective actions and reduce the likelihood of costly redesign, extended water treatment or increased long-term closure liability.

Closure risk assessment is therefore a practical tool for evaluating whether operational practices, site conditions and external drivers remain aligned with closure objectives and criteria. As mines evolve, changes in geology, geochemistry, water management, regulatory requirements, climate projections, stakeholder expectations and corporate priorities can affect the closure strategy. If these changes are not identified and managed, the closure plan may no longer provide a reliable pathway to achieving the intended post-closure condition.

The case study demonstrates that closure risks often arise during operations rather than only at closure. Examples include increased volumes of reactive waste rock, changing water treatment requirements, insufficient water storage capacity and closure criteria that are not measurable or aligned with long-term land use objectives. These risks can increase closure costs (Sullivan & Sanders 2025), extend water treatment durations, reduce the potential for relinquishment and weaken confidence among regulators, stakeholders and Indigenous groups. Operational changes can also create ripple effects, such as modifications to waste management practices that may drive long-term changes to site water management and treatment requirements. Industry pressures to expand operations or extend mine life to meet schedule-driven objectives may further exacerbate misalignment with existing closure strategies and plans (Sanders et al. 2018).

Periodic and event-triggered closure risk assessments provide a structured process to identify these risks, evaluate their consequences and define appropriate mitigation measures. When conducted through multidisciplinary workshops, risk assessments also improve communication between operations, closure practitioners, technical specialists, management and external stakeholders.

Effective closure planning requires early and continuous integration with operational decision-making. Embedding closure risk assessment into life of mine planning, management of change processes and closure plan updates can reduce uncertainty, support defensible work programs and budgets, and improve the likelihood that closure objectives and criteria will be achieved. Ultimately, closure risk assessment provides a practical mechanism for translating uncertainty into actionable decisions that support more resilient, defensible and sustainable closure outcomes.

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