Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)
© 2026 Australian Centre for Geomechanics, Perth, ISSN 2208-8296
doi:10.36487/ACG_repo/2615_149

Transferrable lessons from mine closure in the Arctic to remote Australian mines

Scott Garrison [a,*], Christy Rouault [a], Aaron Weber [b]

[a] *BGC Engineering, Australia*

[b] *BGC Engineering, Canada*

Abstract

Remote mine sites present persistent challenges for mine closure, particularly where access constraints, limited infrastructure, extreme climatic conditions and sensitive receiving environments intersect. These challenges are heightened in this era of increasing scrutiny, climatic uncertainty and long post-closure monitoring time frames. These challenges are similar at mines in developed nations, with extreme climates and in remote locations, including the North American Arctic and much of Australia, yet differences in climate, regulatory frameworks and social contexts have driven the development of distinct closure practices. By synthesising lessons from mine closure experience at remote North American Arctic sites, this paper identifies learnings that may be relevant for Australian mine sites. These lessons are particularly useful for Australian mine sites with extreme climates and restricted or infrequent access due to remoteness.

The paper examines 4 interrelated themes. First, the use of instrumentation at North American Arctic sites is reviewed, highlighting approaches for sites where access may be seasonal or intermittent. Second, advances in remote sensing, including satellite-based deformation monitoring and climate monitoring are discussed as tools to support reduced site visitation while maintaining stakeholder confidence. Third, the paper explores how design and construction decisions made during operations influence long-term closure performance in remote settings, with particular emphasis on robustness, redundancy and the value of site-specific closure trials conducted during operations. Finally, the concept of an integrated knowledge base is discussed; continuity of custodianship of site data is a persistent problem at many remote sites due to turnover during decades-long monitoring time frames. A parallel is drawn with traditional Aboriginal knowledge transfer, with focus on what can be learned by the mining community from Aboriginal groups who have long since mastered the art of passing information from one generation to the next.

Keywords: *Mine closure, remote, instrumentation, remote sensing, knowledge base, landform design, geotechnical*

1 Introduction

Mine closure is no longer a discrete end of mine activity. It involves long-term decisions about landform performance, environmental risk and ongoing responsibility well beyond the operational life of a site (Kabir et al. 2015; Purtill 2023). At remote mines, those decisions matter more because access is difficult, costs escalate quickly and there are limited opportunities to fix problems once operations wind down.

Remote regions of Australia, including parts of the Pilbara, Kimberley, Goldfields, Far North Queensland, Northern Territory, and offshore islands, share many characteristics with Arctic mining regions in Canada and Alaska.

Common features include:

- seasonal or weather dependent access

* Contributing author. Email address: sgarrison@bgcengineering.ca

- generally high operating cost
- reliance on out-of-region workforces
- limited roads and nearby infrastructure and services
- culturally significant landscapes, often with high Indigenous connection to land
- sensitivity to climate change or extreme weather events
- significant mine closure liabilities.

From a regulatory perspective, Canada and Australia also share many similarities. Regulation is primarily state, province, or territory dependent, with significant regulatory variability between nearby jurisdictions. The concept of site relinquishment is frequently discussed but rarely achieved in practice.

This paper synthesises lessons from North American Arctic mine closure that may be applicable to remote Australian contexts. The intent is not to transpose northern practices wholesale, but to identify transferable principles that can strengthen closure outcomes, regulatory confidence and long-term stewardship in remote Australian settings. It is written for practitioners working at remote mine sites in all stages of their life cycle, to produce the best results for closure. The observations here are drawn from site inspections, closure reviews and long-term monitoring programs at remote Arctic mines. While examples are drawn primarily from larger mines with slurry tailings, the topics covered apply equally to small and large operations, open pit or underground, with varying tailings and waste rock types. This paper specifically discusses mines in Alaska, the Yukon, the Northwest Territories and Nunavut. The authors acknowledge that there are mines in other jurisdictions that could be considered part of the North American Arctic, including northern Quebec, northern Newfoundland and Labrador and Greenland, that are not discussed herein; likewise for jurisdictions in Europe and Asia. This paper discusses topics that are broad and complex in nature and does not purport to be a comprehensive comparison between jurisdictions. Kabir et al. (2015) compared mine closure practices between Canada and Australia and concluded that overall, the state of practice is quite similar, and neither is superior. The focus of this paper is deliberately one directional: it examines insights from Arctic mine closure that may inform practice in remote Australian contexts, without attempting a reciprocal comparison. As such, few Australian case studies are highlighted, and instead, comparisons are drawn to how the Arctic experience could potentially translate to the Australian setting.

2 Instrumentation

Managing uncertainty is central to geotechnical and closure design and instrumentation is one of the primary tools available to track how a site is actually behaving over time. Instrumentation is used to measure parameters such as pore pressure, displacement, flow and temperature, which underpin assessments of geotechnical stability, seepage performance and long-term closure behaviour. These data are used to assess the stability and seepage performance of mine structures (e.g. tailings facilities, surface and underground workings, waste rock dumps) throughout the mine life cycle.

During exploration and early development, instrumentation helps establish a baseline understanding of site conditions that informs design. During operations, instrument data are used to compare observed behaviour against predicted performance and to identify emerging risks or the need for design refinement. During closure and post closure, instrumentation becomes one of the few objective sources of information available to assess long-term performance, particularly where routine site access is limited.

At remote sites, this long-term role of instrumentation is especially important. Once operations wind down, opportunities to revisit or retrofit monitoring systems diminish rapidly, and the cost of replacing failed instruments can far exceed the cost of installing them properly in the first place.

2.1 Common shortcomings

Despite its importance, instrumentation at remote Arctic mine sites is often treated as an afterthought rather than as long-term infrastructure. This is evident in the condition of many monitoring networks observed during closure inspections.

Common issues include exposed or poorly protected cables that are damaged by wildlife or degraded by weather; instruments that cannot be located due to poor documentation, burial by sediment or snow, or loss of surface markers; flooded dataloggers caused by inadequate sealing or insufficient elevation; and monuments that have broken, tipped over, or deteriorated over time. In some cases, instruments are technically intact but unusable because specialist cables, software or expertise are no longer available.

From Arctic closure experience, most instrumentation issues at remote sites come down to a few recurring problems. Site access is often infrequent and costly, which limits how often instruments can be inspected, maintained, or downloaded. Instruments are exposed to harsh conditions, including freeze–thaw cycles, strong winds, snow cover, prolonged sun exposure, and regular interaction with wildlife, all of which take a toll over time. Instrumentation is also frequently poorly documented. Calibration records may be missing, cables can be mixed up or unidentified, and key installation details such as drilling method, backfill type, instrument depth and the depth of important stratigraphic horizons are often unclear or lost. In many cases, regional baseline data are limited, meaning that site-specific instrumentation becomes the primary, and sometimes only, source of information for interpreting performance.

These failures matter because repairing or replacing instrumentation at remote sites is often difficult or impractical. Reduced site presence during closure means that damage can go unnoticed for long periods, leading to extended data gaps. Where spare parts are not available on site, repairs may be delayed until the next inspection cycle or the instrument may be abandoned altogether, shortening the useful life of the monitoring network and increasing uncertainty at precisely the stage when data are most needed. At remote Australian mines, the climate drivers are different, but the practical challenges are much the same. Heat, cyclones and extreme rainfall place similar constraints on access, durability and long-term data continuity, and raise similar questions on the reliability of instrumentation long after installation.

2.2 Practical takeaways

Closed sites in the North American Arctic have adopted a number of practical approaches to improve the longevity and usefulness of instrumentation networks.

A common learning is that robustness and redundancy matter, because the opportunity to replace failed instruments is limited. Though it seems trivial, instruments that are simple, physically durable and easy to maintain have a higher likelihood of remaining functional over long time frames. While redundancy increases upfront cost, this cost is typically small compared to the risk and expense of remobilisation once a site has entered closure. For example, at an Arctic mine in Nunavut, Canada, 28 thermistor strings were installed to monitor that tailings remained frozen, and 21 remain functional after approximately 20 years of monitoring in an extremely cold and harsh climate. Despite the expected loss of some instruments over time, sufficient redundancy remains because of both instrument density and the use of complementary monitoring methods. Frost gauges, climate records, air temperature monitoring and piezometers are used alongside thermistors to understand the system more holistically.

Protection of instruments and cables is critical. Effective monuments protect instruments from the point where they exit the ground through to the datalogger or data transmission system, limit ingress of moisture and dust, and reduce damage from wildlife or inadvertent contact with equipment. Although many suppliers offer proprietary monuments, experience has shown that adapted solutions using robust site materials, such as timber boxes or repurposed culvert sections, can provide durable and cost-effective protection where logistics or cost constrain standard options (Figures 1 and 2).

Figure 1 Plywood box constructed to protect a vibrating wire piezometer and its datalogger, its location marked with flagging tape and the shelf keeping the datalogger elevated and dry. The photo is taken 15 years after installation

Figure 2 Collecting readings at a vibrating wire piezometer protected with a piece of culvert and capped with a rubber dock cap. This project in Alaska repurposed this leftover material from road improvements to make robust, cost-effective instrument protection

Good records are as important as good hardware and form an essential part of the project's integrated knowledge base (Section 5). Successful sites maintain clear documentation describing the location, purpose, condition and access requirements of each instrument. Photographs and field notes updated during each inspection have proven invaluable for locating obscured instruments years later. The best example encountered was a remote site that stored laminated instrument installation logs and calibration data, chained inside the protective monument.

Many instrument brands require complex proprietary software or cables in order to download data in the field. This has been the cause of countless wasted hours of time to track down old versions of software or to replace misplaced or damaged cables that may be difficult or impossible to procure years later. Sites that use instrument brands favouring common connections like USB-A or USB-C have proven more practical.

Telemetry systems have a clear role where near-real-time data are required, such as during operations when conditions change rapidly and immediate notification is necessary and near-immediate corrective actions can be taken. Once a site moves into closure, monitoring frequencies are typically reduced and these systems are no longer required, except in specific circumstances. Telemetry can be expensive and difficult to maintain where access to hardware is limited and it generates large volumes of data that require ongoing processing and review. Monitoring objectives should therefore drive data collection frequency, with the simplest system possible. Where real-time data are not essential or cannot be acted upon quickly, a robust standalone datalogger is generally more reliable and easier to support over the long term.

In the Arctic, early installation of instrumentation is both critical and difficult. Rapid warming, permafrost degradation and changing hydrological conditions can significantly affect a given site. Without early, site-specific data, it is hard to distinguish climate-driven change from design underperformance. Similar challenges occur at remote Australian mines, where increasing rainfall intensity, temperature extremes and cyclone impacts place comparable pressure on closure assumptions (Bureau of Meteorology & Commonwealth Scientific and Industrial Research Organisation 2022; IPCC 2023). In both settings, long-term decisions are weakened when instrumentation is not installed early enough to capture how sites respond as conditions evolve.

Although climatic conditions differ, the underlying challenges faced by remote Arctic and Australian mines are closely aligned. Instrumentation installed for closure monitoring must be designed to operate within extreme environments, limited resources and long intervals between inspections. For example, sites in the Arctic may remain frozen for a large portion of the year, affecting the measurement of flows in waterbodies due to ice and low recharge. Conversely, but similarly, some ephemeral streams in Australia only flow during wet periods. These challenges make the application of some sensors such as pressure transducers impractical, requiring other forms of instrumentation or remote sensing, such as those discussed in Section 3.

Experience from the North American Arctic demonstrates that effective instrumentation at remote sites depends less on sophisticated technology and more on practical design, protection and documentation. Instruments that are robust, well-protected, clearly documented and understood by successive site teams have the greatest chance of providing continuous, defensible data over the long term. These lessons are directly applicable to remote Australian mine closure and should be considered when designing monitoring systems intended to persist well beyond the operational life of a site. Instrumentation is the starting point for understanding site behaviour because it provides direct, site-specific measurements. However, instruments have a finite lifespan and are spatially discrete, so additional data collection measures such as remote sensing are needed to connect observations across the site and extend the record through time.

3 Remote sensing

Remote sensing has long-standing use in the mining industry; mining was one of the earliest industrial adopters of these methods (Hegyi 1990; Sabins 1999). By the early 1990s, satellite remote sensing was sufficiently mature to challenge conventional mapping approaches in mineral exploration (Hegyi 1990). Despite the established capabilities in Australia, remote sensing remains an opportunity for advances in mine closure (Digital Earth Australia 2021). In access-constrained regions, Arctic North America and remote Australian sites alike, remote sensing has the potential to influence mine closure just as it has mineral exploration. In these regions, where long monitoring time frames and climatic uncertainty challenge the reliance on inspection-based programs alone, remote sensing fills the gaps between infrequent inspections. Remote sensing is best viewed as additional evidence for assessing closure performance, rather than as a substitute for field monitoring and instrumentation. In this paper, remote sensing refers to satellite, airborne and drone-based data that are categorised into elevation, imagery and climate data.

3.1 Baseline topographic data

For remote closure practice, spatial datasets should be collected proactively, even where the immediate application is not evident. Site-wide topographic datasets such as drone-based lidar or photogrammetry are now inexpensive and simple to collect. They can provide baseline conditions against which future change may be assessed. The importance of these datasets is often only realised years later, when retrospective analysis is required to understand the development of erosion features, drainage evolution or landform changes. These processes often develop over long time frames and may not be readily captured through discrete inspections or point-based instrumentation. The absence of such baseline topographic datasets can significantly constrain the ability to assess change, particularly at legacy sites where closure performance must be evaluated long after construction is complete.

3.2 High-resolution imagery

High-resolution imagery has many uses through closure and can often be compared to historical aerial photographs and regularly collected in closure from a drone or satellite. Imagery can be analysed to quantify vegetation growth to meet closure objectives. Simple indices such as the Normalised Difference Vegetation Index (NDVI), developed for agriculture, are now common in mine closure in Australia and the North American Arctic alike, while more complex methods, such as high temporal comparative indices and machine-learning object identification, are underutilised (McKenna et al. 2020). Most mine closure studies that use these methods are academic in nature, rather than used as part of a regulatory framework to measure performance objectives (McKenna et al. 2020). The availability of historical satellite datasets further allows for retrospective assessment of site behaviour, providing additional context for interpreting current conditions. This comparison can be a powerful tool in in assessing end land use goals, ecosystem resilience, species composition, and the impacts of extreme weather and climate change.

3.3 Satellite-augmented climate data

Another area of development is the increasing availability of satellite-derived or augmented environmental datasets that can provide context for interpreting closure performance. Precipitation, evapotranspiration, temperature and soil moisture can now be estimated at regional scales using satellite observations and climate reanalysis models, from products like the Global Precipitation Model (GPM) or Integrated Multi-satellitE Retrievals for GPM (IMERG). Satellite-augmented reanalysis products like the Canadian Precipitation Analysis (CaPA), derived primarily from rain gauges and weather radar, are combined with a numerical weather prediction that incorporates satellite information indirectly, rather than from satellite precipitation retrievals directly. These datasets can provide insight into the external drivers influencing landform behaviour, particularly where site-based climate monitoring is sparse or discontinuous (Huffman et al. 2020; Muñoz-Sabater et al. 2021). In remote settings, they can support interpretation of observed change, provide context for extreme events and assist in evaluating closure performance under changing climatic conditions, in the absence of maintained weather stations.

3.4 Arctic example

An example from the authors' experience is from a legacy mine site in the North American Arctic. The site has recorded topographic changes of a designed tailings cover for over a decade during annual site inspections. Due to the scale, it is difficult to assess the rate of change of the overall landform and to predict future evolution with visual inspections alone. The interpretation of rate of change differed based on personnel and subjective observations were difficult to interpret. The site is now using Sentinel 1 InSAR, dating back to 2017, to build topographic change models. While understanding the last decade of topographic change is very powerful on its own, the site is constrained by the lack of high-resolution elevation data following closure construction in the early 2000s. Public datasets, including ArcticDEM (Porter et al. 2023) have been used in lieu of baseline topography collected during operations. The weather station at the mine was discontinued once there was no longer a continuous site presence. In its place, satellite-augmented precipitation conditions from CaPA were used to interpret the tailings cover landform evolution and correlated to the nearest maintained weather station. Without the use of remote-sensing data through closure, understanding the landform evolution would not be possible. At present, the mine is building a case to use remote sensing to measure the site's performance objectives by building confidence in the data with in-person verification.

3.5 Practical takeaways

North American Arctic applications demonstrate the value of remote sensing for monitoring remote, data-sparse environments despite considerable limitations, including low satellite revisit frequency, unfavourable observation geometry and persistent snow and cloud cover. These limitations were addressed by correlating satellite-measured changes with high-resolution drone-based lidar and field observations, and by using shorter change detection intervals with careful quality control to compare data only from reliably cloud- and snow-free periods. Although the conditions for remote sensing in Australia are not directly analogous, many of the same approaches are applicable. Compared to North American Arctic, Australia benefits from more frequent satellite observations and more consistent acquisition geometry, although some regions are affected by seasonal cloud cover associated with monsoonal and tropical weather systems. In both regions, the primary driver of remote sensing in mine closure is the ability to monitor site performance without frequent site access.

Key lessons from Arctic practice that may be applicable to remote Australian mines include the early establishment of site-wide baseline datasets (e.g. lidar), integration of topographic change detection (e.g. InSAR), satellite derived climate monitoring (e.g. GPM), high temporal imagery change indices (e.g. dNDVI) into routine closure surveillance of landform performance. These tools can complement field observations, reduce uncertainty between discrete data points and monitoring intervals and improve understanding of landform performance. Once established, the combined knowledge base of instrumentation and remote sensing can inform closure design, construction and long-term monitoring. However, monitoring alone cannot compensate for deficiencies in closure implementation. Long-term performance in remote settings depends on closure objectives being incorporated into design and construction from the outset.

4 Design and construction

Design and construction decisions affect long-term closure outcomes at remote mine sites. Once a site enters closure, opportunities for corrective intervention become increasingly constrained by costs and available staff and equipment. As a result, long-term closure performance in remote settings is often determined more by design and construction decisions made during operations than by actions taken after closure begins.

Experience from Arctic mine closure highlights the value of performance-oriented design approaches that acknowledge long time frames and uncertainty. These approaches include design decisions such as gentler slope angles, thicker or more robust erosion protection, use of natural materials in place of synthetics and landform geometries that reduce sensitivity to localised failures or extreme events. Designs that rely on narrow performance margins, precise construction tolerances, or ongoing intervention are generally poorly suited to remote closure contexts. In short, closure design at mines in these regions merits a more conservative approach to reduce future maintenance and liability.

4.1 Material selection

Material selection is particularly important. Figure 3 shows an example from a mine in the high Canadian Arctic, where careful control of the allowable grain size distribution resulted in material with effective self-armouring behaviour. Coarser particles remain at the surface and provide erosion resistance, despite the loss of some finer material downslope. A closer, cheaper and more abundant shale material was also available and may have been selected under a different design basis. The additional effort invested in material sourcing and quality control during construction has resulted in strong long-term performance and minimal maintenance, even after more than 2 decades of observation.

Arctic and Australian closure designs can face almost opposite borrow material constraints. Arctic sites may struggle to source low-permeability fills because glacial landscapes and low rates of chemical weathering limit the availability of suitable fine materials. Australian sites may have the reverse problem where intense chemical weathering can produce abundant fines, albeit with a higher prevalence of reactive or dispersive clays, while durable coarse rock for armour, drainage, or erosion protection may be scarce. The geochemical acceptance threshold for closure fills is also generally higher in Australia, where the higher rates of chemical weathering break down materials that might remain stable for much longer in an Arctic setting dominated by physical weathering. The transferable lesson from the above Arctic example is the decision process, not the material specification. Closure materials should be characterised and then selected in consideration of the long-term life cycle cost rather than the physical proximity or construction cost alone.

Figure 3 Self armouring on fill slope at an Arctic mine site

Using materials, vegetation and geomorphic features already present on site takes advantage of systems that have demonstrated performance under local environmental conditions. Where possible, landforms can be designed to reflect natural drainage patterns and topographic scales, reducing the likelihood of persistent erosion features or unstable transitions. These principles are especially relevant for cover systems, waste rock landforms and tailings-related structures, where long-term surface processes can dominate closure performance.

4.2 Importance of closure trials

Experience from the Arctic has shown that there is no substitute for site-specific closure trials during operations. Trials left until after cessation of mining are typically less valuable because closure schedules compress the time available for design refinement and construction decisions. Closure trials may include progressive reclamation areas, test covers, erosion trials, water treatment systems, or revegetation plots. They provide insight into actual field performance under site conditions, particularly where regional precedent is limited or absent. Rykaart et al. (2006) point out that most mine waste covers internationally are built without undertaking any trial at all.

In the study jurisdictions, closure trials have become standard practice and are embedded in most legislation and industry guidance, but their practical value is often undermined by poor execution. A Queensland Mine Rehabilitation Commissioner review found wide variation in how mine waste cover trials were planned, implemented, monitored and reported, with case studies affected by short durations, equipment failure, construction deviations and limited demonstration of field-scale constructability or performance (Dunlop et al. 2025). In practice, a trial that is too small, too late, poorly monitored, or disconnected from final design decisions may satisfy a planning requirement while still failing to reduce closure uncertainty.

The Faro Mine Complex in the Yukon illustrates why closure trials should begin before closure becomes the primary site activity. Despite conducting closure trials, a subsequent gap assessment identified key unresolved questions with respect to cover performance and constructability that required additional field trials before design could be advanced (CH2M HILL 2012), resulting in delays. For remote mines, this reinforces the need for high-quality field trials that set out to address key uncertainties, rather than simply satisfy a regulatory criterion. Closure trials undertaken during operations also allow monitoring strategies to be tested and refined. Instrumentation layouts, surface inspection criteria, photo monitoring points and remote sensing approaches can be evaluated under real conditions and adjusted before closure obligations become binding. Importantly, trial areas provide a shared reference point for operators, regulators, consultants and Traditional Owners to develop a common understanding of expected performance, supporting later decision-making.

4.3 Robust design

Robust design is design that remains safe and functional despite uncertainty, variability and imperfect implementation, through the use of redundancy, assumptions that consider appropriate uncertainty and variability, and by avoiding reliance on a single control or narrow performance margin. This concept holds true across different project scales and locations. For example, at small remote mines, closure designs are often developed with less complete datasets than those available at larger or more accessible sites; in such contexts, robustness may be achieved by compensating for uncertainty through the use of more conservative design parameters (e.g. shallower slopes).

Redundancy is a key part of robust design and is a recurring theme in Arctic closure practice. Redundant instrumentation, overlapping monitoring methods and repeatable measurement approaches, such as fixed photography or repeat topographic surveys, reduce reliance on a single dataset or system. While redundancy carries an additional cost, it is often modest relative to the cost of remobilisation once a site enters closure.

4.4 Passive design

Where possible, closure designs favour passive systems that do not rely on ongoing power supply, active operational control, or frequent maintenance. Passive drainage controls, erosion protection and geochemical controls reduce long-term stewardship requirements and are more compatible with infrequent site access. Constructing these systems while operations are still active generally improves quality control and reduces long-term risk. Examples include Ekati Mine's closure objective of limiting concentrated flow to avoid erosion in excess of the natural tundra (Dominion Diamond Ekati Corporation 2018) and sourcing tailings cover material from local carbonate-bearing materials to reduce acid rock drainage potential at Nanisivik Mine (BGC Engineering 2004). The same design challenges apply in Australia, but instead of issues related to icing, frost heave or thaw subsidence, companies have to contend with higher rainfall events, longer dry periods, higher evapotranspiration and faster chemical weathering.

4.5 Flexibility and timing

Closure planning at remote mine sites involves a trade-off between timing and flexibility. Progressive reclamation carried out too early can restrict future mine plan changes or require rework, while delaying closure increases the risk that resources, access and technical capability will no longer be available to complete the work effectively. In practice, this tension is often managed through incremental closure works and operational-phase trials that reduce uncertainty while preserving future flexibility. Nanisivik Mine in Nunavut illustrates the value of closure planning during operations. Although the mine was expected to operate until 2004 or 2005, mining ceased in 2002 after reassessment of economic ore reserves. Progressive reclamation planning and test cover monitoring already completed during operations later informed the cover design and supported regulatory acceptance of the reclamation plan (Claypool et al. 2007).

Conversely, the Baal Gammon Mine in north Queensland was an operation which started and stopped and changed hands. Underground mining occurred at the site for over 100 years, followed by a brief open pit phase from 2011 through 2016 (Hall et al. 2022). After 3 years of suspended operations and environmental compliance citations, the leases were cancelled, the mine abandoned, and responsibility shifted to the Queensland Government. At the time of abandonment, the limited reclamation work completed on the site, such as the liner above the main waste rock dump, were ineffective (Hall et al. 2022). Ultimately, the cover methodology selected for the urgent works was constrained by material availability, budget and contractor capability, instead of a proven and tested system developed during operations. Had these trials been completed similarly to the Nanisivik example, the time to construction may have been reduced and there may have been a tested and constructable method available.

4.6 Practical takeaways

Closure performance is largely determined by decisions and implementation immediately following operations, informed by data collected and planning undertaken throughout the mine life cycle. This is particularly true for remote mine sites, where long-term equipment and labour constraints limit opportunities for intervention. Closure design should therefore be robust, allowing for uncertainty in future conditions and incorporating redundancy and passivity in critical design elements. Reliance on site-specific closure trials, rather than precedent from other sites, is essential, with trials implemented early to preserve flexibility. Together, these measures reduce long-term risk and support pathways to relinquishment.

5 Integrated knowledge base

The preceding sections highlight the need for instrumentation, remote sensing, and design and construction decisions to remain robust with limited future intervention. Each depends on continuity of knowledge. Data, designs and monitoring systems only remain useful if future custodians can understand why they were collected, how they were interpreted and what assumptions they were meant to test. An integrated knowledge base is therefore more than simply document control. The mining industry's main challenge is not a lack of technical knowledge on tailings behaviour, but ensuring that existing knowledge is properly accessed, applied and held by those responsible for decisions across the full life cycle of a facility (Evans & Davies 2020). As a result, the integrated knowledge base has been made a core requirement within the Global Industry Standard on Tailings Management (GISTM) conformance protocols (ICMM 2020). This concept extends beyond tailings, as effective management of knowledge and decision-making continuity is critical across all aspects of mining operations.

5.1 Non-linearity of the mining life cycle

Remote mines can operate for decades, in addition to prior lengthy exploration, permitting and financing phases that can themselves take a decade or more. Subsequent closure construction can take years, and post-closure monitoring can be in perpetuity. Over such time frames, changes in site personnel, mine ownership (or operatorship) and consultants are common. Changes in instrumentation and monitoring technology will occur over this time. Regulatory frameworks may shift or evolve. If this is not already challenging enough, it is also common for 'closed' sites to resume exploration, resume mining operations, or reprocess mine tailings, or for operating mines to go into care and maintenance unexpectedly, for a variety of reasons. This concept is discussed in more detail by Purtill (2023) who explain how the mining profession typically conceptualises the mining life cycle as an idealised linear process, despite the fact that it rarely actually is. This concept is illustrated in Figure 4, which shows the idealised life cycle, and Figure 5 that illustrates an example life cycle with common complexities.

Figure 4 Idealised mining life cycle

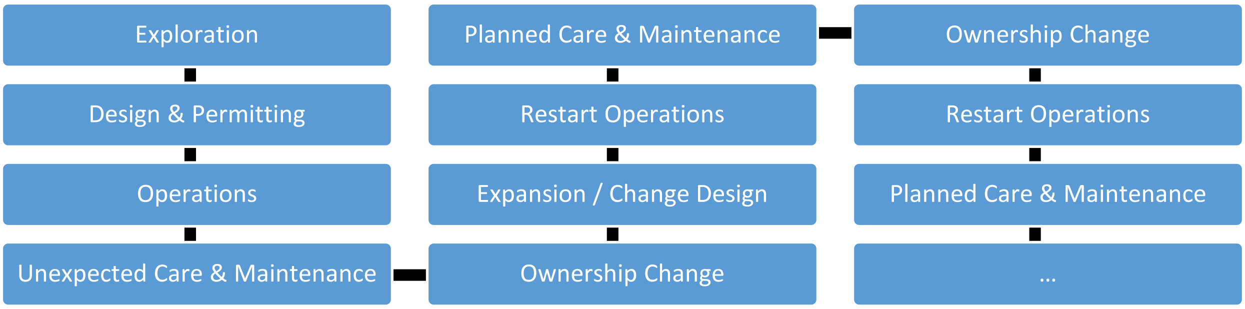

Figure 5 Example mining life cycle

5.2 Loss of institutional knowledge

Each phase of the mining life cycle introduces different requirements for data collection, analysis and monitoring, often leading to changes in personnel and consultants. While the cumulative volume of data generated over the life of a mine can be substantial, experience at remote sites suggests that the more persistent challenge lies in data continuity: variation in data formats, incomplete documentation, loss of contextual information and breakdowns in custodianship. These issues are amplified at remote mines, where access constraints make retrospective investigation expensive and regulatory scrutiny during closure is often heightened.

It may be helpful to briefly mention a couple of simple examples encountered by the authors:

1. During a site inspection of a closed mine, seepage was discovered through a diversion structure that was built in the 1980s. It was unclear if there was a filter material present downstream of the low-permeability core, and therefore the nature of the risk to the structure was uncertain. This could be easily discerned from construction record drawings but not easily determined in the field without expensive and invasive investigation. After significant effort was spent trying to locate the files, eventually hand-drawn hardcopy maps and schematics were found in the file boxes of the retired engineer who designed it.
2. Elevated metals were discovered during routine monitoring of a creek at a closed remote Arctic mine and it was unclear whether these metals had come from a natural or a disturbed area. There was a need to compare the recent results to pre-mining values (not just to the trigger levels that were made based on that data), which had not been reviewed in over 10 years. These trigger levels were developed by a different consulting firm, through a client representative that now works for another company. It was not possible to obtain these original data, which necessitated additional expensive site monitoring that may not have been necessary.

These examples demonstrate how fragmentation or loss of institutional knowledge can introduce uncertainty, delay decision-making and materially increase costs long after mining activities have ceased. Although records may technically exist, the loss of context, design intent and custodianship can render historical information difficult to interpret or apply. Experience from Arctic mine closure demonstrates that this information loss is a significant issue facing mine closure projects.

5.3 Indigenous knowledge systems

Peer-reviewed research demonstrates that, through oral tradition, Indigenous knowledge systems are capable of preserving accurate information over 500–800 years (Barber & Barber 2004) and potentially more than 7,000 years (Nunn & Reid 2016). For example, Aboriginal Australian oral traditions describing coastal inundation have been shown to correspond with independently reconstructed post-glacial sea-level rise occurring more than 7,000 years ago, using geological and bathymetric data (Nunn & Reid 2016). This study, and others like it from around the world, begs the question of why the mining industry often fails at transferring knowledge on far lesser timescales.

This literature identifies several recurring features that underpin successful Indigenous peoples' knowledge transfer:

- Knowledge is embedded in repeated practice rather than stored as static records and is allowed to evolve with new technology (Gómez-Baggethun et al. 2013).
- Indigenous knowledge systems maintain continuity of custodianship.
- Context and intent are preserved alongside observations.

Examples from Arctic mine closure demonstrate how engagement with Indigenous communities can move beyond consultation toward active knowledge exchange. At the Giant and Faro Mine remediation projects in northern Canada, closure planning has involved sustained collaboration with First Nations and local communities, including the use of shared visualisation tools to communicate design intent, gather feedback and incorporate local knowledge into closure design (Franklin et al. 2022). While not equivalent to implementing an Indigenous peoples' knowledge system, these examples demonstrate how a 2-way flow of knowledge can be applied in mine closure.

5.4 Practical takeaways

When viewed through this lens, many information management challenges encountered across the mining life cycle, particularly at remote sites, can be interpreted as failures to replicate these same conditions. So, what can the mining industry take away from these lessons?

5.4.1 Create in-person overlap

An over-reliance on reports and formal handovers rather than shared experience is a detriment. When transitions occur between phases of the mining life cycle, or when personnel or operators change, new teams are often required to build their understanding almost entirely from historical documentation. These records frequently provide limited insight into why decisions were made or how systems were expected to perform. Deliberate overlap between outgoing and incoming teams helps reduce this risk, particularly when it occurs in the field. Site-based overlap allows monitoring results, design assumptions and emerging issues to be discussed directly, supporting a shared understanding that is difficult to capture in documentation alone. Involving Traditional Owners in these activities could build further overlap and trust.

5.4.2 Add redundancy of knowledge

Critical site knowledge is often concentrated with one or two long-standing individuals, who may be a site representative, engineer, or consultant. When those individuals leave or change roles, important context can be lost even when records still exist. Reducing this dependence requires active effort. Practical steps include ensuring that more than one person understands where key data are stored, how monitoring systems are accessed and how results are interpreted. Rotating responsibilities, mentoring less-experienced staff, and keeping shared data systems current and in use all help maintain continuity.

5.4.3 Maintain context

Loss of knowledge can be less about missing data and more about losing understanding of why systems were designed, monitored, or managed in a particular way. Over long time frames, trigger levels, procedures and monitoring requirements can persist even after their original rationale is forgotten. This can lead to rigid application of inherited guidance without meaningful interpretation. Encouraging practitioners to ask why a system performs as it does, why thresholds were selected, and what assumptions they rely on helps maintain useful understanding over time. Questioning first principles supports better interpretation of site behaviour.

5.4.4 Build a digital twin

A digital twin is a virtual representation of a physical site that brings together multiple data sources to support monitoring and decision-making over time. In mine closure, these systems are typically implemented as geospatial digital knowledge bases that integrate instrumentation, remote sensing, environmental monitoring and historical site data within a single platform, allowing site conditions to be viewed and interpreted in context (Burkell et al. 2025). Recent applications demonstrate how these platforms can improve accessibility of historical information, integrate monitoring datasets and support more efficient and proactive interpretation of closure performance over long time frames (Burkell et al. 2025). When kept up to date and built for the right purpose, digital twins encourage knowledge to be revisited and used through routine work, rather than stored and forgotten. By bringing together instrumentation, remote sensing and site observations in a shared environment, knowledge is less dependent on individual people and more likely to persist through changes in staff, consultants and ownership. In this way, digital twins reflect some of the same features of Indigenous peoples' knowledge transfer mentioned above: repetition, shared custodianship and the retention of context alongside observations.

6 Conclusion

Closure at remote mine sites is constrained by access, time and the reality that many decisions become difficult or impossible to reverse once operations cease. Experience from North American Arctic mine closure reinforces that long-term performance is mostly set early, through how sites are instrumented, designed and documented before closure formally begins and before equipment and qualified personnel are off site. This is commonly observed at closed mine sites, where closure performance issues trace back to late operational decisions rather than post-closure management.

Across the examples discussed, approaches that favoured durability over optimisation consistently performed better. Instrumentation that was simple, protected and well recorded proved more reliable than complex systems. Similarly, baseline remote-sensing datasets collected before they were strictly needed later became essential for interpreting change and giving quantitative confidence to regulators of the site's performance. Landform design that compensates for uncertainty, includes passive controls, and has trials carried out during operations, reduced uncertainty far more effectively than remedial measures attempted after closure.

Technical measures alone are not enough. Over the long time frames characteristic of mine closure, loss of context can be as limiting as loss of data. Arctic closure experience highlights how quickly assumptions and design intent can be forgotten as personnel and ownership change. Knowledge systems that preserve intent alongside observations, and that remain actively used rather than archived, are more likely to support sound decision-making decades later. Several North American Arctic mine sites have functioning instrumentation and available remote-sensing data that cannot confidently be interpreted because the original rationale, construction records and assumptions are no longer documented or known.

These practices are not unique to the Arctic, nor can they be transplanted directly into Australian regulatory or environmental contexts. What is transferable are the underlying principles: make decisions while access and knowledge still exist, favour robustness to account for uncertainty, and treat long-term knowledge as essential infrastructure rather than an administrative task. For remote Australian mines, applying these principles offers a practical way to reduce long-term risk and strengthen confidence in closure.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Microsoft Copilot version 20260506.29.3 to improve the clarity of language, and in select cases, to search literature for sources. The authors have reviewed the content and edited it where required and take full responsibility for said content. The authors believe that their use of AI assistance is in accordance with the Australian Centre for Geomechanics policy dated 7 November 2025.

References

Barber, EW & Barber, PT 2004, *When They Severed Earth from Sky: How the Human Mind Shapes Myth*, Princeton University Press, Princeton.

BGC Engineering Inc 2004, *Cover System Design Report for Nanisivik Mine*, Prepared for Nanisivik Mine, A Division of CanZinco Ltd, https://ftp.nwb-oen.ca/registry/1%20INDUSTRIAL/1A/1AR%20-%20Remediation/1AR-NAN2030/3%20TECH/J%20A%20and%20R/2004/G3%20Final%20Closure%20Plan/2004%20Final%20AR%20plan/G.4%20Cover%20Report/G.4%20Report/G.4%20Cover%20Report%20Final.pdf

Bureau of Meteorology, & Commonwealth Scientific and Industrial Research Organisation 2022, *State of the Climate 2022*, Australian Government, https://www.bom.gov.au/sites/default/files/2022-11/state-of-the-climate-2022.pdf

Burkell, K, Adams, M, Zahradka, A, Dagenais, A-M & Lato, M 2025, Driving innovation in mine closure monitoring through automation and an integrated digital knowledge base, *Proceedings of the Life of Mine 2025 Conference,* Australasian Institute of Mining and Metallurgy, Melbourne.

CH2M HILL 2012, *Faro Mine Remediation Project Gap Assessment Report*, prepared for the Faro Mine Remediation Project Management Office, Government of Yukon, https://emrlibrary.gov.yk.ca/aam/gap-assessment-report-faro-mine-remediation-project.pdf

Claypool, GK, Cassie, JW & Carreau, R 2007, 'Reclamation of frozen sulphidic tailings area – Nanisivik Mine, northern Canada', in *Mine Closure 2007: Proceedings of the Second International Seminar on Mine Closure*, Santiago.

Digital Earth Australia 2021, *Extracting the Benefits of Earth Observation*, Geoscience Australia, https://www.ga.gov.au/dea-archived/news/DEA-Report-Extracting-Benefits-of-Earth-Observation-2021.pdf

Dominion Diamond Ekati Corporation 2018, *Interim Closure and Reclamation Plan (Version 3.0)*, Wek'èezhìı Land and Water Board, https://registry.mvlwb.ca/Documents/W2012L2-0001/W2012L2-0001%20-%20Ekati%20-%20ICRP%20-%20Version%203.0%20-%20Part%202%20-%20Aug%2015_18.pdf

Dunlop, J, Nicolson, L & Purtill, J 2025, *Mine Waste Cover System Trials – A Comparative Review of Case Studies: Technical paper 2*, Office of the Queensland Mine Rehabilitation Commissioner, Queensland Government, Brisbane, viewed 25 June 2026, https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0029/395354/mine-waste-cover-trials-case-study-review.pdf

Evans, R & Davies, M 2020, 'Creating and retaining knowledge and expertise', in B Oberle, D Brereton & A Mihaylova (eds), *Towards Zero Harm: A Compendium of Papers Prepared for the Global Tailings Review*, Global Tailings Review, London, p. 150.

Gómez-Baggethun, E, Corbera, E & Reyes-García, V 2013, 'Traditional ecological knowledge and global environmental change: Research findings and policy implications', *Ecology and Society*, vol. 18, no. 4, https://doi.org/10.5751/ES-06288-180472

Hall, TL, Friend, AJ, Stones, AJ & Grabski, AS 2022,' Queensland's abandoned mine lands program and the Baal Gammon Copper Mine Remediation Project', *Proceedings of the12th International Conference on Acid Rock Drainage*, The University of Queensland, Brisbane.

Hegyi, F 1990, 'Remote sensing techniques in environmental monitoring', *Proceedings of the 14th Annual British Columbia Mine Reclamation Symposium*, British Columbia Technical and Research Committee on Reclamation, Vancouver.

Huffman, GJ, Bolvin, DT, Braithwaite, D, Hsu, K, Joyce, R, Kidd, C, … Xie, P 2020, 'Integrated multi-Satellite retrievals for the global precipitation measurement (GPM) mission (IMERG)', in V Levizzani, C Kidd, DB Kirschbaum, CD Kummerow, K Nakamura & FJ Turk (eds), *Satellite Precipitation Measurement,* Springer, Berlin, pp. 343–353.

Intergovernmental Panel on Climate Change 2023, *Climate Change 2023: Synthesis Report*, https://www.ipcc.ch/report/ar6/syr/

International Council on Mining and Metals, 2020, *Global Industry Standard on Tailings Management*, London, https://www.globaltailingsreview.org/the-standard/

Kabir, SMZ, Rabbi, F, Chowdhury, MB & Akbar, D 2015, 'A review of mine closure planning and practice in Canada and Australia', *World Review of Business Research*, vol. 5, no. 3, pp. 140–159.

Mckenna, PB, Lechner, AM, Phinn, S, Erskine, PD 2020, 'Remote sensing of mine rehabilitation for ecological outcomes: a global systematic review', *Remote Sensing*, vol. 12, no. 21, http://doi.org/10.3390/rs12213535

Muñoz-Sabater, J, Dutra, E, Agustí-Panareda, A, Albergel, C, Arduini, G, Balsamo, G, … Thépaut, J-N 2021, 'ERA5-Land: A state-of-the-art global reanalysis dataset for land applications', *Earth System Science Data*, vol. 13, no. 9, pp. 4349–4383, https://doi.org/10.5194/essd-13-4349-2021

Nunn, PD & Reid, NJ 2016, Aboriginal memories of inundation of the Australian coast dating from more than 7,000 years ago, Australian Geographer, 47(1), 11–47, https://doi.org/10.1080/00049182.2015.1077539

Porter, C, Howat, I, Noh, MJ, Husby, E, Khuvis, S, … Morin, P 2023, *ArcticDEM – Mosaics*, version 4.1, Harvard Dataverse, https://doi.org/10.7910/DVN/3VDC4W

Purtill, JA 2023, 'Re-thinking our model of mine rehabilitation and closure—is it time for a new model of mined lands stewardship?', in B Abbasi, J Parshley, A Fourie & M Tibbett (eds), *Mine Closure 2023: Proceedings of the 16th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, https://doi.org/10.36487/ACG_repo/2315_089

Rykaart, M, Hockley, D, Noel, M & Paul, M 2006, 'Findings of international review of soil cover design and construction practices for mine waste closure', in RI Barnhisel (ed.), *Proceedings of the 7th International Conference on Acid Rock Drainage (ICARD)*, American Society of Mining and Reclamation, pp. 1804–1822.

Sabins, FF 1999, 'Remote sensing for mineral exploration', *Ore Geology Reviews*, vol. 14, no. 3–4, pp. 157–183, https://doi.org/10.1016/S0169-1368(99)00007-4