

Navigating uncertainty: towards resilient cost estimation in mine closure

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Abstract

Mine closure has evolved from a linear, end-of-life engineering task into a dynamic, multidisciplinary process integrated across the mining lifecycle. The increasing complexity of closure, driven by regulatory changes, socio-economic volatility, stakeholder expectations and climate change, has rendered traditional cost estimation models inadequate. This paper advocates for a resilient, adaptive approach to mine closure costing, positioning it as a strategic function capable of managing uncertainty and unlocking long-term value.

We propose a shift from deterministic, engineering-centric cost estimation methods to adaptive, lifecycle-aligned models. By integrating probabilistic techniques, scenario planning and stakeholder engagement, mining companies can reduce cost uncertainty and improve transparency to support more informed decision-making. Key recommendations for practitioners and stakeholders emphasise the use of risk-informed methodologies, the mainstreaming of progressive closure, and the integration of social transition and land use considerations into cost estimates.

Ultimately, this paper argues that embracing uncertainty in cost estimation not only achieves compliance but fosters regenerative and community-aligned closure strategies, positioning mine closure as an opportunity for building resilience and legacy.

Keywords: *mine closure, cost estimation, uncertainty, probabilistic techniques, scenario planning, resilience, regenerative strategies, community alignment*

1 Introduction: navigating complexity and uncertainty in closure planning

Mine closure has transformed into a multifaceted, cross-disciplinary process that begins during the operational phase and extends well beyond the mine's productive life. It encompasses rehabilitation, infrastructure decommissioning, residual risk management and post-mining socio-economic transformation (International Council on Mining and Metals [ICMM] 2019; Department of Mineral Resources and Energy [DMRE] 2022).

The growing number of companies facing significant financial exposure due to underestimating closure liabilities has laid bare the limitations of traditional cost estimation models. These models, often rooted in deterministic, engineering-centric assumptions, struggle to accommodate the complex and evolving realities of mine closure, particularly amid rising costs, regulatory tightening, volatile operating conditions and increasing stakeholder scrutiny.

This paper argues for a fundamental shift: closure cost estimation must move beyond compliance-based frameworks towards flexible, scenario-driven models that support informed financial decision-making. Inadequate cost forecasting can result in under-provisioning, while overestimations tie up capital unnecessarily. A risk-informed approach, underpinned by adaptive financial modelling, is essential to manage uncertainties and ensure capital allocation aligns with both closure obligations and business resilience.

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2 Understanding the nature of uncertainty in closure cost estimation

Uncertainty is a defining feature of mine closure planning, particularly in cost estimation. Factors such as long timeframes, shifting environmental conditions and socio-political volatility intersect to complicate forecasting (Laurence 2006). Early-stage closure plans are marked by broad uncertainty bands, and driven by incomplete data, undefined closure criteria and unpredictable stakeholder expectations.

A key driver of this uncertainty is the extended duration of closure responsibilities, which often spans decades. Over this period, macro-economic, regulatory and climatic changes can render early assumptions obsolete. Unplanned or premature closures exacerbate this uncertainty by compressing timelines and forcing rushed decisions, often with incomplete baselines (Fourie 2009).

Furthermore, evolving expectations around environmental rehabilitation, post-mining land use and social responsibility now demand multidisciplinary, adaptive responses. These layers of complexity cannot be adequately addressed through static legacy models, which often overlook key cost drivers such as post-mining water treatment, long-term monitoring or socio-economic rehabilitation (ICMM 2019; DMRE 2022).

2.1 Framing the issue: why uncertainty and complexity dominate closure cost estimation

Several factors contribute to the complexity and unpredictability of closure cost estimates:

- **Extended time horizons:** the lifecycle of mine closure often extends over several decades. Over this period, external conditions such as macro-economic shifts, regulatory frameworks, environmental baselines and technological advances can change dramatically, rendering early assumptions obsolete and adding significant uncertainty to long-range planning.
- **Unplanned or premature closure:** sudden shutdowns, whether due to economic downturns, regulatory enforcement or unforeseen risks, often leave insufficient time for proactive closure planning. This increases the risk of underestimating closure liabilities and exposes operations to increased financial, environmental and reputational consequences.
- **Interconnected and evolving risks:** closure now requires integrated responses across environmental, legal, financial, technical and socio-economic domains. These dimensions are becoming more complex, with heightened scrutiny from regulators and stakeholders. Their interactions are increasingly non-linear and unpredictable, demanding adaptive and cross-disciplinary planning approaches.
- **Ambiguity in closure criteria:** there is often a lack of clarity around what constitutes successful closure, whether in terms of ecological function, groundwater quality or post-closure land use. This uncertainty complicates the development of realistic closure scopes and budgets.
- **Terminological inconsistencies and approaches:** the absence of standardised definitions and frameworks across jurisdictions, regulatory bodies and companies results in fragmented understandings of key concepts such as 'rehabilitation', 'reclamation', 'remediation' and 'closure success'. These inconsistencies hinder alignment in planning, costing and evaluation efforts, introducing risk into compliance and execution.
- **Subjectivity and bias in cost estimation:** closure cost estimates are highly subjective and influenced by the experience, mindset and risk tolerance of the individual preparing them. Even when using the same methodology, different practitioners are likely to produce varied results due to their interpretation of key drivers and requirements, assumptions surrounding known information and data gaps, and differing levels of optimism or caution. These uncertainties, not always transparently managed or calibrated, can significantly affect the accuracy of closure liability estimates.

- Legacy knowledge gaps: many older or inactive operations suffer from inadequate data records. Gaps in environmental, engineering or operational history can severely limit the accuracy of closure planning and cost estimation.
- Evolving regulatory and stakeholder expectations: evolving norms increasingly demand more inclusive, transparent and future-proof closure strategies. In many cases these expectations are applied retroactively, especially in jurisdictions undergoing legislative reform or public scrutiny.
- Global disruptors and trends: climate change adaptation, circular economy initiatives, just transition frameworks and biodiversity restoration targets are introducing new risks and opportunities into closure planning.

These multidimensional uncertainties lay the foundation for why closure cost estimation remains inherently complex and unpredictable. While these challenges span technical, environmental, social and regulatory domains, one of the most volatile and consequential layers is financial uncertainty – a domain that directly impacts provisioning, execution feasibility and long-term liability management. This is explored in detail in the following section.

3 Financial uncertainty and volatility

Among the various risk domains affecting mine closure, financial volatility exerts the most immediate and tangible influence on closure cost forecasting. Cost estimation models are particularly vulnerable to shifts in unit rates, inflation, contractor pricing, labour costs and compliance-related premiums, which can rapidly undermine long-term financial assumptions (International Network for Acid Prevention 2017). Without regular updates and sensitivity testing, cost models may become obsolete, contributing to systemic under-provisioning.

In markets with high economic volatility, unit rates fluctuate unpredictably. Cost escalations due to heightened safety standards, evolving regulatory expectations or inflation in contractor pricing must be reflected in closure estimates to maintain financial readiness (Stacey et al. 2010). During commodity price downturns, rehabilitation is often deferred or deprioritised, compounding closure liabilities and risk. Additionally, for jurisdictions reliant on imports, currency depreciation can significantly inflate material and equipment costs, further challenging cost forecasts.

Discounting practices and inconsistencies in financial assumptions, especially in multinational portfolios, can obscure liability visibility. Equally, site-specific conditions such as acid mine drainage (AMD), tailings instability or entrenched community dependency introduce bespoke cost implications that generic cost schedules often overlook (Younger 2002). These dynamics emphasise the need for tailored, site-specific and risk-adjusted models.

Investor scrutiny is intensifying. Closure liabilities perceived as vague or underreported can attract shareholder activism, delay project approvals or affect credit ratings. Stakeholder expectations now demand transparent, frequently updated and technically defensible closure costing frameworks (Principles for Responsible Investment [PRI] 2021).

4 Navigating from compliance to resilience: evolving the purpose of closure costing

Traditional closure cost estimation approaches have historically centred on minimum compliance, emphasising regulatory sufficiency over strategic insight. While these models fulfilled regulatory expectations, they rarely supported adaptive planning or financial resilience. This is changing. Contemporary mine closure planning must shift from static compliance tools to decision-useful frameworks embedded across the mine lifecycle.

The evolution from compliance toward resilience includes adaptive and risk-based thinking. Cost estimation must serve a broader function: to enable informed trade-offs, support capital planning and assess financial risks over multiple time horizons.

4.1 Historical gaps in compliance-based models

While South Africa's 2005 DMR Financial Provisioning Guidelines advanced closure planning at the time, they emphasised compliance over contextual accuracy. These models employed generic unit rates and assumed uniform closure scopes across diverse assets, leading to under-costing of key liabilities such as AMD treatment, reshaping of legacy residue facilities and socio-economic transition (Stacey et al. 2010). As a result, infrastructure and environmental legacies, especially at unlined tailings facilities, were under-accounted for, with long-term water treatment obligations excluded from early-stage closure financial planning.

Other jurisdictions, such as Western Australia and Ontario, have adopted more risk-aware frameworks. These systems require progressive rehabilitation, stakeholder engagement and regular cost updates linked to relinquishment pathways. While they provide a useful benchmark, challenges remain in their execution and enforcement (Younger 2002).

4.2 Integrating adaptive, risk-based costing approaches

A more strategic approach to closure costing emphasises probabilistic tools, technology integration and scenario-based testing. These include:

- probabilistic modelling and Monte Carlo simulations to quantify uncertainty and provide a range of potential cost outcomes, supporting more defensible provisioning (Rocscience 2023)
- remote sensing and geospatial analysis to monitor landform evolution, vegetation recovery and erosion risk, enabling real-time updates to rehabilitation performance assumptions, which directly influence cost projections by adjusting rehabilitation schedules and resource allocation (Bullen et al. 2020)
- digital twin technologies and GIS-integrated closure models, allowing for dynamic scenario testing and spatially explicit cost tracking over time, improving cost forecasting accuracy by simulating different closure scenarios and adjusting for spatial variances in rehabilitation
- multi-scenario planning frameworks that incorporate a range of potential future states (e.g. climate variability, commodity market shocks or delayed relinquishment), testing financial robustness by modelling the impact of these variables on closure costs and timelines
- integrated environmental, social and governance (ESG) alignment, ensuring closure planning supports broader sustainability goals such as social transition, biodiversity restoration and water stewardship while accounting for potential additional costs related to regulatory compliance, stakeholder engagement and long-term environmental management.

By anchoring closure cost estimates in risk-based frameworks and flexible modelling tools, mine operators can more accurately align financial provisioning with actual risk exposure, enhancing closure credibility, capital planning and stakeholder trust. For example, landform and erosion design alternatives can be modelled and costed under various long-term climate scenarios. Each scenario can be assigned a likelihood weighting based on available data and expert judgement. Probabilistic modelling, such as Monte Carlo analysis, can then be applied to identify the cost-risk intersection point, typically represented by a median or P50 estimate. This approach enables more defensible and adaptive closure costing, grounded in both scientific modelling and real-world uncertainties.

4.3 The resilience imperative

Despite advancements in closure planning, many jurisdictions continue to rely on outdated cost schedules rooted in historical norms and static guidelines. These traditional models often fail to account for key dynamic factors such as market volatility, evolving regulatory requirements and infrastructure degradation over time. Moreover, in cases where clear relinquishment pathways are absent, unresolved liabilities (such as those related to long-term water treatment, land remediation or social disruption) persist, thereby increasing the operator's long-term financial and reputational exposure.

A resilient financial model is forward-looking and adaptive. It incorporates the flexibility to absorb unforeseen shocks, whether economic, environmental or social, and adjust provisions based on new data, changing risk profiles or regulatory shifts. Key features include:

- Probabilistic risk integration: incorporating uncertainty through probabilistic modelling techniques (e.g. Monte Carlo simulations) enables quantification of a range of potential costs rather than a single-point estimate, allowing contingency planning for low-probability, high-impact events.
- Dynamic data inputs: resilient models continuously integrate updated operational, environmental and social monitoring data to refine cost projections in near real-time, supporting adaptive management.
- Scenario-based forecasting: by testing multiple closure pathways and regulatory scenarios, these models identify cost implications under different futures, ensuring financial provisioning remains robust across plausible conditions.
- Stakeholder engagement alignment: incorporating feedback from regulators, communities and investors into cost assumptions fosters trust and improves model relevance and acceptance.

5 Embracing the boundaries: reframing closure costing as a strategic enabler

As the mine closure landscape becomes increasingly complex, closure cost estimation must be reframed not merely as a budgeting tool but as a strategic enabler of long-term value creation and risk governance. Moving beyond deterministic models and static projections, closure costing should be positioned within a broader systemic approach that considers historical legacies, evolving socio-ecological risks and intergenerational obligations (Van Zyl et al. 2017).

Legacy infrastructure such as unlined tailings dams and ageing water system represent more than technical liabilities; they are deeply embedded in dynamic systems that include regulatory shifts, land use transitions and social expectations. Addressing these complexities requires models that accommodate variable timelines and integrate catchment-wide feedback, rather than isolated engineering assumptions (Keneally & McCullough 2023).

This systemic framing demands a mindset shift. Closure must be seen as part of a continuum of stewardship and regeneration where financial models not only provide for liabilities but actively support adaptive, resilient outcomes.

For example, instead of viewing a waste dump solely as a final liability requiring capping and vegetation at its end of life, a regenerative approach would use dynamic modelling to assess real-time erosion, revegetation success and material availability throughout the mine life. The financial model would then provision adaptively, redirecting surplus in the rehabilitation budget from overperforming areas to underperforming ones, or facilitating investment in landscape-level interventions that deliver both compliance and community co-benefits, such as water harvesting or grazing corridors. In this way, the closure fund becomes a living tool not a static reserve – supporting continuous improvement and risk reduction while enhancing long-term environmental and social value.

6 Designing adaptive and flexible costing frameworks

In the context of growing environmental volatility, socio-economic flux and rising stakeholder scrutiny, resilient mine closure requires more than static cost models or deterministic budgeting. Instead, it demands the design of adaptive and flexible costing frameworks that not only respond to uncertainty but actively leverage it to enhance decision-making and long-term risk governance.

These frameworks serve a dual function: first, as tools to dynamically adjust financial provisioning in response to changing site conditions; and second, as strategic enablers that align closure funding with broader

sustainability, compliance and social licence objectives. This section outlines four interdependent components of such frameworks.

6.1 Dynamic modelling with real-time data inputs

Traditional closure cost estimates are typically derived from a static set of assumptions captured at a fixed point in time. This approach can become rapidly outdated as site conditions evolve due to factors such as unexpected rainfall events, geotechnical instability, changing regulatory expectations or shifting socio-economic contexts.

In contrast, dynamic modelling frameworks integrate real-time environmental, engineering and socio-economic monitoring data into continuously updating cost models. These adaptive systems establish ongoing feedback loops that enable proactive risk tracking, real-time rehabilitation progress monitoring and timely recalibration of forecasts (ICMM 2019). This improves the accuracy and responsiveness of closure cost estimates and supports more agile decision-making.

However, many closure cost drivers are inherently interdependent; for example, changes to landform design affect material movement volumes, which in turn influence water management requirements, cover system selection and revegetation timelines. Dynamic models must therefore account for these interconnected cost levers, ensuring that adjustments in one domain are appropriately reflected across related components.

Advanced modelling platforms achieve this by linking parameters through scenario-based simulations, enabling planners to test the cascading effects of proposed changes. This systemic approach mitigates the risk of isolated or misleading cost adjustments, enhancing the robustness of forecasts and supporting more informed closure planning and provisioning.

6.2 Scenario-based planning for flexibility

Future conditions at closure cannot be predicted with certainty, but they can be systematically prepared for. Scenario-based planning introduces structured foresight into financial provisioning by modelling high-, medium- and low-cost futures. These scenarios incorporate variables such as long-term water treatment needs, land use transitions, legal liability exposure and socio-political shifts, including climate change and regulatory reform (Van Zyl et al. 2017). By assigning confidence levels and cost ranges to each scenario, planners can better assess the likelihood and scale of liabilities and ensure that funding strategies are robust across a spectrum of plausible futures.

Mine planning is often treated as a separate function from, and therefore unimpacted by, closure planning and its associated cost, whereby the cost of closure is simply deducted from the operational value achieved by the mine rather than being integrally incorporated into the planning process (Nehring & Cheng 2016). Progressive or operational rehabilitation is often also de-prioritised in favour of achieving short-term production indicators. However, experience has shown that integrating operational rehabilitation and closure planning and costs into day-to-day mine planning may provide the opportunity for cost optimisation scenario evaluation. For instance, targeted waste material deposition guided by a mine residue facility final closure landform design conducted in parallel with final shaping and progressive rehabilitation can result in significant cost reductions if scheduled appropriately (Levinson & Dimitrakopoulos 2024).

Continuous progressive rehabilitation conducted as part of standard mining operation rather than being implemented piecemeal is more likely to effectively utilise the mine's operational fleet and resources, cutting down on mobilisation, maintenance and running costs. Additionally, front-ending rehabilitation execution creates the opportunity for longer rehabilitation trialling, monitoring and aftercare, and achieving a greater consistency of outcomes and, ultimately, a better overall result. Conversely, while implementing site-wide rehabilitation only at the time of closure may result in a greater financial economy of scale through targeted and efficient use of the mine fleet over a short period of time, it runs the risk of relying on untested rehabilitation strategies and limited trial data to support the approach. Robust and iterative scenario planning

and testing, informed and refined by operational trial data, allows mines to identify the optimal approach from an operational and cost-efficiency perspective without sacrificing environmental quality outcomes.

6.3 Continuous improvement

Adaptive closure costing is not a one-time exercise but rather a continuous process. Iterative frameworks enable cost models to evolve in parallel with progressive rehabilitation, engineering feedback and community engagement. As new information becomes available, whether through pilot trials, environmental audit results or shifting community expectations, cost assumptions must be regularly revisited. This ongoing refinement fosters greater accountability, improves transparency for regulators and investors, and ensures cost models reflect site realities rather than static assumptions (ICMM 2019). Regular iteration also allows for earlier identification of cost-saving opportunities and improved alignment with end land use visions.

6.4 Designing for uncertainty: embedding resilience into financial logic

Uncertainty is a defining characteristic in mine closure planning rather than a peripheral consideration. Resilient financial frameworks should be designed to accommodate this uncertainty rather than attempting to eliminate or avoid it. Tools such as sensitivity analysis, probabilistic risk assessment, and Monte Carlo simulations are used to stress test key assumptions and identify cost tipping points for high-risk closure aspects such as long-term subsidence in undermined areas or extended water treatment requirements.

These techniques enable the calculation of upper-, median- and lower-bound cost scenarios, with scenario weightings informed by the relative likelihood and significance of contributing factors. Averaging across multiple simulation runs provides a more representative and defensible basis for financial provisioning. This approach supports transparent, data-informed decision-making while reducing exposure to unforeseen liabilities.

In parallel, the use of flexible financial instruments such as contingency reserves and phased drawdown mechanisms further strengthens the system's resilience. These tools ensure that funds can be accessed in alignment with closure milestones and emerging needs, preventing both over- and under-provisioning (Keneally & McCullough 2023). Together, these strategies promote adaptive financial planning that is both robust to change and aligned with regulatory and fiduciary obligations.

7 Overcoming organisational barriers to effective cost estimation

Resilient closure costing is often hindered by organisational constraints including short-term budgeting, siloed operations and knowledge fragmentation:

- Budget pressures. Arbitrary cost cutting often undermines the realism of closure plans. Financial provisioning should be framed as a long-term investment that supports compliance and stakeholder trust (Mackenzie 2012)
- Fragmented planning. Siloed departments inhibit integrated planning. Embedding closure into the broader asset lifecycle requires shared platforms and cross-functional governance (ICMM 2019)
- Knowledge discontinuity. Institutional memory loss due to staff turnover weakens costing integrity. Establishing knowledge management systems and documentation protocols is critical for continuity (ICMM 2019).

8 Communicating uncertainty with purpose

In the context of mine closure, uncertainty is not only a technical challenge but also a communication challenge. Effectively conveying uncertainty, rather than concealing or oversimplifying it, can enhance stakeholder trust, strengthen regulatory confidence and support a long-term licence to operate. Rather than undermining credibility, transparent and purposeful communication of uncertainty demonstrates strategic foresight and responsible stewardship.

8.1 Assumptions transparency

Clear documentation of model assumptions, input parameters, data sources and confidence levels is critical. This includes disclosure of the basis for unit rates, time frames for post-closure liabilities, dependencies between cost elements (e.g. how vegetation success affects erosion control) and limitations in available data. Transparency in these areas improves credibility during regulatory reviews, enhances investor confidence and is increasingly viewed as a minimum expectation in ESG reporting frameworks (ICMM 2019). Articulating the ‘knowns’ and ‘unknowns’ helps stakeholders understand where professional judgement has been applied and where future updates may be needed.

8.2 Stakeholder alignment

Scenario-based planning and proactive disclosure of uncertainty enable better alignment with stakeholders’ evolving expectations, particularly regarding climate resilience, social transition and financial assurance. As environmental and social risk becomes more material to investment and reputational value, stakeholders (including communities, regulators and financiers) expect full visibility of latent liabilities and their potential future impact (PRI 2021). Engaging stakeholders early and consistently on key uncertainties (e.g. long-term water treatment needs, land access, infrastructure repurposing) promotes co-ownership of solutions and reduces the risk of future conflict or mistrust.

8.3 Evidence-based confidence

Rather than relying on isolated estimates or single-point assumptions, closure cost inputs should be supported by triangulated evidence such as benchmarking against peer operations, trial or pilot project data and multidisciplinary expert opinion. Confidence intervals (e.g. P50, P90) should be presented where appropriate to reflect uncertainty ranges. This enhances the robustness of internal decision-making and improves audit readiness as auditors and regulators increasingly scrutinise the traceability and defensibility of closure liability estimates (ICMM 2019). Demonstrating that key assumptions are supported by data and regularly reviewed signals that the organisation is proactively managing uncertainty, not simply reacting to it.

8.4 Visual tools for engagement

In mine closure planning the ability to clearly communicate complex technical and financial data is as critical as the data itself. Visual tools help translate uncertainty into decision-relevant insights, making them accessible to diverse stakeholders including executives, regulators, communities and investors, who may not have technical expertise but are instrumental to closure success. These tools include:

- Interactive dashboards. These consolidate large datasets and enable users to dynamically explore closure scenarios, cost drivers and timelines. Dashboards enhance transparency and support real-time sensitivity testing and ‘what-if’ analysis, making uncertainty more tangible and engagement more interactive
- Monte Carlo simulations. By providing a probabilistic view of outcomes based on input variability, Monte Carlo outputs (e.g. histograms, cumulative probability curves) support more nuanced communication of financial or environmental risks. These visualisations help stakeholders grasp not just expected costs but the full range of possible outcomes and their likelihoods
- Scenario visualisation tools. GIS-enabled maps, time-sequenced flow diagrams and 3D landform models show how different closure scenarios may evolve over time and space. These tools are especially powerful for illustrating concepts such as landform evolution, water flow paths and post-closure land use, helping stakeholders visualise both the risks and opportunities of different decisions
- Infographics and decision trees. These tools distil complex regulatory, environmental or social processes into simple, approachable formats. They are useful for mapping trade-offs between

closure options, explaining regulatory pathways, or illustrating social transition strategies in a format that supports broader understanding and alignment.

Visualisation software such as Power BI, ArcGIS and 3D mine planning platforms, along with scenario-modelling engines like GoldSim or @Risk, are increasingly used in the industry to support this level of engagement. These tools complement probabilistic modelling by improving transparency and supporting informed, inclusive decision-making.

9 Rethinking closure cost estimation for a complex future

9.1 Key shifts in practice

Emerging trends to redefine closure cost estimation are as follows:

- Move beyond engineering assumptions to include social, legal and environmental risks.
- Accept and model uncertainty using probabilistic tools.
- Reframe closure as an opportunity for ecological and economic regeneration.
- Embed closure in mine planning to spread costs and reduce risk (Van Zyl et al. 2017).

9.2 Strategic recommendations for key stakeholders

For mining companies:

- Adopt adaptive, risk-informed costing frameworks. Use AACE Class 3 or 4 methodologies, integrate cost-risk registers and apply probabilistic tools to reflect closure uncertainty more accurately.
- Incorporate social transition into costing. Include costs related to livelihood restoration, community infrastructure handover, workforce retraining and health services in closure estimates.
- Institutionalise progressive closure. Treat closure as a continuous process throughout the life of the asset, enabling iterative learning, improved forecasting and early issue resolution.

For regulators:

- Mandate transparent and risk-contingent estimates. Require disclosure of key assumptions, data confidence levels and contingency rationales, especially for high-uncertainty items such as long-term water management or tailings stability.
- Align closure with development objectives. Ensure that closure frameworks support national and regional development plans to avoid misaligned land use, stranded assets or long-term liabilities.
- Incentivise progressive rehabilitation. Use tax, permitting or reporting incentives to reward early and ongoing closure works.

For practitioners and advisors:

- Foster integrated and contextual design. Closure plans should balance technical feasibility with local socio-economic and ecological realities, from early feasibility through to relinquishment.
- Deepen stakeholder participation. Engage stakeholders in cost-relevant decisions, especially in defining land use options and community transition pathways.
- Leverage data and emerging tech. Apply geospatial tools, predictive analytics and real-time monitoring to refine assumptions and update cost models responsively.

10 Conclusion: final reflection – embracing uncertainty as strategic opportunity

Uncertainty need not be feared. In a world shaped by systemic risks and climate, socio-economic and geopolitical uncertainty, resilient closure cost estimation must become a core pillar of responsible mining. By embedding adaptability and transparency into costing practices, the sector can unlock long-term value, build trust and support meaningful regeneration.

Closure is not an end – it is the foundation for transformation.

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