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The future of the past: rational closure for legacy sites

Chris Meikle [a,*]

[a] *SLR Consulting, Australia*

Abstract

The application of contemporary closure performance standards to legacy mine landforms presents significant technical and regulatory challenges. Evolving stakeholder expectations regarding long-term geotechnical stability, environmental performance and post-mining land use frequently conflict with the physical constraints, data limitations and design uncertainties inherent to legacy sites. This paper presents selected case studies to illustrate closure decision-making in the context of such constraints and examines the role of risk-based frameworks in guiding proportionate closure responses.

A key constraint is reconciling contemporary factors of safety with the limited geotechnical data typically available for historical landforms. Slopes historically regarded as stable often lack sufficient evidence to demonstrate ongoing performance against current standards, prompting costly investigations and, in some cases, complex or invasive remediation. Determining appropriate remedial actions is particularly nuanced where closure criteria are undefined, original designs are unavailable or future land uses remain uncertain. These uncertainties can result in interventions that generate additional disturbance or introduce new environmental risks, contrary to closure objectives.

Uncertainty around post-mining land use(s) significantly complicates the definition of closure performance criteria. Many legacy landforms were constructed without an intended post-closure function and their potential repurposing, whether under a new tenure, a native ecosystem or industrial re-use, remains undefined. The concept of "designing for relinquishment" introduces further complexity by requiring clear performance thresholds for the transfer of liability, which may not be practically achievable under legacy conditions.

In the context of mine waste landforms, the direct application of contemporary standards such as the Global Industry Standard on Tailings Management is often infeasible. The conservatism embedded within these frameworks, while appropriate for new facilities, may be disproportionate when applied retrospectively. This paper explores the growing use of pragmatic, risk-informed approaches such as ALARP (as low as reasonably practicable), which allow for performance-based assessments that maintain acceptable risk thresholds while acknowledging natural landform evolution and the diminishing hazard profile of aged structures.

It is argued that regulatory frameworks must accommodate flexibility and proportionality in closure expectations. Imposing prescriptive standards without consideration of a legacy context may delay closure, increase long-term liability and divert resources from higher-risk or higher-value interventions. A tiered, risk-based regulatory model is proposed as a pathway to enable fit-for-purpose closure outcomes. This paper advocates for adaptive closure strategies that integrate geotechnical, environmental and land use considerations within a risk and performance-based design framework.

Keywords: *legacy, stability, regulatory, ALARP, GISTM, mine waste, tailings*

1 Introduction

Mine closure has become an increasingly complex and scrutinised aspect of the mining life cycle, particularly at the front end of mine planning, and is embedded within permitting and approvals as contemporary standards demand higher levels of social, environmental and engineering performance (United Nations

[*] Corresponding author. Email address: cmeikle@slrconsulting.com

Environment Programme 2019). Mine closure is fundamentally a landform challenge arising from the need to stabilise, rehabilitate and integrate a diverse set of constructed landforms into sustainable post-mining landscapes. The Global Industry Standard on Tailings Management (GISTM) and various international regulatory frameworks (Miller & Owens 2014; Cullen 2018) require integrated geotechnical, geochemical, hydrological and ecological design solutions that address long-term stability, water quality, erosion and climate resilience; all aligned with future land use and community expectations. However, challenges arise when contemporary requirements are retroactively applied to legacy mine sites, many of which were developed under vastly different engineering, regulatory and financial conditions.

In mining, the term "legacy" is commonly used to refer to sites where mining has occurred and for which no party holds full responsibility for rehabilitation. Worrall et al. (2009) define legacy mining land as "land which has been mined and is now being used for another purpose, or is orphaned, abandoned or derelict and in need of remedial work". Globally, hundreds of thousands of such sites exist. Pepper et al. (2014) estimated there are over 50,000 legacy mine sites in Australia, and the US Government Accountability Office (2019) reports approximately 500,000 abandoned mines across federal, state and tribal lands. These sites were often closed under minimal standards, leaving behind hazards such as unstable void slopes, tailings storage facilities (TSFs) and waste rock dumps (WRDs). Due to historically deficient standards, these legacy sites frequently exhibit soil and water contamination, acid and metalliferous drainage (AMD), and public safety risks (Bennett 2016; Zang et al 2023). In the absence of clear ownership, the burden of remediation typically falls to governments and local communities.

In the context of this paper, the term "legacy" is used more broadly. It encompasses not only orphaned or abandoned mines but also active or recently inactive sites, still under the ownership of an operator, where a clear closure vision was never conceived or was materially deficient. These may include components within the existing mining lease, such as waste landforms or disused infrastructure, which were developed without integrated closure planning and lack criteria beyond being deemed "safe, stable and non-polluting". Such sites present similar long-term risks and uncertainties and require retrospective application of closure principles to ensure sustainable post-mining outcomes.

Historically, mine closure has focused narrowly on physical stability and simple revegetation at the lowest cost (Ayres 2023). By contrast, contemporary best practice, guided by industry frameworks like the International Council on Mining and Metals (ICMM) (International Council on Mining and Metals [ICMM] 2025) aims for optimised, fit-for-purpose outcomes that balance multiple objectives. For example, the ICMM (2025) emphasises stakeholder-supported closure visions and holistic sustainability rather than mere regulatory compliance. Legacy site closure planning often lacks such foresight, so applying contemporary closure approaches requires special adaptations and an understanding of how these contemporary goals may or may not be achieved, given site constraints.

Whilst contemporary practice expects that closure planning is integrated into the mine plan, design and operation from the outset (Johnston 2016), legacy mines often present inherent design limitations, including steeper slope angles, poorly configured waste facilities and inadequate drainage controls. Furthermore, the absence of financial provisioning for closure at many historic sites makes large-scale remediation projects economically prohibitive. Additionally, the uncertainty of future land uses, whether for ecological rehabilitation, industrial redevelopment or community use, creates further ambiguity regarding appropriate closure design criteria.

On this basis, there is a growing need to examine alternative approaches that balance geotechnical stability, environmental remediation, environmental sustainability and economic feasibility. A particular focus is given to the role of regulators in defining pragmatic expectations and the application of the ALARP (as low as reasonably practicable) principle to landform slope stability. Additionally, the concept of natural stability attenuation is considered as a means of moderating closure standards to reflect real-world landscape evolution processes. By integrating examples, this discussion paper provides a framework for legacy mine closure that prioritises risk-based, adaptive solutions over rigid engineering interventions.

2 Geotechnical design challenges

One of the principal challenges in applying contemporary closure criteria to legacy mine sites is the geotechnical complexity of retrofitting stability measures to historically constructed landforms (Zhao & Zang 2021). Contemporary geotechnical design principles often demand higher factors of safety (FoS) than those found in natural slopes, often exceeding 1.5 for long-term landforms and, in extreme cases, up to 1.75 for tailings dams (Coffey & Plunket 2019; Erskine & Lorimer 2020). An FoS of 1.5 is widely regarded as a conservative baseline for static slope stability design across the US, Europe and Australia (European Committee for Standardization 2004; Chowdhury et al. 2010), reflecting international norms in balancing acceptable risk and engineering conservatism.

However, many historical waste dumps and TSFs were built using methodologies that did not account for long-term stability at these levels. Applying contemporary standards often determines that regrading, buttressing or capping is required, which can lead to additional environmental disturbances, increased slope failure and operator health risks, and significant financial costs (Bocking & Jewell 2021).

In the context of legacy TSFs and WRDs, meeting the objectives of contemporary standards such as the GISTM requires extensive site characterisation. This process is inherently complex and resource-intensive, often demanding a comprehensive understanding of geotechnical, hydrogeological, hydrological and geochemical conditions (ICMM 2025). At legacy sites, these investigations are further complicated by limited historical data, access constraints and degraded or altered site conditions.

Once characterisation is complete, the resulting designs may necessitate substantial additional disturbance to the natural environment. This can include vegetation clearing, extensive earthworks or borrow pits in ecologically sensitive or hydrologically constrained areas, which potentially compromise the surrounding landscape and biodiversity (Worrall et al. 2009; Chugh et al. 2023).

Even with rigorous design processes, the uncertainty of construction impact is a prominent issue. Many legacy TSFs and WRDs are poorly documented, with some exceeding a century in age. Subsurface conditions may include undetected slime layers, anthropogenic debris, and unknown and industrial waste that were never recorded or monitored (Pepper et al. 2014; Nash 2020). These factors can significantly affect slope stability and material behaviour during remediation or buttressing activities.

Moreover, implementing such designs may inadvertently introduce new environmental and human health risks. These include increased dust and air quality issues from large-scale earthworks, potential surface and groundwater contamination from mobilised materials, and long-term impacts from construction traffic and quarrying (LaBerge et al. 2004; Otto & Nash 2023). While a high FoS may be achieved on paper, the real-world execution of that design may come at a cost that offsets the intended stability benefits.

An example of this is BHP's Globe-Miami TSF in Arizona, USA: a facility that has remained stable for nearly a century but is now subject to a ~USD 250 million remediation program (Figure 1). This includes the construction of a massive buttress requiring continuous quarry operations and haulage of rock along public roads for over a year; an effort that itself introduces construction-phase geotechnical risks and environmental disruption (Ayres 2023).

Figure 1 The Miami Avenue tailings project, Globe-Miami, Arizona (BHP ca. 2020)

In such cases, the challenge is not only technical but philosophical: can the push for contemporary FoS targets in legacy settings unintentionally elevate the overall environmental and social risk footprint? A more nuanced balance between stability, sustainability and disturbance may be needed.

Another example is the Mount Morgan mine in Australia (O'Kane et al. 2006), where historic WRDs exhibit marginal stability but have remained largely intact for decades. Applying contemporary FoS requirements would necessitate large-scale reworking of slopes, leading to additional land disturbance, increased erosion risk, greater short-term environmental risk and heightened rehabilitation costs. In contrast, a risk-based, adaptive management approach that accounts for gradual landform evolution could offer a more practical and cost-effective solution.

Another key challenge is the heterogeneity of waste materials at legacy sites. Unlike engineered waste facilities designed under contemporary standards, historical tailings dams and waste dumps often contain highly variable materials, unconsolidated fines and uncontrolled seepage pathways, making them inherently more challenging to stabilise and introducing short-term slope failure risk during construction. The application of rigid engineering criteria can be counterproductive as interventions such as slope flattening or material reprocessing may destabilise previously stable conditions.

Furthermore, geotechnical uncertainty is exacerbated by limited historical data. Many legacy mines lack detailed geotechnical records, making it difficult to accurately assess stability risks without extensive and costly site investigations. Given these constraints, a one-size-fits-all regulatory approach or design standard is unlikely to be effective, necessitating site-specific, risk-informed closure planning.

3 Regulatory expectations and the role of ALARP in mine closure

Regulators play a crucial role in defining what constitutes a reasonable and acceptable closure outcome for legacy mines. While contemporary legislation typically mandates long-term physical stability and minimal ongoing maintenance, there is no consistent standard for interpreting these requirements in the context of older sites with inherent geotechnical and environmental constraints. This regulatory ambiguity places mine operators in a difficult position, navigating evolving legal expectations while managing financial and technical limitations. Moreover, a rigid regulatory approach that fails to account for natural attenuation processes and the variability of ecological conditions can unnecessarily constrain adaptive closure strategies and limit opportunities for beneficial post-closure land uses.

The ALARP principle offers a framework for assessing acceptable levels of risk in mine closure (Department of Mines and Petroleum & Environmental Protection Authority 2015; Sullivan & Murphey 2017; Orboni ca. 2002). Used to guide decision-making in environmental, health and safety contexts, ALARP is based on the principle that risks should be reduced to the lowest *practicable* level, considering technical feasibility, financial costs and environmental trade-offs. This is not the same as *as low as possible*, which implies eliminating risk regardless of cost or feasibility. The distinction matters because ALARP acknowledges that some level of risk is unavoidable and that excessive measures may be disproportionate to the benefit gained. It promotes pragmatic, evidence-based decisions that protect people and the environment without imposing unreasonable burdens (Figure 2).

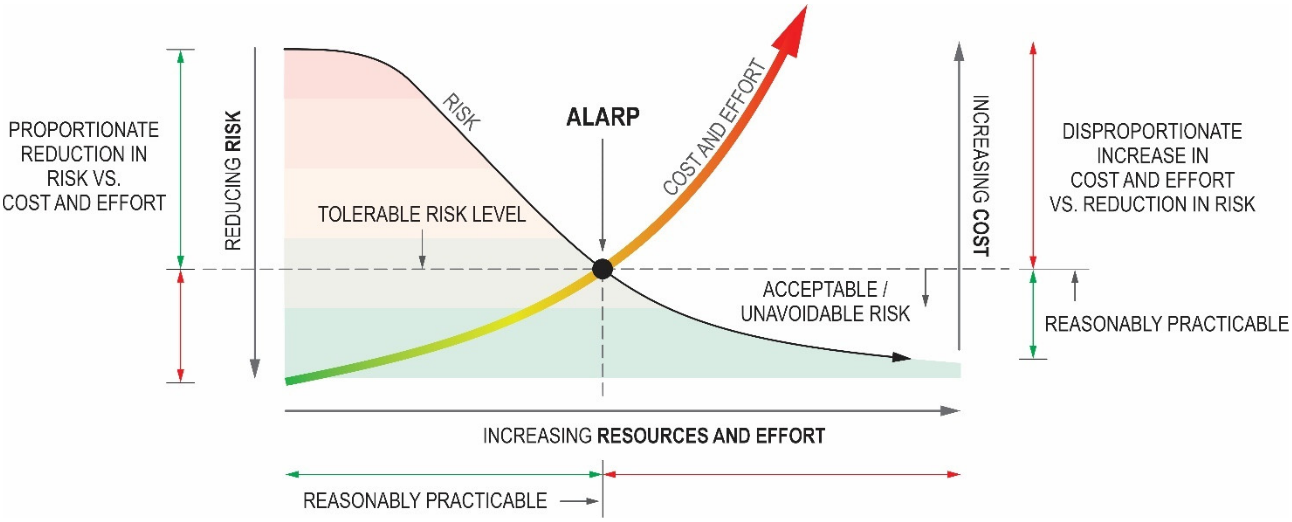

Figure 2 The ALARP (as low as reasonably practicable) principle

ALARP is a key requirement of the GISTM (ICMM et al. 2020) for TSF and WRD design, which in part considers ALARP for closure. However, when applied site-wide and to the broader concepts of mine closure, ALARP allows regulators and mine operators to:

- prioritise interventions that yield the greatest risk reduction benefits rather than mandating absolute stability
- avoid excessive remediation efforts that introduce secondary environmental impacts (e.g. excessive land disturbance from slope reworking)
- balance cost-effectiveness with long-term stability objectives by considering a range of closure options.

The former Rum Jungle uranium mine in Australia's Northern Territory, initially rehabilitated between 1983 and 1986, required a revised closure strategy due to legacy AMD and the inadequacy of former works against contemporary environmental standards. A new rehabilitation plan developed in 2020 (O'Toole et al. 2022) incorporates contemporary environmental and stakeholder expectations and includes relocating acid-forming waste rock, treating contaminated water and realigning the East Branch Finniss River through the flooded pit. In alignment with the ALARP principle, the rehabilitation design integrated detailed climate change modelling based on Intergovernmental Panel on Climate Change and Commonwealth Scientific and Industrial Research Organisation projections to assess potential long-term risks. Long-term erosion modelling under climate change scenarios demonstrated that peak flood levels would not impact the WRDs and that maximum gully erosion on the WSFs over a 500-year horizon would remain well within the design thickness of the erosion protection layer.

Similarly, the Zortman-Landusky gold mine in Montana, USA, (Figure 3) incorporated the ALARP principle in its closure strategy, particularly in the design of waste rock management and slope stability to reduce environmental impacts. A key aspect was minimising the risk of further AMD and addressing the slope stability of WRDs and TSFs. (Williams 2021). While the closure plan involved significant waste regrading and capping to mitigate water infiltration, the design acknowledged that the treatment of AMD and slope stabilisation were necessary for long-term containment. However, due to the complexity of the site and the unpredictability of certain environmental factors (e.g. extreme weather events), there were considerations regarding the ALARP principle, including balancing cost and technical feasibility with the need to ensure stability and mitigate ongoing environmental risks. In particular, the ALARP approach was relevant in terms of determining the optimal amount of effort and resources to be allocated to slope stability measures, such as capping and revegetation, and the appropriate level of water treatment required to maintain environmental safety without over-engineering the site (Kuipers 2000).

Figure 3 Zortman-Landusky gold mine, located on the southern edge of the Fort Belknap Indian Reservation in Montana, USA (NBC News ca 2004)

Patterson & Trevor (2019) also provide examples from two former gold mines where groundwater quality changes occurred and were preventing certification of closure by the regulator. In each example, due to the lack of baseline data, the initial supposition was that post-mining water quality change was related to a release of mine waste or mine water. However, extensive monitoring and modelling led to demonstration that the cause was the redistribution of natural conditions and the change was subsequently considered low enough to be acceptable.

By incorporating the ALARP principle into mine closure regulations, regulators can provide greater flexibility for legacy sites, allowing owners to achieve risk-proportionate, long-term closure outcomes without imposing unrealistic remediation expectations that may be counterproductive.

4 Alternative approaches beyond the GISTM for legacy waste

Introduced in 2020, the GISTM has set stringent requirements for tailings and mine waste engineering but does not mandate specific numerical FoS. Instead, it implicitly promotes high safety margins through its comprehensive, risk-informed approach. The GISTM requires facilities to be classified based on the potential consequences of failure, not just the probability. Facilities with higher consequence classifications are subject to more stringent design, monitoring and governance requirements. This inherently drives the adoption of higher FoS to mitigate the elevated risks associated with certain failure scenarios. While these measures are critical for the design of new TSFs and WRDs; and raises to these structures, they present practical and economic challenges when retroactively applied to legacy sites. For legacy TSFs and WRDs, alternative approaches are often needed to achieve safe and sustainable closure outcomes without resorting to large-scale, cost-prohibitive engineering interventions.

One such strategy is in situ stabilisation, involving treating tailings in place to improve their geotechnical and environmental performance. The use of cementitious or lime-based binders can reduce the mobility of contaminants and improve the physical integrity of tailings. Zhang et al. (2022) discuss the used of calcium-based additives could effectively immobilise heavy metals in lead/zinc mine tailings, reducing leachate concentrations and improving structural stability.

Similarly, geomorphic landform design can be applied to reshape mine waste into more stable, naturalistic landforms that mimic the surrounding topography and incorporate natural drainage patterns. This method avoids removing waste or adding more material and promotes longer-term erosion resistance and landscape integration. In the Athabasca oil sands region of Canada, geomorphic landform design has been applied to tailings facilities to create landscapes that support native vegetation and withstand climatic extremes, reducing the need for ongoing maintenance (Wilson 2016).

The reprocessing of historic tailings to recover residual metals is also another alternative strategy that can reduce closure liabilities while generating economic returns (Fleming et al. 2010). In Chile, several legacy sites have been reprocessed to extract the remaining copper and gold, demonstrating both environmental and financial benefits (Galvez et al. 2019). Similarly, the Mount Morgan project in Queensland, Australia, aims to reprocess gold-copper tailings using contemporary extraction technologies, thereby reducing contamination and supporting regional development (Fraser 2023).

5 Environmental considerations

Environmental considerations are ubiquitous but also specifically critical when closing legacy mine sites, as many of these sites have caused environmental impact during their operational and post-operational life span. Unlike newer mines, where environmental impacts are typically addressed through ongoing impact assessments and mitigation measures from the outset, legacy mines often leave behind uncontrolled pollution including AMD, contaminated seepage and soil contamination. As such, mine closure at these sites must balance the need for geotechnical stability with environmental remediation.

One key environmental challenge at legacy mines is managing AMD, a phenomenon where sulphidic minerals in waste rock and tailings react with water and oxygen to produce sulphuric acid, which can leach harmful metals into the surrounding environment (Lottermoser 2010). Historical approaches, such as excavation and relocation of contaminated materials to lined facilities, are often prohibitively expensive and can cause further environmental disturbance (Younger et al. 2002). Contemporary closure strategies offer a broader toolkit that includes subaqueous disposal, evapotranspiration covers and the exclusion of either water or oxygen to suppress acid generation (International Network for Acid Prevention 2017). Additionally, both active and passive treatment systems, such as constructed wetlands, limestone drains and reactive barriers, are increasingly used to treat AMD at its source (Skousen et al. 2017; Lindsay et al. 2009). While all these approaches come with technical and financial challenges, regulatory frameworks must remain flexible enough to permit a range of solutions. This flexibility is especially critical at legacy sites, where a one-size-fitsall remediation standard may not be practical or environmentally optimal (Department of Industry, Tourism and Resources 2006; Parsons et al. 2021).

An example of passive treatment is the Upper Animas River watershed in Colorado, USA (Newman et al. 2024), where historical mining activities led to water contamination from AMD. The site's closure strategy emphasised biological treatment systems, including the installation of constructed wetlands, which neutralise acidity and reduce metal concentrations. These types of passive closure measures are less intrusive than engineered interventions and are often more cost-effective in the long term.

Another critical aspect of environmental restoration at legacy mines is the rehabilitation of disturbed habitats such as wetlands, forests or grasslands. Legacy mines often have extensive areas of disturbed land that need to be restored to a functional ecosystem to mitigate environmental impacts. The restoration of biodiversity can take decades or even centuries, particularly at sites where vegetation and wildlife have been heavily impacted by mining activities or where the natural environment is extreme, such as deserts or the arctic. However, successfully rehabilitating the land can reduce erosion, improve water quality and create sustainable ecosystems that will eventually help stabilise the site.

A further example of the effective use of vegetative cover in mine closure is the rehabilitation of the East Pit at the Ranger uranium mine in the Northern Territory, Australia. As part of its closure strategy, Energy Resources of Australia has adopted a store-and-release cover system where the vegetative layer plays a critical role in reducing infiltration, enhancing surface and geotechnical stability, and minimising erosion. The system is designed to temporarily store rainfall in the soil profile and subsequently release it via evapotranspiration, a process heavily reliant on the establishment of native woodland vegetation. This vegetative cover not only mitigates deep percolation that could lead to contaminant transport from the underlying waste but also reduces surface erosion through soil reinforcement and protection against raindrop impact and runoff (O'Sullivan & Fahey 2017; Ross et al. 2020). Additionally, the root structures contribute to shallow slope stability by binding near-surface soils, reducing the risk of shallow failures or cover deformation. The design is supported by extensive climatic, geotechnical and hydrological modelling, and ongoing performance monitoring implemented to validate long-term efficacy under variable environmental conditions (Energy Resources of Australia 2021). This highlights the multifunctional role of vegetation in contemporary mine closure and underscores the importance of permitting a range of technically sound cover approaches adapted to site-specific constraints.

An example of biodiversity restoration is the Sullivan mine in British Columbia, Canada, where revegetation has involved the reintroduction of native species to promote habitat regeneration and restore natural ecological functions, improving soil stability and attracting native wildlife (Przeczek & Ryder 2011). Native plants are well adapted to local conditions, making them more resilient and better able to support biodiversity and long-term ecosystem recovery (Figure 4).

(a) (b)

Figure 4 The Sullivan lead-zinc mine: (a) During operations in 1989; (b) After operations, in 2020 (after Teck)

The closure of legacy mines also necessitates careful management of water resources, particularly where there are concerns about groundwater contamination or impacts to nearby surface waters (Smee & Young 2020). Legacy mines often have unlined tailings ponds or uncontrolled seepage that can lead to contaminated groundwater plumes migrating offsite. The reconstruction of water management systems may involve the creation of long-term monitoring wells, the installation of seepage barriers and the establishment of controlled discharge systems to mitigate the risk of further contamination (Meikle et al. 2023).

At the Lihir gold mine in Papua New Guinea (Williamson & Vogwill 2001), which is challenged by geothermal waters, legacy tailings management practices led to extensive water quality degradation. In response, a combination of surface water diversion, tailings reprocessing and reinforced containment measures were implemented to mitigate the risks of future water contamination.

6 Economic considerations and financial provisioning

The economic implications of closing legacy mines cannot be understated. Unlike many contemporary mines, where closure costs are factored into operational budgets and financial provisions are made in advance, legacy mines often lack the necessary financial resources to cover the cost of remediation and rehabilitation (Pope & Huges 2018). This situation creates a significant financial burden for mine owners, governments and communities alike, particularly where legacy sites are poorly characterised or entirely uncharacterised, requiring extensive geotechnical, hydrogeological, ecological and contamination studies to inform closure design. Importantly, these sites are often located in remote or inaccessible places without adequate infrastructure and logistical support, which further increases the cost and complexity of site access, investigation, monitoring and, ultimately, construction. The remoteness not only impacts labour and equipment mobilisation but also limits the feasibility of ongoing site management post-closure. Therefore, even without known instability or contamination, the sheer unknown nature and remoteness of many legacy sites present substantial economic and operational challenges for achieving safe and sustainable closure.

Financial provisioning for legacy mine closure is a complex issue as mine owners may no longer be financially solvent or may not have established sufficient closure bonds during the operational phase. Without a clear financial structure in place, the costs of closure may fall to the government or other stakeholders, creating financial and social burdens (Lange & Williams 2019). In some cases, regulators may have to step in to enforce closure obligations under the polluter pays principle (Organisation for Economic Co-operation and Development 1972), which holds operators responsible for the costs of environmental clean-up.

To address this gap, many countries have implemented financial assurance mechanisms such as performance bonds, environmental guarantee funds or financial guarantees to ensure that sufficient funds are available for remediation and rehabilitation. However, the adequacy of these mechanisms for legacy sites remains a key concern. In cases where financial guarantees are insufficient, government intervention may be required to ensure that the mine site is closed in a way that meets environmental, safety and regulatory standards.

An example of an effective financial assurance mechanism is the Australian Northern Territory Government's Mine Rehabilitation Fund (2005), which has been used to fund closure works at legacy mining sites. This fund has been established to ensure that money is available to rehabilitate sites with inadequate financial provisions, and it is supported by mandatory contributions from mining operators. The fund has proven to be an effective tool for securing financial guarantees and addressing the significant costs associated with closing legacy mines.

In addition to financial assurance mechanisms, a critical economic consideration in mine closure is the potential to generate long-term economic value through the repurposing of former mining lands and infrastructure. While closure is typically associated with substantial costs, innovative planning can uncover opportunities for economic revitalisation. Former mine sites can be redeveloped for renewable energy generation, agricultural activities or ecotourism, transforming legacy liabilities into community assets. For example, the Government of Western Australia Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) Guideline for preparing Mine Closure Plans (DEMIRS 2025) requires mine closure plans to nominate acceptable post-mining land uses, with renewable energy generation as an example of viable alternative land use involving advanced infrastructure. Similarly, water that requires treatment as part of closure obligations can be treated to a standard suitable for beneficial re-use, such as potable water, agricultural irrigation or industrial processing; further supporting regional development and improving the return on investment from closure activities (Doley & Audet 2013; Sánchez & Morrison-Saunders 2025).

7 Consideration of climate change

Adapting closure strategies for legacy mine sites requires proactive incorporation of climate change considerations to ensure long-term stability and environmental performance. Unlike contemporary mine designs, which may integrate climate-resilience planning from inception, legacy sites were often developed without accounting for future climatic variability. As such, retrofitting these sites presents unique challenges and necessitates scenario-based planning approaches (Bulovic et al. 2023).

Changing precipitation patterns, extreme weather events, temperature increases and shifts in hydrological cycles can all influence the integrity of mine waste landforms and water management systems. For example, increased rainfall intensity and frequency can heighten erosion risks and slope instability, particularly where tailings dams or WRDs were not designed to withstand such events (O'Toole et al. 2022). Conversely, prolonged droughts may compromise vegetation cover, reducing evapotranspiration and increasing dust and erosion hazards (Baisley et al. 2016).

Closure designs must also consider future climate envelopes when evaluating long-term landform stability and ecosystem recovery. Engineers and regulators are increasingly adopting dynamic design criteria that anticipate a range of climate futures over the post-closure period, typically spanning 1,000 years or more. This includes adjusting design storm intensities, re-evaluating catchment hydrology and modelling landform response under different representative concentration pathways or shared socio-economic pathways (Rissik & Iles 2022).

Furthermore, climate resilience should be embedded in the risk assessment and decision-making frameworks guiding closure. This may involve integrating climate change into ALARP evaluations, stability thresholds and rehabilitation success criteria. Closure performance monitoring programs must also remain adaptive to detect early signs of climate-induced failure mechanisms (Bulovic et al. 2023).

Ultimately, achieving sustainable closure of legacy mines demands a shift from static to climate-adaptive design thinking, ensuring the evolving environmental and climatic context does not undermine the integrity of rehabilitated sites or the safety of surrounding communities (Baisley et al. 2016).

8 Risk-based and adaptive approaches

A key takeaway from examining the challenges of retrofitting contemporary closure standards to legacy mine sites is the need for a risk-based and adaptive approach; one that is scalable to the level of available data, can drive justification for more data and can evolve as more information becomes available. Contemporary approaches to mine closure are becoming increasingly prescriptive and rigid, relying on strict compliance with global standards without sufficient consideration of site-specific conditions or future land use. In contrast, a risk-based (including qualitative) approach focuses on evaluating the long-term environmental, geotechnical and social risks associated with a mine site and then developing closure strategies that are proportional to those risks.

One of the central assumptions of this approach is the identification and management of residual risks; those risks that remain even after the closure process has been completed. These include geotechnical instability, water contamination and loss of biodiversity (Lloyd et al. 2002). A comprehensive risk assessment can help to determine the most appropriate closure measures, ranging from passive water treatment and habitat restoration to more active interventions such as landform reconstruction and tailings reprocessing.

A flexible, adaptive approach allows closure plans to evolve over time, based on new information, monitoring data and changing environmental conditions. This approach recognises that mine sites are dynamic systems and that closure is not a one-off event but a long-term process that requires ongoing evaluation and adjustment. For example, the Wismut mining company in Germany implemented an adaptive closure strategy involving continuous monitoring of water quality and tailings containment systems, and adjustments to closure methods, as rehabilitation progressed (Schmidt et al. 2009; Federal Ministry for Economic Affairs and Climate Action, Federal Institute for Geosciences and Natural Resources 2023).

The application of adaptive management principles can help to ensure that closure is responsive to evolving risks and that mine operators can address unforeseen challenges as they arise. By integrating monitoring programs into closure plans, mine owners and regulators can make data-driven decisions about whether further interventions are necessary and whether the closure strategy is achieving its long-term objectives.

9 Conclusion

Applying contemporary closure standards to legacy mine sites presents complex challenges that require a multifaceted approach. Contemporary geotechnical and environmental standards, while essential for the design of new and developing mining operations, often pose significant barriers when applied to legacy sites with pre-existing limitations in both design and financial provisioning. A flexible, risk-based approach coupled with the ALARP (as low as reasonably practicable) principle can provide a pathway forward for closing legacy mines in a manner that is both technically sound and economically feasible. A methodology is required that integrates analysis of risks, opportunities and impacts.

Through the application of alternative closure strategies, such as in situ stabilisation, passive treatment systems and adaptive landform reconstruction, regulators and mine owners can achieve environmental, geotechnical and economic goals without imposing excessive financial or environmental burdens. Furthermore, the integration of financial assurance mechanisms and a focus on future land uses can help to ensure that legacy mines are closed in a manner that protects both social and natural capital.

Ultimately, by embracing a risk-based, adaptive management framework that considers site-specific conditions and long-term sustainability, regulators can ensure that legacy mines are effectively and responsibly closed, leaving behind a legacy that is not only safe but also beneficial to the surrounding communities and ecosystems.

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