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# A quarter century as a mine closure practitioner: landform design lessons to inform the future

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## Abstract

*Landform design should be recognised as an inter-disciplinary process that ideally commences prior to the onset of mining. At the project development stage – including during preliminary economic assessments – strategic planning should explicitly incorporate the design of landforms. Infrastructure such as tailings storage facilities (TSFs), mine rock stockpiles (MRSs), open pits, and heap leach facilities must be conceptualised as landforms from the outset, well before ground disturbance occurs.*

*This approach reflects the principle of 'designing for closure', introduced by John Gadsby in the 1970s and elaborated in his seminal 1990 publication. This design philosophy should extend seamlessly through construction, operation, closure, and post-closure, providing a framework for land stewardship, and a journey of continuous improvement, as the mining lease transitions between successive land uses throughout the asset's life cycle. Despite the maturity (or at least longevity) of this concept, it remains insufficiently embedded in the operational culture of the mining industry, leading to an analogous question: is mine closure planning institutionalised in the mining industry to the same degree as safety or TSF management?*

*Awareness and adoption of integrated mine closure practices have advanced over the past four decades, yet a persistent disconnect remains. In most cases, integration between mine planning and closure planning occurs late in the life of mine – if not post closure – resulting in operational inefficiencies, regret costs, and underfunded closure liabilities. This occurs despite longstanding regulatory frameworks mandating closure and reclamation planning, including progressive closure and reclamation.*

*In this paper, key developments in landform design and mine closure are synthesised from representing nearly a quarter century of actionable, experience-based insights, to strengthen the implementation of an integrated closure design philosophy. Central to these insights is the development of a co-created (i.e. including all stakeholders and rightsholders) closure vision for each site – whether a new project, active operation, or legacy asset – which serves as a consistent strategic thread throughout the asset's life cycle. Further, the governance structures currently applied to safety and TSFs, such as systems, processes, and lines of accountability, must be extended into the concept of 'designing for closure' across the landscape. This would include all domains and landforms within these domains, such that governance for mine closure replicates that which exists for safety management and 'safe closure' of TSFs. Both technical and non-technical considerations are addressed to support the operationalisation of this integrated closure approach.*

**Keywords:** *closure vision, design for closure, integrated mine closure, transition, landform design, stakeholder engagement, land stewardship, future land use, post-mining land use*

## 1 Introduction

The International Institute for Sustainable Development defines closure as a multifaceted process involving community engagement, site reclamation, and support for post-mining community resilience (Stevens et al. 2022). The International Council on Mining and Metals (ICMM 2025) describes integrated mine closure as a

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dynamic, iterative process that incorporates environmental, social, and economic considerations from the outset of mine development. It emphasises closure as a core business function and provides structured guidance through its *Good Practice Guide*. Despite this guidance, there is no universally accepted, jurisdiction-neutral definition for 'good' mine closure.

Over the past quarter century, mine closure practices have advanced significantly. Historically viewed as an afterthought, the concept of closure was often synonymous with abandonment. Closure now involves deliberate planning and funding with most jurisdictions requiring financial assurance to support closure execution and, increasingly, post-closure monitoring and maintenance. Despite this progress, integration of closure into the full mine life cycle is still often viewed as leading[1] rather than best[2] practice.

Progressive closure and reclamation – closely aligned with integrated mine closure – are widely regarded as best practice in the mining industry. They involve the systematic rehabilitation of disturbed land during mining operations, rather than deferring all activities until after closure. Definitions and practices from five jurisdictions illustrate this global recognition:

- British Columbia: reclamation conducted concurrently with mining to support end land use objectives.
- Australia (Queensland and national): national guidelines promote early integration of closure. Queensland's progressive rehabilitation and closure plan outlines a staged process for progressive rehabilitation throughout the mine life.
- Peru: regulations mandate progressive reclamation during operations, with adaptive planning and early implementation (e.g. waste rock dumps rehabilitated ~4 years pre-closure).
- South Africa: legal requirements call for ongoing rehabilitation during operations to restore land to intended use and meet environmental obligations.
- United States of America: under the Surface Mining Control and Reclamation Act of 1977 (United States of America 1977), reclamation (e.g. topsoil replacement, revegetation) must occur promptly after mining in each area, ensuring progressive land restoration for post-1977 regulated mines; an extensive and expensive, separate program funded by the active mines addresses reclamation and closure for the older, unregulated mines.

Despite clear guidance, progressive closure and reclamation is often lacking in practice, especially when dependent on a site's operational fleet, as use of this equipment can be in conflict (i.e. cash flow from production versus cost to progressively execute rehabilitation programs). This is less a technical issue, or a 'values' issue, and more a reflection of poor alignment between mine planning outcomes (ore delivery) and closure planning outcomes (longer-term liability and risk). The root cause is typically a failure by closure practitioners to demonstrate the value of progressive closure to mine planners and business decision-makers. Based on the author's experience, common symptoms of this misalignment are as follows:

- Lack of alignment: closure teams often struggle to get operational support, with a common lament being, "How do I convince them to consider tomorrow's risk today?". Closure actions are frequently deprioritised in discounted cash flow models.
- Material and system imbalances: operational water, material, and energy balances often fail to transition to closure conditions, leading to significant post-closure imbalances.

[1] Leading practice: goes beyond currently understood best practice and refers to innovative, forward-thinking approaches that set new benchmarks, whose application is considered to be more expensive, not widely adopted, and generally recognised in voluntary frameworks (e.g. International Council on Mining and Metals).

[2] Best practice: refers to widely accepted, proven, and effective methods established through experience and research, which represents the current standard for achieving compliance and good performance.

- Inexecutable closure plans: many closure plans lack the granularity needed to justify progressive implementation. As a result, they remain conceptual and rarely ready for execution.
- Unproven technology dependence: closure plans may rely on untested or unregulated technologies without adequate research and development support, signalling poor readiness.
- Unrecognised and underfunded liabilities: most critically, lack of executable closure plans results in unforeseen liabilities, often manifesting as water quality issues requiring long-term collection, conveyance, storage, and treatment, and/or the requirement to move large volumes of material long distances to achieve required rehabilitation outcomes.

# 2 An analogy to mine closure and the need for growth and change

The author's experience from over a quarter century visiting mine sites around the world offers insight with respect to advancement of a culture around mine closure. Further, it affords the author opportunity to appreciate and compare to changes in culture around safety in the mining history. For example, at one of the first mine sites visited in the mid-1990s, the safety slogan was 'zero harm'; more recently, the safety slogan has evolved to 'towards zero harm' at that same mine site. The change reflects the maturation of safety within the mining industry where 'good safety' has changed from being a 'destination' (i.e. zero harm) to a 'journey of continuous improvement' (i.e. towards zero harm).

Dekker (2011) defines safety as "…not the absence of incidents…it is the presence of adaptive capacity…". In other words, safety is not just avoiding things going wrong, but rather the presence of systems and organisations that can anticipate, adapt, and respond to unexpected events. More specifically, to highlight the contention that there is no universally accepted, jurisdiction-neutral definition for mine closure, Dekker's definition of safety reflects a perspective rooted in resilience engineering, a principle that where "…the capacity to cope and adapt to variability, surprises and complexity is central to maintaining sage operations…". Dekker's definition focuses on people and systems to bring about success under pressure, rather than compliance and control.

A mining company in the Western free-market tradition is generally in business to turn 'natural' capital into financial capital by extracting resources in a way that generates consistent economic return while managing risk and meeting regulatory and legal obligations across the asset's life cycle. Hence, what is 'core business' to mining companies is the extraction and sale of mineral resources to maximise acceptable return on investment (as well as increasing shareholder value through dividends, capital gains, and stock price appreciation). This is accomplished by delivering sustainable free cash flow which funds operations, pays down debt, finances capital projects, and supports dividends or share buybacks; sustainable free cash flow is essential for long-term viability and investor confidence. Thus, the argument remains that the status quo for mine closure is that it is not 'core business' in the mining industry because the mining industry's lived experience is that mine closure does not provide a readily identifiable return on investment to a mining company.

Substantive change can be brought about via several means, such as a traumatic experience (i.e. systems failure) or when conditions force the change (such as regulatory or changed societal expectations). Substantive change in the industry requires not only organisational change but change on a personal level. Trauma is not a necessary nor exclusive condition for meaningful personal transformation, although it often does bring change. Substantive personal change can also arise from positive experiences, including the birth of a child, love, spirituality, as well as other key and meaningful aspirational life changes. In short, people, and ultimately organisations, can embrace growth and change proactively, while others only respond when conditions force the change.

The substantive response of key mining industry investors to tailings storage facility (TSF) failures is reflective of a 'forced' condition on the mining industry resulting from a traumatic experience in order to bring about change. A particular example would be when the Church of England Pensions Board, alongside the Council on Ethics of the Swedish National Pension Funds, spearheaded the Investor Mining and Tailings Safety

Initiative (Church of England 2019) in response to an increasing number of TSF failures, most notably the catastrophic Brumadinho disaster in Brazil in January 2019. The initiative's objective was to enhance safety and transparency of tailings management in the mining industry and included over 100 institutional investors managing more than USD 25 trillion in assets.

As part of the Investor Mining and Tailings Safety Initiative, several key actions were undertaken by the mining industry which included disclosure requirements, creation of a global TSF database, increased shareholder engagement, and perhaps most notable for operators and practitioners in the industry, the development of a global standard (Global Tailings Review 2020). The Global Industry Standard on Tailings Management (GISTM) sets out the appropriate governance (systems, processes, accountabilities, people) for tailings management. Related to mine closure, GISTM defines 'safe closure' as: "…a closed tailings facility that does not pose ongoing material risks to people or the environment which has been confirmed by an ITRB [Independent Tailings Review Board] or senior independent technical reviewer and signed off by the Accountable Executive…".

Depending on perspective, it can be argued that the same level of 'trauma' is currently occurring in respect to mine closure but is not recognised among mining industry investors to the same extent as TSF failures. In every mining jurisdiction, and within many mining companies, there exists so called 'legacy sites', commonly referred to as abandoned sites, or sites that are in perpetual care and maintenance. There are very few, if any, mines – even modern ones that have gone through permitting and operations in the last two to three decades – where the importance of mine closure is widely recognised. These mines have rarely executed closure and achieved their closure objectives using cash flow from operations or even using diverted cash flow from other operations within the mining company to fund closure at the first site.

Incremental and positive change is occurring in the mining industry in respect to mine closure as a result of both traumatic experiences and forced initiatives, but mine closure is not, as of yet, part of the mining industry's culture. There is a need to proactively, and rapidly, develop the same focus on governance for mine closure, as was brought about by investors to the mining industry in response to TSF failures. Mining industry investors must lead this change, and mine closure must become part of the core business in the mining industry and part of mining culture in the same way that safety has evolved to become core business in the mining industry and culture.

Success in this endeavour would result from defining mine closure using the same framework Dekker uses for safety such that there is a universally accepted, jurisdiction-neutral, definition for mine closure. Such a definition may be initiated by defining 'mine closure' as:

- not the absence of things that go wrong
- not a destination
- not the absence of non-compliance, and/or
- not the absence of unrecognised and poorly funded liability.

Rather, 'mine closure' could be defined as:

- a site-specific and shared closure vision, as well as stewardship of the project to this shared vision, throughout its life cycle
- a journey of continuous improvement
- centred around land stewardship, or more simply
- centred around care of the land, and
- bringing opportunity to transition land such that closure provides a readily identifiable return on investment.

The above definition of mine closure explains the statement earlier herein that the GISTM definition for 'safe closure' is only part of mine closure. The GISTM Safe Closure definition makes no explicit reference to land stewardship.

Currently 'in vogue', and required in many jurisdictions, is that mining must focus on 'post-mining land use' or 'future land use' or 'end land use'. It is even common at current industry mine closure conferences to see the statement "we must begin with the end in mind", a statement popularised from Covey (1989). In his book, Covey states as Habit 2: "To begin with the end in mind means to start with a clear understanding of your destination. It means to know where you're going so that you better understand where you are now and so that the steps you take are always in the right direction." Application of this phrase to mine closure seems logical at first glance. However, the statement speaks specifically to 'an end' and 'a destination'. This is contrary to the definition of mine closure proposed here, in that if we apply Dekker's perspective, mine closure must be a continuous journey of improvement, and that closure of the mine is not the end land use, but rather the first step in the next part of its journey. There must be awareness, however, to not be fearful of 'starting' the journey, simply because we don't know exactly how to define the journey. We must focus on the vision, and the appropriate journey will emerge.

An application of this new definition can be seen when considering the shared closure vision co-developed for the Skeena Resources' Eskay Creek Revitalization Project (Baisley et al. 2023):

> *"To co-design and deliver integrated, respectful, and progressive mine closure and reclamation plans to re-establish the health of the Land and Tahltan way of being for future generations following the Land's temporary use."*

In defining such a closure vision, it establishes that mine construction and operations are simply a temporary use of the land, with care of the land for generations as the guiding principle to closure planning. This shared co-created closure vision speaks to land stewardship, or more simply care of the land – both of which are inclusive of land use transition, as is progressive mine closure and reclamation.

# 3 Integrated mine planning and mine closure: the what and how

There exist facets of mine closure, presented as questions, which build off the core issue of mine closure not being part of mining's culture and not core business, namely:

1. Is there a shared, globally applicable definition of what constitutes 'good' mine closure – one that isn't tied to any specific jurisdiction or regulatory system?
2. Are we aligned in how we identify and manage risks related to mine closure?
3. How well are we matching our decision-making tools to the complexity and timing of a project?
4. Is discounted cash flow analysis a useful tool for evaluating mine closure options and trade-offs?

The following sections address these questions.

## 3.1 A global definition for mine closure

The first question has been addressed in Section 2 of this paper; in short, there is no shared, globally applicable definition of what constitutes 'good' mine closure – one that isn't tied to any specific jurisdiction or regulatory system. As noted in Section 2, our industry tends to think of the symptoms of a lack of integrated mine planning and mine closure as being issues in of themselves. Perhaps, given that as closure practitioners we must 'move to' mine planners and better understand their constraints, a simpler definition of integrated mine closure is more applicable rather than the relatively complex definitions offered in guidance documents. A statement such as "integrated mine closure is the process of considering both the extraction plan and the closure plan concurrently, such that on an annual basis, a change to one plan should directly affect the other" would sufficiently capture the goal of closure plan and operation plan integration. The extent to which the closure plan 'health' is 'checked' can be determined on a site-specific basis. At the least, the specific experience has shown that this approach of an annual 'closure plan health check' brings the opportunity to substantially reduce the presence of unrecognised and poorly funded closure liability.

## 3.2 Alignment on identification and management of mine closure risk

This paper purposefully does not include substantive content on the question of whether or not we are aligned, meaning alignment between mine planning and mine closure, in how we identify and manage risks related to mine closure. The reality is such that very rarely can this question be answered with a definitive 'yes'. This alignment is a function of the discussion on the definition of mine closure and its relationship to land use; without this definition, alignment is nearly impossible. Perhaps more specifically it is because there are, in general, different 'groups' of people involved at different stages of an asset's life cycle each with different constraints and opportunities at each stage.

The International Network for Acid Prevention (INAP 2024) describes this issue from a Western free-market tradition as differences in 'decision drivers for change', which change throughout the asset's life cycle, as shown in Figure 1. Traditional mine planning prioritises maximising resource value and minimising cost and risk, with early-stage decisions driven by capital expenditure and near-term revenue. As projects progress, regulatory expectations shift from permitting to environmental compliance through operations and closure. Ideally, this creates a need for integrated closure planning from the outset to ensure cost-effective, sustainable outcomes across the mine life cycle. However, many projects overcompensate for uncertainty with layered conservatism, which can hinder risk optimisation. Regardless of design choices, clearly defining and communicating the project's risk profile as a whole, recognising that it can change during the asset's life cycle, is essential for informed sustainable decisions.

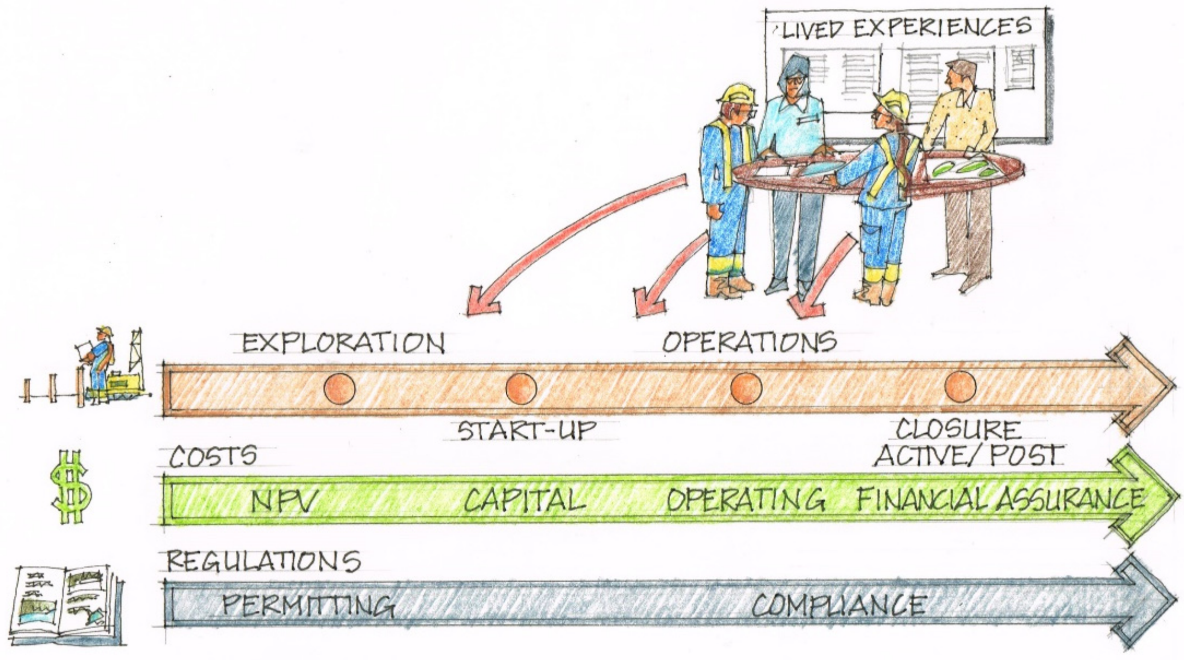


**Figure 1 Asset lifecycle risk identification and management considerations (INAP 2023). Illustration by D Shuttleworth**

The most compelling drivers for change are internal lessons learned, or 'lived experiences' – where poorly recognised operational and closure conditions and processes, and thus typically underfunded liabilities, have impacted project outcomes. In the absence of these lived experiences being applied, regulatory pressures will often push to being overly conservative and multiple levels of conservatism, while operational pressures can result in a failure to deliver on these promises. A structured and experience-based decision process can improve outcomes and reduce long-term liabilities.

## 3.3 Matching decision-making tools to project complexity and timing

Answering the question of how well we are matching our decision-making tools to the complexity and timing of a project requires insight and reflection for each phase of the project's life cycle. This author's experience is that early in project development, for example as part of developing a project description (PD) or when determining a preliminary economic assessment (PEA), there is often a rush to choose a singular design for a project component. A common mistake is the design team 'transferring a successful design' from a previous project, rather than applying/transferring the successful process of the successful design and applying site-specific controls on key mechanisms. Then, because this first 'design', is typically viewed as 'the design', it is very challenging to materially change the initial design as a result of the 'project development meat grinder'.

There are many mine design aspects of a PD which are also included as input to a PEA, and consideration of each of them would require substantial effort and case by case consideration in excess of the scope of this paper. As such, the example presented focuses on managing metal leaching and acid rock drainage (ML/ARD) risk during operations, in closure, and in post-closure. There can be ML/ARD risk from the presence of TSFs, MRSs, ore and low-grade ore stockpiles, heap leach pads, exposed pit walls, and underground workings; however, this paper speaks only to MRSs and TSFs. While global attention has been brought to TSFs due to headlines about the environmental and social disasters associated with tailings dam failures, acidity measured from more than 40 sites over the last 25 years illustrates that around 60–80% of the acidity generated at a mine site typically comes from the presence of MRSs (INAP 2020), with another 20–30% attributed to TSFs, the latter of which may at least partly come from mine rock used in the construction material of TSF dam embankments and starter dikes.

ML/ARD can emanate from mine landforms, such as TSFs and MRSs during construction, mine life, and following cessation of mining as a result of two foundational 'imbalances' created when a material that was below surface is placed on the surface within a TSF or an MRS; namely, a thermodynamic imbalance and a gravitational imbalance. The thermodynamic imbalance results from material that was in a reducing environment for the most part (i.e. sulphide minerals such as pyrite that formed at depth in the absence of oxygen), is placed into an oxidising environment (i.e. in an MRS or TSF). The gravitational imbalance results from meteoric water, as well as groundwater and run-on, landing on, and/or coming into/on to the mine landform. The system (the landform) continuously works from a state of higher potential energy to lower potential energy, physically and chemically.

The imbalances described above need to be defined for each landform as they are unique in time and space, and conceptual models of performance are a foundational step in the landform design process. This conceptual model of performance, which is foundational and must be developed reliably in light of site-specific empirical constraints, must be developed before any numerical modelling occurs. A conceptual model is a tool used to identify and outline key processes happening in a real-world system that the user is interested in quantifying. Building a conceptual model is therefore the first step in building numerical, mathematical, or reactive transport models (Barbour & Krahn 2004; Raymond et al. 2024), as it is necessary to understand processes important to a particular system, and their site-specific controls, before diving into the calculations. Similarly, for the conceptual model, it is foundational to determine the 'bin' (or value) a component of the conceptual model is in, because accuracy is in reference to how close the value or measurement chosen to be measured is to the true value. Precision is in reference to how close measurements of the same item are to each other, is independent of accuracy and focuses on repeatability or consistency. At the conceptual model stage, which is the model stage at the PD and PEA stage of an asset's life cycle, a focus on accuracy is far more important, as compared to a focus on precision. However, it is not often this approach is applied.

In the context of ML/ARD, an appropriate conceptual model tool should leverage these ideas idea by outlining key inputs necessary to estimate metals release from TSFs and MRSs. A conceptual model should communicate inputs, ideally phrased as questions, to capture important features of TSFs and MRSs, using a 'binning', or categorisation approach to capture the variability in parameters important for metal release from tailings and mine rock on a landform scale. The four high-level 'bins', are captured schematically in Figure 2 (Raymond et al. 2024) and Figure 3 (INAP 2024), for TSFs and MRSs, respectively.

The conceptual model or tool's inputs are first determined by defining the TSF (or MRS) system (i.e. regional considerations and how/where the TSF [or MRS] is constructed). Regional considerations include the 'sub-bins' of climate, hydrogeologic conditions, and geologic systems – the latter of which defines geochemical characteristics. Generally, these are conditions inherent to the location of the mine and cannot be engineered. The 'how it's built' overarching bin considers tailings deposition and TSF construction method(s) or MRS construction method(s) as sub-bins, whether conventional or with a focus on source control. These are engineering design choices that are selected by the mine and influenced by regional considerations. Inputs are then used to evaluate model outcomes for water balance and water quality. Water balance calculations will include the sub-bins of operations versus closure water balance, groundwater and surface water interaction (i.e. recoverable–unrecoverable seepage ratio(s), coupled surface–atmosphere water balance(s), and landform-based water balance(s). The resulting water quality, controlled by risk of ML/ARD, oxidation depth, exposed surface area (for a TSF), and construction method (for an MRS), are sub-binned in terms of acidity and metals release from the different landforms considering flow pathways and hydrologic retention time defined by the TSF (or MRS) design and water balance.

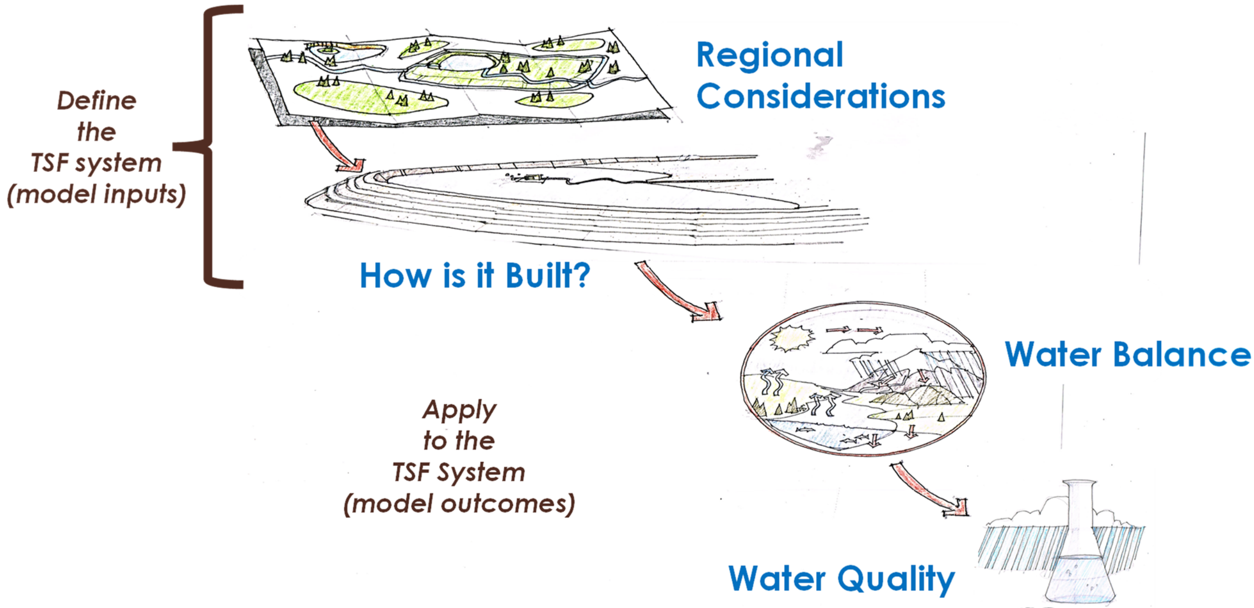


**Figure 2 Summary of the conceptual model, or tool, for predicting the evolution of metal mobility of tailings deposited within tailings storage facilities (TSFs). Illustration by D Shuttleworth**

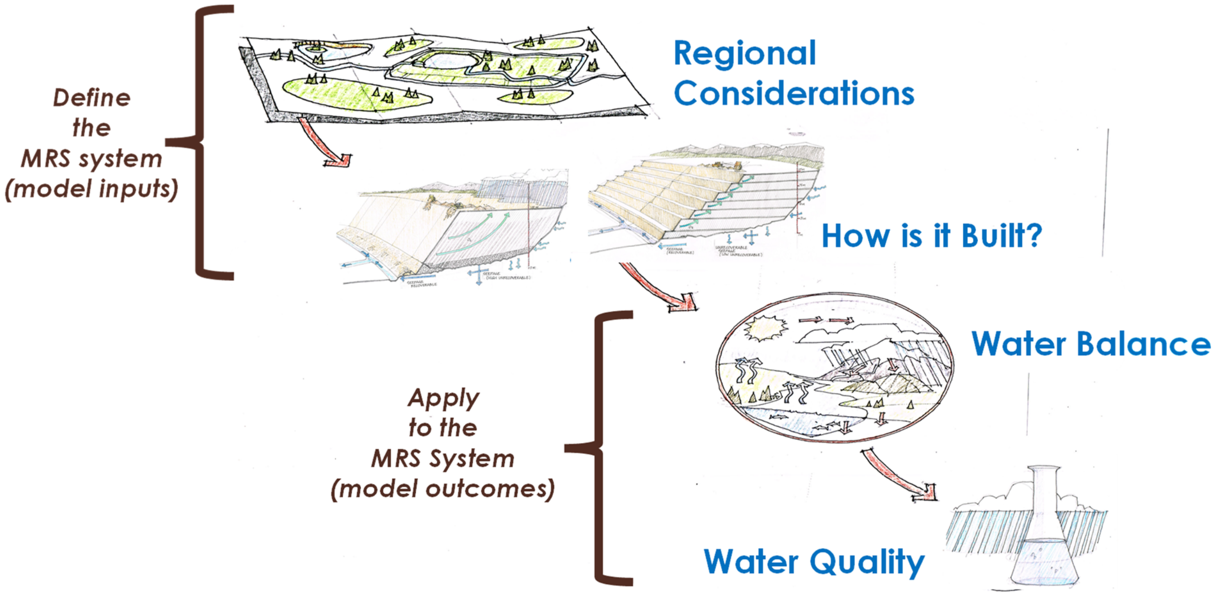


**Figure 3 Summary of the conceptual model, or tool, for predicting the evolution of metal mobility of mine rock placed into a mine rock stockpile. Illustration by D Shuttleworth**

Note that for TSFs, the conceptual model tool's fourth overarching bin, water quality, is very easily replaced by geotechnical stability, with the connection to the preceding water balance overarching bin including determination of a TSF pore-water regime on the basis of the water balance.

The conceptual model developed following the framework above has the appropriate level of site-specific focus, while still being at a high level, and can be applied in the timeframe typical of PD and PEA development, while also 'forcing' breakdown of 'design silos'. Perhaps as important, the conceptual model tool forces the designer to focus on accuracy, rather than on being precise. Precision comes later in project development during pre-feasibility, and feasibility. This conceptual model approach provides a strong framework, and starting point, for pre-feasibility and feasibility studies, which will include numerical modelling.

## 3.4 Discounted cash flow analysis for evaluating mine closure options and trade-offs

Despite common anecdotal and recently documented critique (e.g. Lilford 2024), discounted cash flow analysis is a useful tool for evaluating mine closure options and trade-offs. Perhaps most importantly, it is the tool used in the mining industry for developing and evaluating projects. As with earlier perspectives in this paper, the closure planning practitioner must 'move to' others, rather wait to be understood. However, the closure practitioner must strongly advocate for use of a site's closure vision and recognise that at each stage of the asset life cycle, particularly early in project development, there is an opportunity for the discounted cash flow analysis to only be one component of 'the larger story' and hence not the sole 'decision-making' metric.

Early in project development, especially at the PD and PEA stage, it is foundational there is recognition that a scenario planning approach (Peterson et al. 2003) is the appropriate decision-making tool to develop the 'stories' of each scenario. Scenario planning provides a tremendous opportunity to develop questions, which is so important because the solution to any problem lies in the underlying questions asked. However, at this stage when developing scenarios, it is recommended there be as much focus on developing 'and' questions, as is typically placed on asking 'or' questions; because 'or' questions result in efficient and compliant solutions, whereas 'and' questions result in effective and sustainable solutions. The latter solutions are strongly aligned with application of an integrated mine closure approach and defining mine closure as a continuous journey of improvement, rather than as a destination. Even with 'or' questions, incorporating discounted cash flow analysis as part of the approach, rather than relying on it entirely, will raise necessary awareness of future risks. This prevents being blind to these risks simply because they are discounted into the future.

# 4 Conclusion

Key developments, as well as recommended improvements, in approaches to landform design and mine closure are presented in his paper. Actionable, experience-based insights to strengthen implementation of mine closure across an asset's life cycle are provided. A robust conceptual model tool for tailings storage facility and mine rock stockpile design, which can be applied at the project description and preliminary economic assessment stage of a project, allows for focus on integrated mine planning and closure planning, such that a change in one plan results in a change to the other on the same temporal scale.

Central to these insights in this paper is the development of a co-created, site-specific shared closure vision, whether a new project, active operation, or legacy asset. The rationale for use of this approach, together with advances in governance around mine closure, to a similar extent as has been developed for design, construction, and operation of tailings storage facilities, is discussed at length within the paper.

Mining industry investors must lead change in governance for mine closure, the same way as was achieved for design, construction and operation of tailings storage facilities. Incremental improvements are clearly evident; however it is critical mining industry investors lead this governance change now.

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