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Strategic monitoring of closure objectives associated with tailings storage facilities as defined through stakeholder engagement

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Abstract

Mine closure represents one of the most complex challenges posed to the mining industry. Technical, social, regulatory and financial considerations intersect at this confluence of closure. Despite increasing emphasis on sustainable land custodianship, there remains a lack of a structured, stakeholder-aligned monitoring framework aligned with the appropriate selection of monitoring technologies for facility consequence classification to demonstrate compliance to closure objectives.

The closure of tailings storage facilities demands transparent, stage-gated evidence to support regulators in granting closure certificates and the relinquishment of funds provided for closure activities. This article proposes a consequence-based monitoring framework to link stakeholder-defined closure objectives and key performance indicators (KPIs) to proportional monitoring technologies across the closure life cycle.

A mixed-methods design was used and incorporates a structured literature survey and a multistakeholder survey informed by respondents associated with the mine closure industry. The study identifies critical closure objectives, current KPI practices and barriers to technology adoption in closure practices. Three decision tools are proposed to aid in operationalising the framework (a 2-variable risk matrix, a technology life cycle S-curve, and a technology balance sheet). Findings show mature, frugal methods dominate practice, while InSAR, Internet of Things and artificial intelligence analytics of the Fourth Industrial Revolution to remain constrained by capex, data and skill set development. The framework calibrates monitoring intensity to consequence classification and ties evidence into life cycle stage gates to provide a defensible chain from objective to decision.

This study contributes a practice-informed and adaptable framework to strengthen regulatory confidence and align closure practices with facility consequence classification, ultimately towards providing mining houses with a clearer pathway to closure certification and the relinquishment of their financial provision for closure.

Keywords: *tailings storage facilities, mine closure, key performance indicators, risk management, Global Industry Standard on Tailings Management, Fourth Industrial Revolution, frugal innovation, consequence-based monitoring*

1 Introduction

There is growing pressure on the global mining industry associated with environmental, social and governance (ESG) controls to improve the safe practice of mine waste management which are critically linked to tailings storage facility (TSF) operational control and the implementation of robust closure plans. Recent TSF failures such as the 2016 Mt Polley disaster in Canada (Zabolotnii et al. 2022), the 2019 Brumadinho disaster in Brazil and the 2022 Jagersfontein collapse in South Africa (Torres-Cruz & O'Donovan

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2023) have focused the lens of regulatory scrutiny on the industry and highlight an urgent need for robust, transparent and sustainable mine closure frameworks for implementation, monitoring and risk management.

Demonstrating that closure objectives have been achieved through agreed key performance indicators (KPIs) appropriate to a facility's consequence classification is likely to inform regulatory decisions regarding closure certification and the relinquishment of financial provision. However, regulatory uncertainty and the complexity of assessing long-term closure performance frequently delay certification, encouraging some mining companies to transfer mining rights rather than pursue final closure (Watson & Olalde 2019).

Mines are beginning to respond to growing ESG mandates with an appreciation that mining institutions should transition towards real-time, data-driven monitoring strategies, ensuring the implementation of proactive risk management, regulatory compliance and intent to ensure the perpetual sustainability of facilities in their post-operational state (Cacciuttolo et al. 2024). Current closure and reclamation strategies typically rely on manual inspection and periodic survey as monitoring strategies and may not capture early warning signs of instability or provide sufficient data for predictive risk assessments. Many TSFs lack real-time monitoring and adaptive management systems, leading to structural deterioration, excessive seepage and failures decades after mining has ceased (Lacasse et al. 2023).

The Fourth Industrial Revolution (4IR) offers digital technologies capable of transforming TSF closure monitoring through real-time, automated and predictive data acquisition. Technologies such as lidar, InSAR, Internet of Things (IoT) sensors and artificial intelligence (AI) can strengthen risk management by enabling earlier detection of emerging failure mechanisms and more proactive post-closure decision-making (Cacciuttolo et al. 2024).

A key challenge lies at the intersection of defining clear closure objectives and measurable KPIs through stakeholder engagement and monitoring these KPIs within a risk framework that demonstrates acceptable control of closure activities in consideration of a TSF's consequence classification (International Council on Mining and Metals [ICMM] 2020a). Under the Global Industry Standard on Tailings Management (GISTM), consequence classification categorises TSFs according to the severity of the consequences associated with a credible failure scenario rather than the probability of failure.

This research is novel in that it aims to explicitly integrate stakeholder-defined closure objectives and KPIs within a monitoring framework based on a TSF's consequence classification. Various international guidelines provide high-level closure guidance. However, they do not necessarily provide operational direction on how closure objectives may be demonstrated, monitored and verified through measurable KPIs across diverse consequence classifications to aid in the process of closure relinquishment and the release of obligatory financial provision for closure activities to mines. Moreover, the explicit application of 4IR technologies combined with an appreciation of frugal monitoring methods to closure phases and facilities of varying consequence classifications remains largely unexplored in academic and practitioner literature. This dual emphasis aims to enable scalable monitoring strategies suitable for both high-consequence facilities and lower-consequence, resource-constrained facilities.

The study hopes to address this gap by contributing a practical, adaptive framework intended to strengthen stakeholder trust through inclusivity, regulate decision-making by providing measured compliance to agreed relinquishment criteria and ultimately accelerate the issuance of mine closure certificates, which remains an area of rarity on a global scale.

Research question (RQ)

- RQ1: How can stakeholder-defined closure objectives for TSFs be translated into measurable KPIs and integrated within a consequence-based risk management framework supported by appropriate 4IR and frugal monitoring technologies?

Research objectives (RO)

- RO1: identify common objectives for the safe closure of TSFs.
- RO2: identify stakeholder KPIs commonly set for these objectives.
- RO3: identify current methods and risk management frameworks used to monitor these identified KPIs.
- RO4: identify 4IR and frugal technologies which would appropriately support such a framework and may be effectively adopted by the mining industry at large.
- RO5: develop a suggested risk management framework to appropriately address common objectives for safe closure and their respective KPIs.

2 Literature review

2.1 Closure monitoring and the evidence gap

The ability of mines to monitor TSFs from a state of operation through to post closure is critical to managing closure concerns. The shortcoming of mines in their efforts to monitor and inform action is not always in their collection of data but rather in their use of these data to support responses, actions or frameworks which provide stakeholders with valuable insight (Le Borgne et al. 2022). There is a clear requirement for a comprehensive, implementable and practical framework integrating closure objectives, real-time monitoring data and a proactive risk mitigation framework.

The Brumadinho dam, known as Dam 1, at the Córrego do Feijão mine in Brazil failed in 2019 and resulted in 272 fatalities. The facility was undergoing decommissioning efforts at the time and had been subject to monitoring and surveillance (Lumbroso et al. 2021). Its ultimate failure resulted from creep-induced instability (Robertson et al. 2019), a gradual mechanism of failure without major signs of external deformation. Conventional monitoring measures were not sufficient to detect the mechanism, highlighting further the importance of advanced, real-time monitoring solutions to enhance post-closure risk management. The 2022 failure of the Jagersfontein tailings dam in South Africa further emphasised the shortcomings of conventional monitoring approaches. The facility primarily depended on scheduled inspections rather than continuous real-time data tracking, which may have delayed the identification of stability issues (Torres-Cruz & O'Donovan 2023).

2.2 Stakeholders at closure

The stakeholder body mostly comprises mining companies, regulatory agencies, local communities, engineering consultants, technical teams and environmental organisations. Under the GISTM, mining companies bear the primary responsibility for executing closure plans and ensuring compliance with local and international regulations (ICMM 2020a). Involving local communities in TSF closure planning is crucial for fostering trust and ensuring long-term sustainability.

Communities often face direct environmental and economic impacts. Their participation in decision-making can facilitate collaborative solutions that align closure plans with local development goals. Effective engagement may also enhance public confidence in post-closure land use strategies (Parshley & MacCallum 2016). Additionally, participatory monitoring programs that incorporate local knowledge into closure assessments can enhance the social licence to operate while ensuring that closure activities align with community priorities (Jenkins & Yakovleva 2006).

2.3 The need for clear key performance indicators

The process of setting appropriate and measurable KPIs is a process which requires input from the integrated engagement of the mine's stakeholders. The ICMM outlines a high-level guide for what these KPIs might be and although its use may require expansion and specific application to arrive at clear criteria for success, the document shows the intent of collective agreement of stakeholders in order to arrive at the desired outcome for closure (ICMM 2020b).

KPIs can be site specific although there are common, foundational requirements to most closure and reclamation projects, such as hydrological stability, geotechnical stability, chemical stability, environmental restoration and ecological stability, and social sustainability. Each of these requirements can be assigned criteria for acceptable completion. Further to this, KPIs provide a means to enable cultural and organisational changes required within an effective and integrated closure process. The implementation of these KPIs at an early stage of operations such that closure is progressively undertaken throughout the life of mine can render the process more effective and less expensive towards the end of the life of mine (Shaw et al. 2022).

2.4 Risk and consequence

Risk is a widely used concept in technical and strategic contexts. There is, however not a collectively and universally accepted theoretical definition for the concept. There are certain commonalities in the interpretations of its definition which include, most notably, the elements of uncertainty and the potential for an adverse outcome. Risk is founded on the presence of some level of indeterminacy, presuming the existence of multiple possible outcomes linked to an uncertainty of a predicted outcome. A risk arises where at least one of the possible outcomes results in a potential, unfavourable consequence. An unfavourable consequence does not exclusively result in a direct loss but may also relate to a scenario whereby anticipated gains are diminished, or costs exceed forecasted expectations (Wiid 2006). This is an important consideration within a closure planning framework as successful closure involves variability, and long-term planning requires a rich understanding of quantifiable and qualitative uncertainty.

Risk and consequence are a delicate balance and must be appreciated in context with the closure of TSFs. Various internationally accepted guidelines provide frameworks for assigning consequence classifications to facilities. These frameworks are intended to provide a consistent manner with which to establish minimum external loading design criteria for the safe design of tailings facilities and a basis for recommended management and governance frameworks.

The consequence classification of the facility gives rise to recommended design parameters for surface water hydrology, seismicity and structural integrity, inter alia. At closure, the external design loadings are seen to be selected according to exceedance probabilities of the highest consequence classification despite their assigned consequence of failure. A facilities consequence classification is not assessed based on the probable risk of the facility failing but rather the assumption that a breach has occurred as a result of the development of a credible failure mode (ICMM 2020a).

2.5 Risk management practices

Various international bodies have outlined governance and risk management practices for the safe delivery of tailings management in the form of guidelines. These bodies, in addition to outlining guidelines for the design of, and consideration toward, external loadings for facilities, promote requirements for operation, maintenance and surveillance (OMS) manuals. The requirements of OMS manuals are intended to guide rather than to prescribe, leaving the 'how' up to the operator. Some of the international bodies providing guidance toward the development of robust OMS manuals include the:

- Canadian Dam Association (Canadian Dam Association [CDA] 2019)
- Mining Association of Canada (Mining Association of Canada 2021)
- International Commission on Large Dams (International Commission on Large Dams 2013)

- Australian National Committee on Large Dams (Australian National Committee on Large Dams 2019).

There is very little provided from these guidelines when it comes to suggested practices for the closure period in a TSFs life cycle for typical closure objectives and how to monitor them within a risk monitoring framework.

Traditional approaches have relied on engineering models that assume static geotechnical conditions, sometimes failing to account for climate change-induced variability, including extreme precipitation and seismic activity that can alter the state of materials and the resulting stability of TSFs. This is particularly pressing for regions that are exposed to extreme environmental climates with respect to annual rainfall and rainfall intensity, seismic activity and extended periods of drought (Bolton et al. 2021). This is especially valid when considering that closed TSFs are deemed to be perpetual landforms (ICMM 2020a).

2.6 Monitoring practices and innovation potential

Typical innovations in First World economies are mostly centred around new, expensive and complex innovations as their access to integrated systems, resources abundance and availability of materials provide a means with which to afford such innovation and technology (Qin 2024). This is not always the case, as frugal innovation (FI) commonly occurs in Third-World economies in the Global South (Pansera 2023). FI represents a paradigm around new product and technology innovation with an intent to produce solutions that are fit for purpose, efficient and implementable in resource-scarce environments. FI must be both affordable and of simple architecture (Hossain et al. 2023). In the case of TSF monitoring systems, this research aims to explore FI that meets the following criteria:

- provides an innovative, simple and sustainable solution
- makes use of readily available, local resources
- remains economically accessible for resource-limited settings
- can cater for neglected or underserved market segments
- has a low- to zero-electricity supply requirement.

There may well be a place for manual and rudimentary methods otherwise defined in this paper as FI monitoring methods, however, these should be assessed for their appropriateness according to the consequence classification of a facility. There are several existing solutions for implementation in the tailings field used to monitor various parameters that describe the physical and chemical stability of facilities. It is more common that monitoring efforts are undertaken manually with rudimentary monitoring technologies, demonstrating the lack of technological innovation applied in the field with a restricted monitoring database, and less advanced processing capabilities and integrated risk management systems (Cacciuttolo et al. 2024).

In addition to FI methods, the 4IR presents an opportunity to implement remote closure monitoring solutions capable of addressing these challenges by enabling professionals with a real-time insight into the current state of facilities. Technological advancements under the 4IR are reshaping TSF risk management by enabling real-time, data-driven decision-making (Yudhistyra & Srinuan 2024). Unlike conventional monitoring approaches that depend on periodic inspections and static engineering models, modern digital solutions such as automation, AI and IoT-enabled analytics offer continuous, predictive monitoring. These innovations strengthen early warning systems and enhance the long-term stability of TSFs by providing more responsive and accurate risk assessments (Cacciuttolo et al. 2024).

There is a growing recognition of the need to strengthen the connection between TSF monitoring practices and the achievement of sustainable closure outcomes. In many cases, traditional methods have struggled to clearly demonstrate whether closure designs are effectively delivering on long-term performance expectations. This often stems from completion criteria that are either poorly defined or altogether absent.

3 Methodology

A mixed-methods design was used and incorporates a structured literature survey and a multistakeholder survey informed by respondents associated with the mine closure industry.

The survey combined quantitative rankings and Likert scales with qualitative open-ended feedback, enabling both measurable trends and richer contextual insights. In total, 38 responses were collected, predominantly from consultants and mining houses, with limited representation from regulators and community stakeholders. While this distribution introduces certain limitations, it nonetheless provides a credible basis for developing a first-stage framework.

The survey was structured in 4 thematic blocks:

1. Respondent profile: participants were asked to provide their professional background and number of years of applied experience. This ensured disaggregation of responses and the ability to identify patterns across stakeholder groups
2. Closure objectives and KPIs: respondents were asked to rank common closure objectives (geotechnical, hydrological, chemical, environmental and social), suggest additional objectives and indicate consequences if objectives were unmet. They were also asked to reflect on the role of stakeholder consultation in developing KPIs
3. Monitoring technologies and barriers: participants were asked to report which technologies were currently in use, under pilot testing or considered obsolete, and to rank barriers to adoption (capital cost, technical capacity, stakeholder buy-in, regulatory ambiguity and remote conditions)
4. Framework feedback: respondents were invited to provide feedback on the draft consequence-based monitoring framework, including its practicality, scalability and acceptability as a decision-support tool.

The survey was designed to produce valuable insights; however, it is important to acknowledge its limitations. A total of 38 responses were collected. While modest relative to the global stakeholder community involved in mine closure and TSF management, the sample represents a sufficient critical mass of experienced industry professionals to identify consistent trends and inform the development of a first-stage framework The survey design anticipated fewer than 100 respondents. The focus of the study captured practice-informed insights to be integrated with the literature to build a defensible basis for framework design. Future studies with larger and more diverse stakeholder participation with particular focus on regulators and community representatives will allow the framework to be further tested, refined and validated as part of a process of continuous improvement.

4 Results and discussion

The results of the survey and guidance on future work are interpreted with acknowledgement of the limitations of the study. The dataset informing the results reflects a targeted group of professionals with demonstrable expertise in mine closure and TSF monitoring, and it provides a credible basis for the findings presented in this article.

In recognition of limitations there are 2 noteworthy points to consider in this interpretation:

- Although the 38 responses provide clear evidence of trends, a larger dataset would improve opportunities for disaggregation across stakeholder groups.
- Consulting engineers and mining houses were strongly represented, while regulators and community stakeholders were underrepresented.

Despite these constraints the study provides a robust, practice-informed foundation for developing the consequence-based monitoring framework. The findings establish a credible platform that can be strengthened through further research and broader stakeholder engagement.

The majority (84%) of respondents had more than 5 years of professional experience in tailings or mine closure, with a significant proportion (27% of respondents) reporting over a decade of applied experience. This indicates that although the stakeholder mix was uneven, the dataset represents a knowledgeable group of practitioners with a substantial depth of expertise.

Participants prioritised common closure objectives in alignment with the research intent to identify common objectives for the safe closure of TSFs. A rating scale from 1–5 was used, with a rating of 1 representing an objective of least importance. It is observed that stakeholder perceptions of risk and regulatory importance are largely concerned with 3 main objectives. These objectives are physical, hydrological and chemical stability. The ranking of closure objectives is essential for defining appropriate KPIs for closure monitoring and guiding the consequence-based monitoring framework.

Figure 1 indicates the alignment of various professional backgrounds with closure objectives. It is observed that geotechnical stability is universally prioritised, particularly by consulting firms and regulatory bodies. Community representatives, in contrast, place higher emphasis on environmental and ecological rehabilitation and social integration.

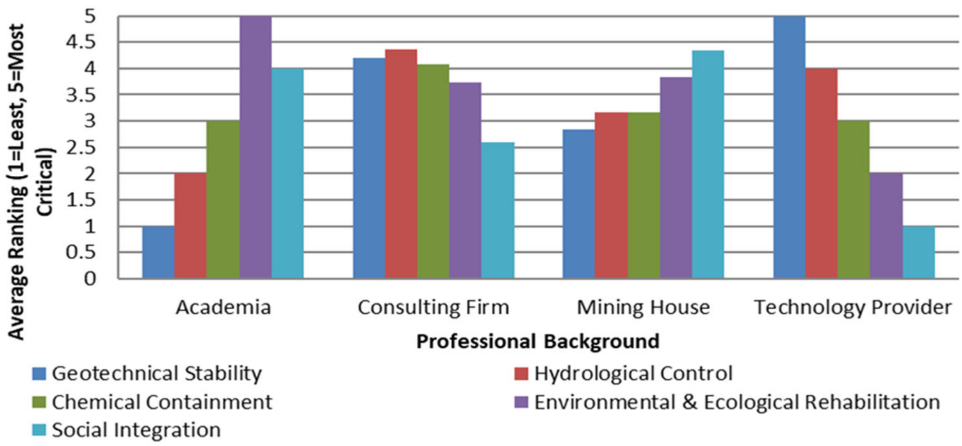

Figure 1 Distribution of closure objective weightings by professional background

4.1 Consequence and likelihood of unmet closure objectives (RO1 and RO3)

Respondents assessed the likelihood, and potential consequences, of closure objectives being unmet. To further understand stakeholders' perceptions of risk, respondents were asked to rate the consequence should each closure objective not be achieved. A scale ranging from low to extreme, converted to a Likert scale from 1 to 5, was used in the rating process. The results presented in Table 1 show that participating stakeholders consistently rated failures related to geotechnical stability and hydrological control as having the highest consequences, with most responses falling within the very high or extreme categories. It is also observed that chemical containment is similarly rated at a level between very high and extreme. Consequences associated with social integration are seen to be rated lowest of all presented overarching, objectives, which suggests that stakeholders tend to prioritise immediate physical and chemical risks over longer-term socio-institutional impacts.

Table 1 Consequence severity ratings for unmet closure objectives (stakeholder perspectives)

Unmet closure objective	Average rating (Likert scale)	Interpretation
Geotechnical stability	4.7	Extreme. Stakeholders see failure here as catastrophic
Hydrological control	4.6	Extreme. Nearly identical to geotechnical objectives
Chemical containment	4.3	Extreme. Recognised as long-term environmental liability
Environmental and ecological restoration	3.4	Between high and very high. Serious, however, not seen as immediately catastrophic
Social integration	2.9	Between significant and high. Consequences are real but less urgent compared to physical and chemical risks

Respondents were also asked to indicate the frequency at which closure objectives are not achieved, based on their experience and observation. The question shifts the focus from the impact of failure to the likelihood of objectives not being met in practice. The value of gaining understanding of these frequencies is seated in identifying where closure performance may commonly break down. Table 2 presents the aggregated stakeholder perceptions resulting from responses received from participants to this survey. The results indicate that, in the respondents' experience and observation, social integration and environmental and ecological rehabilitation are most frequently reported as unmet closure objectives. This highlights key difficulties in aligning post-closure land use with community expectations and sustaining long-term ecological systems. Contrastingly, geotechnical stability is seen as least often unmet and thus reflects a greater confidence in engineering design and its implementation to meet structural stability requirements at closure.

Table 2 Frequency of closure objectives not achieved (stakeholder perspectives)

Unmet closure objective	Average rating (Likert scale)	Likelihood	% Rated likely or certain
Geotechnical stability	2.5	Unlikely to moderate	21.1
Hydrological control	3.1	Moderate	34.2
Chemical containment	3.2	Moderate	34.2
Environmental and ecological restoration	3.4	Moderate to likely	42.1
Social integration	3.5	Moderate to likely	52.6

4.2 Stakeholder consultation in key performance indicator development (RO2)

Respondents were required to indicate the frequency to which stakeholders outside of the mining house are consulted in the development of a closure design. It was observed that most respondents (67%) indicated 'sometimes'. A smaller but meaningful proportion (28%) reported 'often', while 6% of respondents stated that stakeholder consultation 'never' occurs. No respondents selected that stakeholders are always 'always' consulted.

The distribution of responses suggests that stakeholder input into KPI development is often sporadic rather than a systematic process of inclusivity. It is apparent that inclusive consultation does happen in some projects, however, it may be heavily dependent on context, company culture or regulatory pressure. It was strongly noted by a lack of response that stakeholders are 'always' engaged that a gap exists where formal, structured and routine integration of stakeholders in a KPI-setting is not yet standard practice in efforts to present a robust closure with intent for relinquishment.

The topic of inclusive stakeholder engagement was explored further by inviting respondents to provide examples of KPIs or indicators that could be strengthened through further stakeholder engagement. The responses converged around 5 key domains:

- geotechnical stability by monitoring slope deformation, phreatic surface levels, visual inspections and use of trigger action response plans
- hydrological control by freeboard measurement, stormwater and drainage inspections, erosion monitoring and diversion structure performance
- chemical containment by groundwater and surface water quality monitoring (pH, heavy metals, plume stability), dust monitoring and liner performance
- environmental and ecological rehabilitation by indicators of vegetation cover, survival rates of native species, fauna return, erosion resistance and landscape function analysis
- social integration by community satisfaction surveys, utilisation of post-closure land uses (e.g. agriculture, solar farms), local employment and skills development, and regulatory or community acceptance of land use.

Several respondents also emphasised long-term monitoring and funding, regulatory acceptance, and health and safety (e.g. dust exposure, accident rates) as cross-cutting areas that require clear KPIs.

4.3 Monitoring technologies and methods in use (RO3 and RO4)

Respondents were asked to indicate the monitoring technologies currently used for TSF closure. The survey results are summarised in Section 5.2 and interpreted using the technology life cycle described by Rogers (2003), which recognises that technologies typically progress over time from emerging concepts to widespread adoption before eventually reaching maturity or decline. The technologies identified in this study were positioned on this life cycle according to their current level of industry uptake, illustrating their relative maturity rather than their performance or effectiveness. This provides a practical basis for considering the suitability of different monitoring technologies within the proposed consequence-based monitoring framework.

4.4 Barriers to technology adoption (RO4)

Respondents were provided an opportunity to suggest barriers other than those that were identified and were asked to rank these primary barriers that prevent the widespread adoption of technology-based monitoring in closure practices. Respondents ranked their 3 most important barriers. The importance of understanding these barriers is to provide context as to why certain monitoring methods remain engrained in monitoring practices, where interventions (whether through innovation, regulation or stakeholder processes) could aid in enabling a more reliable closure monitoring framework. Rankings were weighted using a scoring system (first = 3 points, second = 2 points, third = 1 point). The values shown in the Rank 1, 2 and 3 columns in Table 3 represent the weighted point contribution from each ranking position rather than the number of respondents selecting that ranking.

Table 3 Barriers to the implementation of technology-based monitoring strategies

Barrier	Rank 1 points	Rank 2 points	Rank 3 points	Weighted score	Order of barriers
Capital cost	57	12	5	74	1
Lack of technical capacity	15	18	7	40	2
Lack of stakeholder buy-in	18	14	7	39	3
Regulatory ambiguity	9	12	5	26	4
Remote site conditions	6	8	8	22	5
Data management complexity	3	8	4	15	6

5 Towards a consequence-based monitoring framework

The collation and observation of the survey results enable the development of a practical framework to connect stakeholder-defined closure objectives and monitoring technologies that are considered relative to the consequence of failure related to TSFs and closure objectives. Earlier sections have established that geotechnical, hydrological and chemical containment objectives are consistently rated at the highest consequence levels. It was also established that ecological rehabilitation and social integration are less often prioritised by respondents, yet they remain essential for long-term relinquishment. This consequence lens aims to root in GISTM principles (ICMM 2020a) to provide systemised logic for a consequence-based monitoring strategy whereby technologies and KPIs are not selected generically but in proportion to the severity of consequences if objectives are unmet, and the holistic inclusion of stakeholders.

5.1 Two-variable risk matrix for unmet closure objectives

The first integration step for the framework is to map closure objectives within a 2D risk matrix using responses on consequence ratings and likelihood ratings (Section 4.1). This approach provides clarity on where monitoring investments should be prioritised. The interpretation of the results of the survey with respect to closure objectives are described in a 2-variable risk matrix shown in Figure 2.

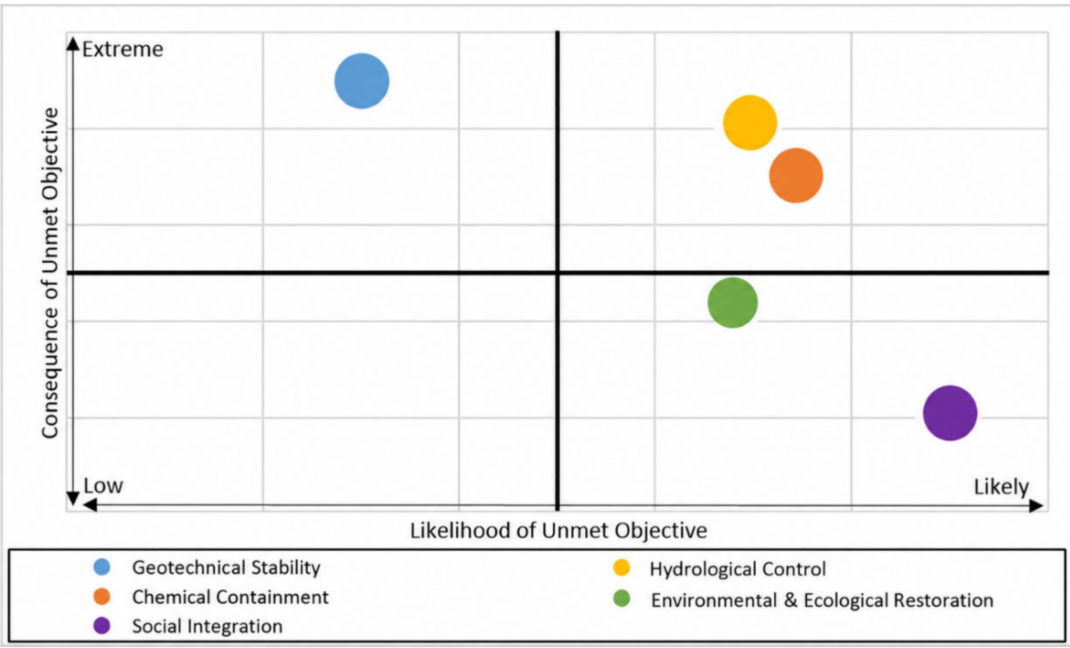

Figure 2 Two-variable risk matrix for unmet closure objectives

5.2 Adapted technology life cycle for concept model (S-curve)

The results obtained from respondents on the current use of technologies used to monitor TSF performance have been assessed based on use and placed in various growth phases (Table 4). These growth phases have been assigned a characteristic colour which then represents the technology phase on a summary technology life cycle S-curve as shown in Figure 3.

Table 4 Technology phases according to survey responses

Technology/method	Ref ID	In use (%)	Pilot (%)	Not used (%)	Historical (%)
Emerging phase					
AI-driven predictive models	E1	2.8%	44.4%	41.7%	0%
Machine learning algorithms	E2	8.3%	41.7%	41.7%	0%
Augmented reality	E3	0%	27.8%	58.3%	0%
Virtual reality	E4	2.8%	30.6%	52.8%	0%
Growth phase					
Drones (visual/multispectral)	G1	61.1%	27.8%	5.6%	0%
Ground-based InSAR	G2	52.8%	16.7%	22.2%	0%
Wireless piezometers	G3	75%	13.9%	11.1%	0%
Wireless inclinometers	G4	47.2%	11.1%	30.6%	0%
Lidar	G5	77.8%	11.1%	5.6%	0%
Satellite remote sensing	G6	72.2%	13.9%	13.9%	0%
Maturity phase					
Manual sampling	M1	91.7%	0%	5.6%	0%
Piezometers (manual)	M2	94.4%	2.8%	2.8%	0%
Dumpy level surveys	M3	86.1%	0%	5.6%	5.6%
Freeboard surveys	M4	80.6%	0%	5.6%	11.1%
Decline phase					
Freeboard pole markings	S1	86.1%	0%	0%	11.1%
Erosion monitoring stakes	S2	63.9%	2.8%	22.2%	8.3%
Dip meters for open wells	S3	83.3%	2.8%	0%	5.6%
Inclinometers (manual)	S4	63.9%	8.3%	11.1%	5.6%

An S-curve for closure technology positioning has been developed for the purposes of this study (Figure 3). The S-curve positions monitoring technologies according to their reference ID (as given in Table 4) across the stages of the technology life cycle (Rogers 2003). Mature technologies include manual sampling, piezometers (manual), dumpy level surveys and freeboard surveys, which remain prevalent for compliance and baseline monitoring efforts.

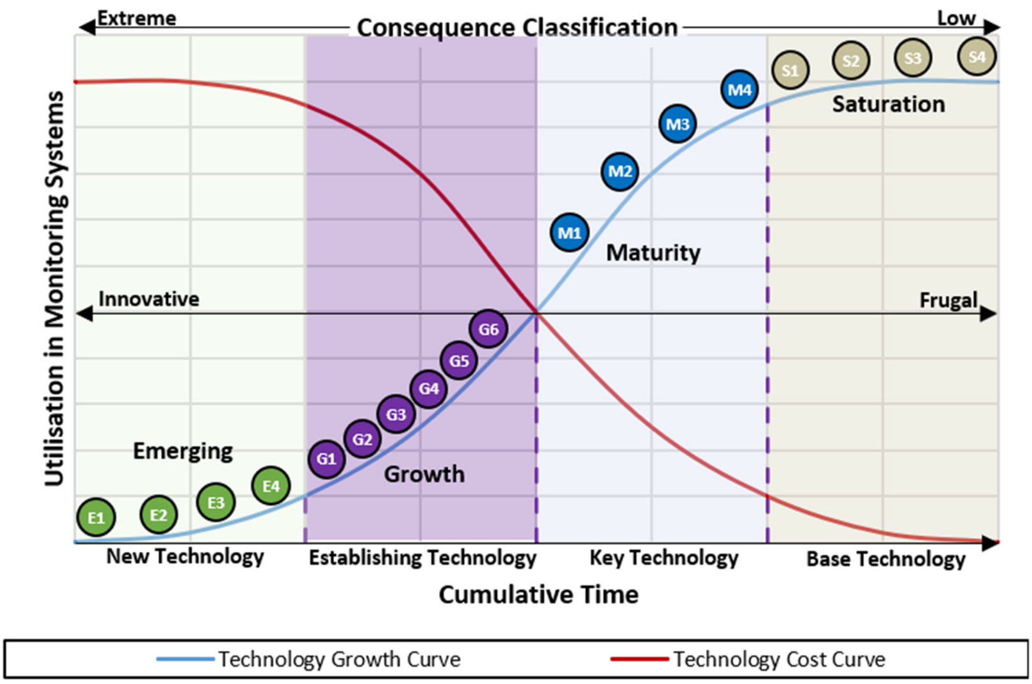

Figure 3 S-curve of closure monitoring technologies and tailings storage facility consequence classification

6 Consequence-based monitoring framework

The framework and its operationalised use are described in the sections below for the TSF life cycle described by the timeline shown in Figure 4, as created for the purposes of this study.

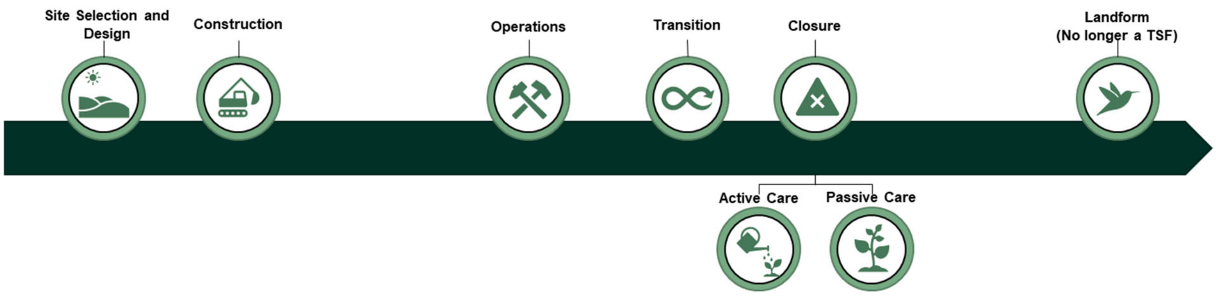

Figure 4 Life cycle of a tailings storage facility (TSF) landform

The framework aims to integrate information gathering, stakeholder engagement and decision-support tools. It is important that monitoring technologies remain a flexible choice to the user of the framework and that they are chosen according to the consequence classification of the facility. The framework also identifies where structured tools, as presented in this research, are applied to guide decision-making and reinforce accountability towards monitoring KPIs and justifying relinquishment.

6.1 Phase 1: baseline and visioning (operations and early planning)

The first phase of the framework begins during the site selection and design stages, prior to the construction of a facility. The GISTM requires that closure must be considered as early as the design phase to ensure that long-term risks are accounted for; embedding closure objectives into the life of mine strategy from the project outset (ICMM 2025). This early project stage incorporates investigations directed at operational performance as well as at credible consequence of failure associated with credible failure modes that may persist beyond the closure phase. Baseline data are critical to project success and must encompass geotechnical, hydrological, chemical, ecological and social fields comprehensively.

Stakeholders should play a crucial role in this process as operators and consultants develop closure objectives in consultation with regulators, engaging affected communities to validate that these objectives align with post-mining land use expectations. The 2-variable risk matrix (Section 5.1) is first applied during this phase to translate baseline data into a structured appreciation of the likelihood and consequence of unmet closure objectives to establish risk-based closure objectives. The most critical component towards relinquishment is established at this stage, with regulators who should provide early confirmation that these agreed KPI-linked risks will be recognised as formal relinquishment criteria, thereby offering clarity and confidence to all parties at the outset of the project that relinquishment is achievable.

6.2 Phase 2: design integration (transition to closure planning)

The second phase of the framework aims to move visioning to projects execution. The critical role of Phase 2 is that closure-readiness is embedded into the technical and operational design of the facility. Considering the baseline investigations and early stakeholder engagement, KPIs are then grouped into functional design- and performance-based criteria to allow for clarity of alignment between monitoring methods and the facility's closure strategy.

Tools presented in this research, such as such as the S-curve (Section 5.2), are applied in this phase to assess the monitoring technology's positioning in terms of maturity, industry uptake, the facility's consequence classification and the economic climate. Technologies in the emerging or growth phases are generally preferred for high to extreme consequence facilities as they are seen to provide predictive monitoring potential, whereas mature or declining tools that present as FI options may be suitable for low or significant consequence facilities where budget constraints and simplicity are driving considerations for practical implementation.

6.3 Phase 3: transition to closure (construction and rehabilitation)

Phase 3 begins at the commencement of active closure works. This period typically occurs post-operations in a phase of transition to closure. In some contexts, staged, progressive rehabilitation may also fall under this phase, and it is encouraged. The emphasis in this phase is on project execution and assurance of robust implementation.

Closure activities (where required) such as capping, construction of water management infrastructure, stabilisation of slopes, breaking of slope lengths and ecological restoration are implemented. Monitoring systems specific to the closure phase are now deployed to track performance of these implementations, and the collection of monitoring data now becomes critical for both construction quality assurance and the validation of closure performance towards relinquishment.

New technologies must be assessed according to the value provided by existing technologies and the requirements for monitoring stakeholder-driven KPIs. This phase transitions the vision and theoretical design into practical a demonstration to advance closure as a constructed reality that requires evidence of performance.

6.4 Phase 4: active care and adaptive management

Phase 4 extends across the long-term monitoring and adaptive management period following the completion of active closure works during the transition phase. The emphasis shifts from construction quality assurance to performance confirmation, risk anticipation, and adaptive response to changes to the facility and its surrounding ecosystem.

This phase has an adaptive nature and reflects the reality that closure is an ongoing process requiring periodic recalibration. The risk matrix and S-curve are revisited at this stage to evaluate the fit of chosen monitoring suites for acceptance or strategic adjustment. This may require the phasing in of more predictive tools such as AI-driven models for facilities with extreme consequence classifications or evaluating monitoring frequencies at sites with consistently demonstrated stability.

6.5 Phase 5: post-closure, relinquishment and legacy stewardship

This final phase of the framework is intended to lead towards relinquishment. Responsibility for the site is now transferred from the operator to the state or community, and closure objectives are formally recognised as completed by the regulator. Relinquishment requires a fourth and final stage gate where a record such as a design basis report is updated to consolidate all design, construction, assessment tools and performance data to provide a traceable record demonstrating that closure KPIs have been met and that no unacceptable risks remain. This is to support closure certification and stakeholder acceptance. Regulators play the decisive role in this phase by confirming compliance of the closure implementation against pre-agreed objectives. Communities and the state assume stewardship following approval.

The framework presented in Figure 5 is a response to the industry's increasing need for risk-informed and stakeholder-aligned management as well as the lack of regulatory approval towards the relinquishment of TSFs for final closure by regulators (Watson & Olalde 2019). The framework has been developed through practitioner engagement to integrate closure planning from the conception of design through to post-closure stewardship and is guided by phase-specific clarity around key processes, stakeholder roles, monitoring tools and proposed regulatory gatekeeping requirements.

The framework is intended as a practical decision-support process, guiding closure objectives and monitoring strategy definition and priority through its operationalisation. Each facility is unique and differs in scale, design, environmental setting, legacy conditions, and stakeholder expectations. Therefore, the user of the framework must consider tailored application rather than a prescriptive checklist.

Figure 6 complements the framework with a systems-level view of data flows and information platforms of the framework across closure phases for a TSF. This Sankey-style flow diagram illustrates 4 principal dimensions:

- information and tooling integration (how consequence assessments drive technology selection)
- tool-to-outcome pathways (monitoring data linked to regulatory outputs)
- phase-based information requirements
- stakeholder roles and their points of influence across the closure life cycle.

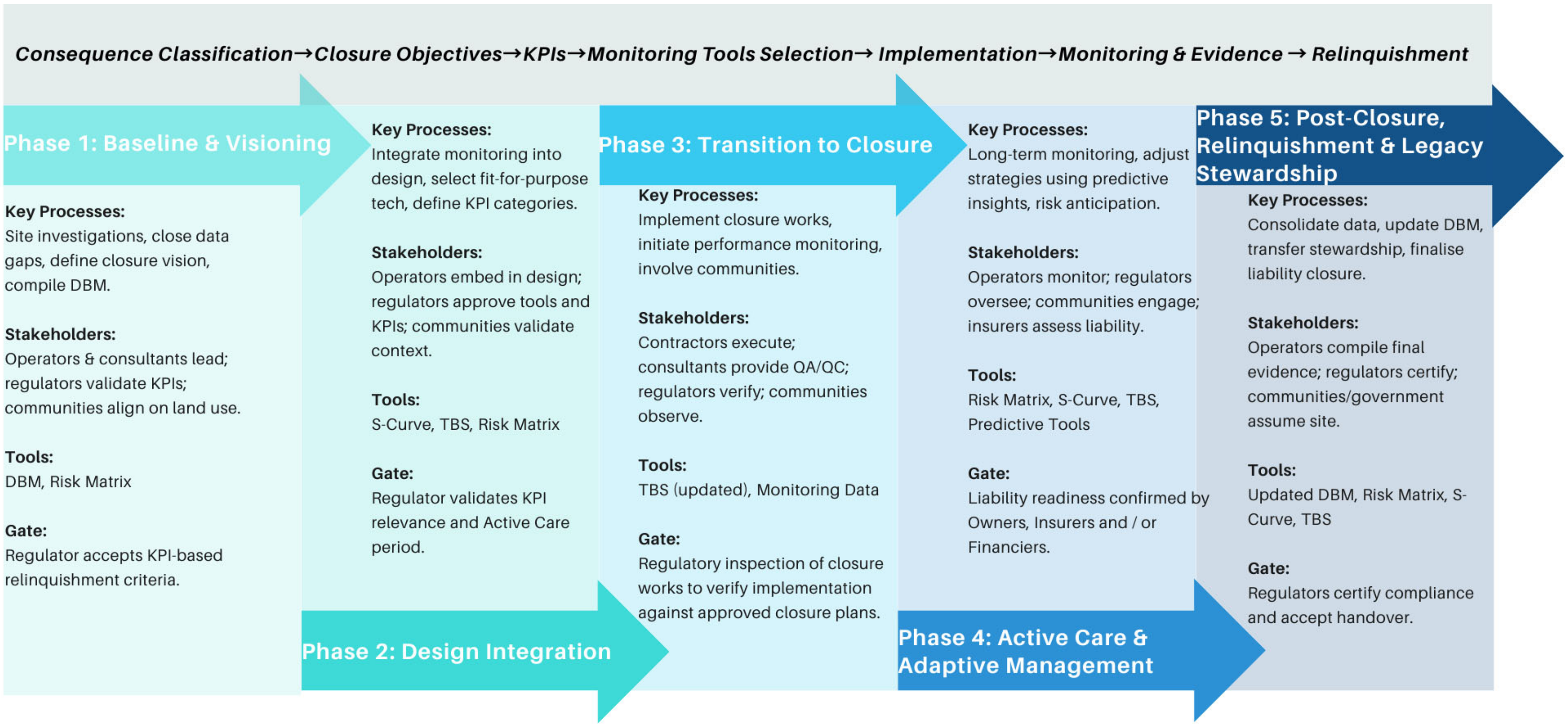

Figure 5 **Consequence-based monitoring framework. Note: The consequence classification established under the Global Industry Standard on Tailings Management acts as the principal scaling mechanism throughout the framework. While all tailings storage facilities follow the same 5 life cycle phases, the consequence classification determines the proportionality of monitoring technologies, monitoring frequency, evidence requirements and regulatory confidence required before progressing through each closure stage gate towards relinquishment. List of abbreviations: design basis memorandum (DBM); key performance indicator (KPI); technology balance sheet (TBS); quality control (QC); quality assurance (QA)**

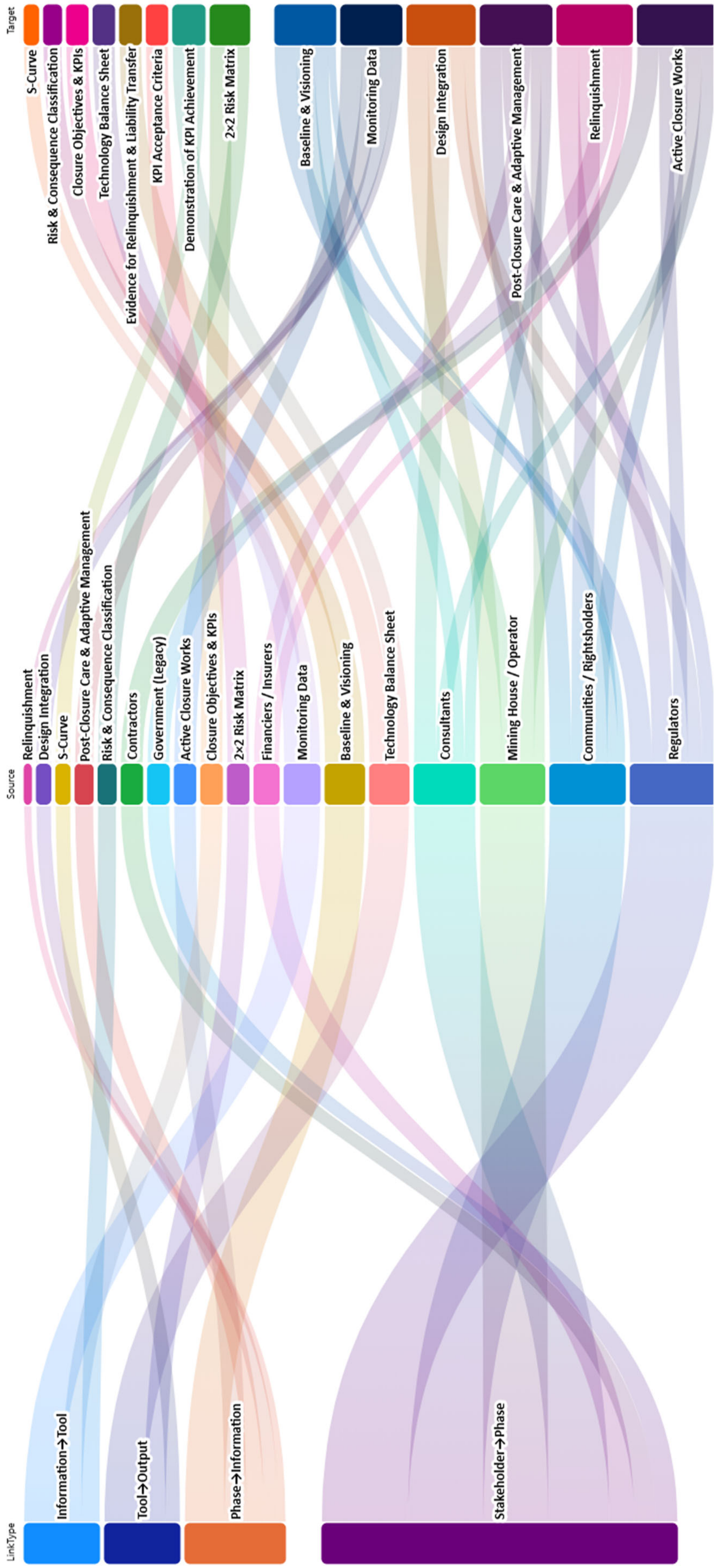

Figure 6 Data flows and information platforms of stakeholder integration and tool application across closure phases for a tailings storage facility

7 Conclusion

This research was guided by a central question: How can tailings storage facility (TSF) closure objectives, as defined through stakeholder engagement, be monitored strategically to support a safe and defensible mine closure?

Based on the findings of the research, the following conclusions are drawn:

- Common objectives for the safe closure of TSFs were identified through the literature survey and by means of survey analysis, which highlighted variability in stakeholder engagement practices. Closure objectives were also mapped to risk likelihoods and consequences using a 2-variable risk matrix.
- Current methods and risk management frameworks used to monitor KPIs were explored in the literature review, and presented a lack for the detection of early warning signs of failure (CDA 2019). The traditional approach to monitoring highlights several gaps which make KPI monitoring challenging due to data collection gaps, resulting from the lack in capturing dynamic stability condition variations. High labour costs and the likelihood of human error in data capturing also reduce the accuracy and effectiveness of reported findings (Le Borgne et al. 2022).
- Specific KPIs linked to closure objectives were explored through the survey tool. The study confirmed that KPIs were most often aligned to geotechnical stability, water quality, ecological restoration and social licence objectives.
- Fourth Industrial Revolution and FI technologies to support the framework were explored in the literature survey and were assessed through survey responses for their current maturity and use in the industry as monitoring tools. These tools were considered by means of technology life cycles to assess the practical implementation of various technologies for various TSF consequence classifications from a technology and innovation management perspective.
- A suggested risk management framework to appropriately address common objectives for safe closure and their respective KPIs was developed in Section 6.5 and is presented in Figure 5.

The study makes the following contributions:

1. It incorporates innovation and technology management by providing the first integrated application of the risk matrix and S-curve as complementary tools for closure monitoring.
2. It demonstrates how stakeholder engagement can be operationalised into measurable KPIs and validated through appropriate monitoring strategies as relinquishment criteria.
3. It offers a replicable, practice-informed framework that regulators and operators can adapt to varying TSF contexts.

References

Australian National Committee on Large Dams 2019, *Guidelines on Tailings Dams: Planning, Design, Construction, Operation and Closure*, Sydney, viewed 24 June 2026, https://ancold.org.au/product/guidelines-on-tailings-dams-planning-design-construction-operation-and-closure-revision-1-july-2019/

Bolton, C, Macfarlane, G & Maritz, A 2021, 'Considering climate change in tailings dam design', *International Mining Supplement: Paste & Tailings 2021*, viewed 24 June 2026, https://www.srk.com/en/publications/consider-climate-change-in-tailings-dam-design

Cacciuttolo, C, Guzmán, V, Catriñir, P & Atencio, E 2024, 'Sensor technologies for safety monitoring in mine tailings storage facilities: Solutions in the Industry 4.0 era', *Minerals*, vol. 14, no. 5, article 446, https://doi.org/10.3390/min14050446

Canadian Dam Association 2019, *Application of Dam Safety Guidelines to Mining Dams*, Markham.

Hossain, M, Park, S & Shahid, S 2023, 'Frugal innovation for sustainable rural development', *Technological Forecasting and Social Change*, vol. 193, article 122662, https://doi.org/10.1016/j.techfore.2023.122662

International Council on Mining and Metals 2020a, *Global Industry Standard on Tailings Management*, London.

International Council on Mining and Metals 2020b, *Key Performance Indicators Tool for Closure*, London, https://www.icmm.com/website/publications/pdfs/environmental-stewardship/2020/guidance_kpi-tool-for-closure.pdf

International Council on Mining and Metals 2025, *Integrated Mine Closure Good Practice Guide*, 3rd edn, London, https://www.icmm.com/integrated-mine-closure

International Commission on Large Dams 2013, *Sustainable Design and Post-Closure Performance of Tailings Dams*, Bulletin 153, Paris.

Jenkins, H & Yakovleva, N 2006, 'Corporate social responsibility in the mining industry: Exploring trends in social and environmental disclosure', *Journal of Cleaner Production*, vol. 14, nos. 3–4, pp. 271–284, https://doi.org/10.1016/j.jclepro.2004.10.004

Lacasse, S, Liu, ZQ & Piciullo, L 2023, 'An integrated risk assessment and management framework for mine tailings storage facilities', *Proceedings of Next Generation Tailings – Opportunity or Risk*, Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 211–224, https://www.saimm.co.za/Conferences/files/tailings-2023/22%20590_Lacasse.pdf

Le Borgne, V, Siamaki, A & Dulmage, A 2022, *Review of Modern Recommendations for Monitoring of Tailings Storage Facilities*, GKM Consultants, Sainte-Julie, viewed 24 June 2026, https://www.gkmconsultants.com/assets/documents/application/pdf/review-of-modern-recommendations-for-monitoring-of-tailings-storage-facilities-by-dr-vincent-le-borgne_01.pdf

Lumbroso, D, Davison, M, Body, R & Petkovšek, G 2021, 'Modelling the Brumadinho tailings dam failure, the subsequent loss of life and how it could have been reduced', *Natural Hazards and Earth System Sciences*, vol. 21, no. 1, pp. 21–37, https://doi.org/10.5194/nhess-21-21-2021

Mining Association of Canada 2021, *Developing an Operation, Maintenance, and Surveillance Manual for Tailings and Water Management Facilities*, version 2.1, Ottawa, viewed 24 June 2026, http://mining.ca/oms-guide

Pansera, M 2023, 'The apolitical framing of frugal innovation in the global south: Beyond the tales of scarcity, heroic inventors and techno-fixes', *Handbook on Frugal Innovation*, Edward Elgar Publishing, Cheltenham, pp. 54–68, https://doi.org/10.4337/9781788118873.00011

Parshley, JV & MacCallum, CS 2016, 'Attractive nuisances and wicked solutions', in AB Fourie & M Tibbett (eds), *Mine Closure 2016: Proceedings of the 11th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 229–240, https://doi.org/10.36487/ACG_rep/1608_15_Parshley

Qin, W 2024, 'How to unleash frugal innovation through internet of things and artificial intelligence: Moderating role of entrepreneurial knowledge and future challenges', *Technological Forecasting and Social Change*, vol. 202, article 123286, https://doi.org/10.1016/j.techfore.2024.123286

Robertson, PK, de Melo, L, Williams, DJ & Wilson, GW 2019, R*eport of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I*, Expert Panel Investigation, https://bdrb1investigationstacc.z15.web.core.windows.net/assets/Feijao-Dam-I-Expert-Panel-Report-ENG.pdf

Rogers, EM 2003, *Diffusion of Innovations*, 5th edn, Free Press, New York.

Shaw, J, Pedlar-Hobbs, R & Chubb, D 2022, 'The role of key performance indicators throughout the mine life in achieving closure objectives', in AB Fourie, M Tibbett & G Boggs (eds), *Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 803–812, https://doi.org/10.36487/ACG_repo/2215_58

Torres-Cruz, LA & O'Donovan, C 2023, 'Public remotely sensed data raise concerns about history of failed Jagersfontein dam', *Scientific Reports*, vol. 13, article 5228, https://doi.org/10.1038/s41598-023-31633-5

Watson, I & Olalde, M 2019, 'The state of mine closure in South Africa – what the numbers say', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 119, no. 7, pp. 673–679, https://doi.org/10.17159/2411-9717/331/2019

Wiid, GJ 2006, 'The role of closure planning in the environmental and financial reporting processes for mining operations', in AB Fourie & M Tibbett (eds), *Mine Closure 2006: Proceedings of the First International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 513–524, https://doi.org/10.36487/ACG_repo/605_44

Yudhistyra, WI & Srinuan, C 2024, 'Exploring the acceptance of technological innovation among employees in the mining industry: a study on generative artificial intelligence', *IEEE Access*, vol. 12, pp. 165797–165809, https://doi.org/10.1109/ACCESS.2024.3493242

Zabolotnii, E, Morgenstern, NR & Wilson, GW 2022, 'Mechanism of failure of the Mount Polley tailings storage facility', *Canadian Geotechnical Journal*, vol. 59, no. 8, pp. 1503–1518, https://doi.org/10.1139/cgj-2021-0036