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Application of digital innovation and automation for sustainable mine closure monitoring

Marc Adams [a,*], Katie Burkell [b], Anne-Marie Dagenais [a], Matthew Lato [a], Aron Zahradka [b]

[a] *BGC Engineering, Canada*

[b] *Cambio Earth, Canada*

Abstract

Effective mine closure monitoring is crucial for environmental protection, regulatory compliance and long-term stability of post-mining landscapes. Closure monitoring provides information on the site's condition and progress towards meeting the defined success criteria. Current techniques and approaches can be robust, but often lack integration and automation, leading to inefficiencies and missed opportunities for proactive management. This paper demonstrates how a geospatial digital knowledge base can transform mine closure monitoring by integrating diverse datasets, automating analysis and providing actionable insights.

The proposed approach includes the automatic ingestion, processing and visualisation of remote sensing, instrumentation and inspection data. By pairing historical data with closure criteria, and automatically integrating real-time data, owners have a comprehensive and up-to-date understanding of site conditions, facilitating timely and informed decision-making. By enhancing data management and analysis, project efficiency and compliance can be significantly improved, ultimately leading to more effective mine closure outcomes.

Integrating real-time instrumentation data provides a dynamic view of site conditions, enabling early detection of potential risks. Summary dashboards consolidate these datasets and compare them against closure criteria, streamlining reporting processes and facilitating regulatory compliance. Finally, access to historical site information through the knowledge base accelerates root cause analysis in the event of anomalies or failures, saving time and resources while improving decision-making.

This paper highlights the application of innovative monitoring approaches by providing an example application to a closed tailings storage facility. By leveraging the Cambio™ platform, complex earth science data can be transformed into actionable insights, enabling better decision-making and risk management. For mine closure, this approach provides a holistic, proactive and cost-effective solution for long-term site management.

Keywords: *mine closure, monitoring, knowledge base, automation, lidar, photogrammetry, InSAR, multispectral/hyperspectral imagery, remote sensing, change detection, Cambio*

1 Introduction

Effective mine closure monitoring is crucial for the environmental protection, regulatory compliance and long-term stability of post-mining landscapes. Current techniques and approaches can be robust but often lack integration and automation, leading to inefficiencies and missed opportunities for proactive management. This paper demonstrates how a geospatial digital knowledge base can transform mine closure monitoring by integrating diverse datasets, automating analysis and providing actionable insights.

[*] Corresponding author. Email address: madams@bgcengineering.ca

1.1 Overview of mine closure monitoring

Mine closure objectives vary for each project but are considered to commonly include achieving physical, chemical and ecological stability, effectively managing risks and achieving long-term care of the facility. The International Council on Mining and Metals (ICMM) has provided a Good Practice Guide for Integrated Mine Closure (ICMM 2025) that describes common objectives and how monitoring fits into the closure project. A mine closure plan requires a comprehensive understanding of site conditions, as well as an understanding of how the established high-level objectives translate to site-specific objectives. Site-specific objectives can include defined post-closure land use, meeting criteria for success, achieving social transition and defining what relinquishment of the site looks like – all of this aligned with the expectations of engaged stakeholders. Closure monitoring provides information on the condition of the site and the performance towards meeting the criteria for success.

A robust knowledge base is needed to inform the closure design but also to support monitoring, maintenance and management during execution. As described in ICMM (2025) the knowledge base supports the domain model as well as monitoring, measurement and inspections. The domain model includes not only technical information, but also historical information and local/traditional knowledge (when available). Such a diverse knowledge base is necessary in the management of a closed mine site; however, that broad nature of the knowledge base creates challenges in the management and accessibility of relevant information to inform decisions. Tones et al. (2021) provide a useful summary of the challenges of building and maintaining a knowledge base that provides coherent and timely access to data that informs closure planning but is also directly applicable to closure execution. Incorporating closure monitoring data from a broad spectrum of sources and instrument types into the knowledge base adds to the challenge, particularly when the post-closure reduction of site resources is considered.

1.2 Current data management and software strategies

Historically, data management and project information have been maintained through reports, drawings and fragmented geographical information systems. This traditional approach, while necessary for documentation and regulatory reporting, often results in static interpretation of data which may be difficult to interpret and understand in a more comprehensive sense and would benefit from being viewed and analysed dynamically as new information becomes available. Relying on consultants or computer-aided design teams to produce drawings or models can lead to significant delays in decision-making, with turnaround times extending to weeks or months. By then the data may be outdated, obsolete and unable to impact real-time decisions effectively. By digitising the data, it becomes possible to manipulate and interrogate it in real-time, facilitating informed decisions.

Engineers and owners often require multiple applications to achieve a comprehensive understanding of onsite activities, and many software applications are limited to office use due to network connectivity requirements. A more effective approach could be a digital knowledge base that continuously integrates near-real-time data with historical data, providing a dynamic and evolving understanding of the current conditions at the mine site and a holistic understanding at every stage of the mine life cycle. As the project progresses and more data becomes available, effectively managing and analysing this growing dataset becomes increasingly crucial. Automated data integration empowers teams to assess hazards, changing conditions or potential non-compliance issues in near-real-time. This paper describes an approach that aligns with the recommendations from ICMM, utilising a geospatial digital knowledge base, Cambio™, which integrates diverse datasets, provides automation in support of analysis and results in actionable insights.

Cambio integrates data sources, including remote sensing, instrumentation, field observations and historical project information (designs, reports, site characterisation data, and baseline and operational monitoring data), into a single platform available on web and mobile (Figure 1). Its application program interface-driven architecture supports integration with existing systems, maintaining data ownership while enhancing visualisation and analysis.

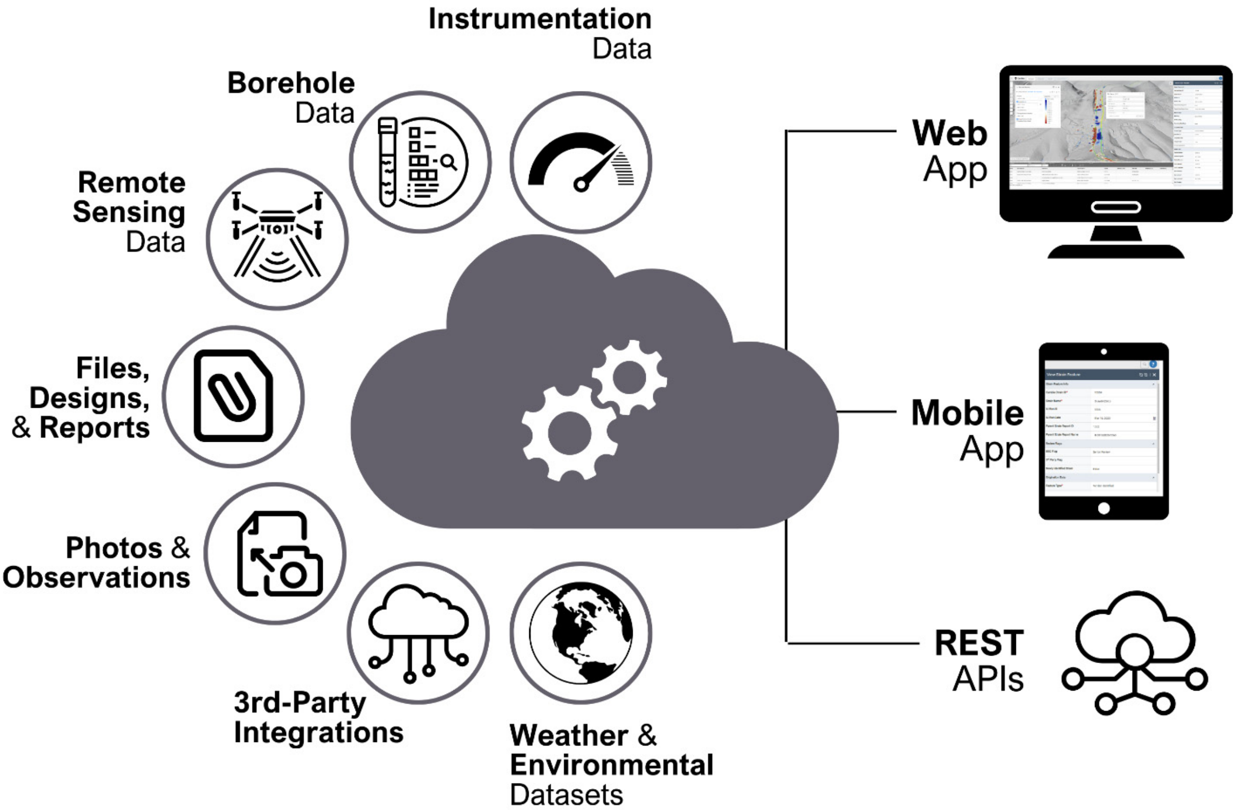

Figure 1 Schematic of an integrated platform model with automated ingestion pathways and various data accessibility options

The following sections discuss closure landforms and the associated monitoring requirements for closure, then highlight how key aspects of the Cambio platform could be used to enhance the monitoring of closed mining projects.

2 Closure landforms

Closure landforms resulting from mining, whether they are waste rock piles, mine pits, various stockpiles or tailings storage facilities, will require some form of monitoring to inform closure performance assessment and for regulatory compliance. The main components of a closure landform can include vegetation, cover systems, its geometry and surface water (SW) management infrastructure.

Vegetation can be a control of both physical stability (controlling erosion and pore water pressure) and chemical stability (controlling water ingress and the creation of contact water). Landform covers themselves (upon which the vegetation may be established) also contribute to the control of these same stabilising processes. Covers can isolate and divert clean water from disturbed (source) materials and keep it clean. They can limit infiltration and mitigate the creation of contact water, as well as reduce the driving forces for migration of that contact water. Limiting infiltration can also lower pore pressures to enhance physical stability. Oxygen ingress might also be controlled to limit conditions that degrade the contact water.

The geometry of the landforms themselves can also limit the creation of contact water and limit the impact extent of that contact water. It can contribute to water management such that recharge is further limited, and clean water is directed around areas at risk of chemical impacts.

The physical stability of landforms must be monitored to confirm those landforms are performing as the design intended. The health of the vegetative component (if present) of cover systems can also be monitored to confirm those covers are performing as the design intended. Discharging water (seepage and run-off) from the site can be monitored to confirm it is meeting the performance objective of promoting ecological stability of the receiving environment. Quantification of water within the water management system can confirm the overall water balance is meeting the design intent.

3 Closure monitoring principals

3.1 Current monitoring techniques and challenges

Following is a description of the primary processes or components of the closure landscape and how they might be monitored to assess performance in closure:

- Vegetation establishment monitoring ranges from onsite inspection with ground level surveys (and, in some cases, sample analysis) to lidar surveys and InSAR remote sensing techniques. Sage et al. (2022) present an example of the latter approach.
- Landform geometry monitoring typically involves topographic surveys or deformation instrumentation, sometimes with comparison to (and calibration of) settlement models as well as inspections. Identification of settlement or other geometry changes can trigger maintenance to preserve the function of the landform. Brink & Heymann (2024) discuss post-closure fill settlement and a risk management framework to address it, including monitoring observations (as part of a broad knowledge base).
- SW flows/drainage pattern disruption is typically monitored through instrumentation, inspection and surveys. Observations can identify stagnation points (i.e. ponding that can enhance infiltration) or drainage patterns that depart from the design. Departures from the design can result in unanticipated concentration of flows, causing erosion that can further disrupt drainage patterns and degraded SW quality, and can degrade the cover system. Flow quantity readings can trigger site inspections as SW flow patterns vary from historic or modelled values. Crisp et al. (2024) present an example of the application of lidar to monitor stability and erosion of rehabilitated landforms.
- Water balance updates can assess changes in water movement. The flow pattern changes discussed above can be precursors to larger shifts in the water balance that can have a significant impact on the overall performance of the landform’s physical and chemical stability. For example, this shift can give rise to changes in the area or volume of a pond that forms part of the closure landscape, which can lead to shifts in infiltration and evaporation quantities, changes in discharging water quality, etc.
- Cover performance can be inferred by analysis of SW flows, water balance updates and pore pressure measurements, or it can be directly assessed by monitoring the infiltration rates or the soil moisture profile of the cover system. Ultimately, measurement of groundwater levels, or the quality of the underlying or downgradient groundwater (see below) may inform this aspect.
- Water quality monitoring is typically done at a minimum at the receiving environment and other compliance points (e.g. upgradient points to inform timely remedial responses). A rising trend of contaminants at the site discharge point without any apparent changes in the landform may indicate that the landform is not achieving chemical stability. This is a direct and comprehensive measure of overall performance of the closure controls; however, it does not immediately identify the location of the performance gap and is reactive to performance shortcomings that may have been years in the making.
- Monitoring the ecological health of the receiving environment is perhaps an ultimate measure of performance, as it is a comprehensive measure of performance of the site controls in combination with other natural or ancillary processes. Responses to these monitoring triggers are reactive and require an understanding of the root cause of the observed trigger.

The monitoring components described above are at different placements along the pathway from source to receptor. Identification of performance gaps earlier in the pathway provides more time to address issues while maintaining compliance, often more easily remediated than if addressed later and likely nearer to the root cause of the performance gap. For example, deficiency in the integrity of the cover or in the diversion of clean water can be more efficiently and effectively addressed than remediation of a fully developed contact water plume.

Effective mine closure monitoring including all the monitoring aspects described above is crucial to achieving closure objectives. There are many approaches to mine closure monitoring that strike individual balances between effectiveness and efficiency. An opportunity exists to apply an approach that integrates the disparate aspects of mine closure monitoring, allows automation of data gathering or management and supports proactive management of the site.

3.2 Geospatial digital knowledge base for closure monitoring

Safe mine closure and monitoring require collaboration across multidisciplinary groups and clear communication of complex subjects to stakeholders with varying levels of technical backgrounds. Large quantities of data are produced throughout a mine's life cycle and, as data collection becomes easier, the effective management of the data becomes more challenging. Additionally, the regulatory landscape is evolving, and conformance to standards such as the Global Industry Standard on Tailings Management (Global Tailings Review 2020) encourages operators to develop and maintain an interdisciplinary knowledge base of social, environmental, economic and technical data to inform decisions throughout the tailings facility life cycle, including closure and post-closure phases. The development of an integrated knowledge base allows project teams to access key data (geological, environmental, operational, remote sensing, instrumentation and weather) via a central location which can be used to inform decision-making during mine closure and long-term monitoring. The knowledge base functions as virtual representations of project sites.

The preceding discussion has outlined a framework of closure monitoring, the drivers for each component and some examples of the approaches used to monitor those components. Research is abundant and the body of experience in the application of general monitoring approaches is extensive. This paper will explore three challenges that can be encountered in applying monitoring to closed sites:

- Data accessibility: as closure-related datasets grow it becomes more difficult to access and navigate the historical monitoring data needed for a comprehensive understanding of site performance.
- Remote sensing data: technologies like photogrammetry, lidar and satellite imagery offer valuable support for inspections but they generate large, complex datasets that require effective management and integration.
- Instrumentation data: instrumentation from the operational phase provides critical inputs for interpreting closure monitoring results and triggering repair or maintenance actions, but managing and correlating this data with current conditions is a growing challenge.

4 Closure monitoring solutions

Mine closure monitoring is used to help decommissioned sites achieve long-term stability and meet environmental and societal expectations. The process encompasses two primary aspects: performance monitoring, which assesses site conditions against predefined success criteria; and information gathering, which involves documenting and maintaining a database of site conditions throughout the life cycle of the mine, spanning from baseline data collection through operations and into closure. A digital geospatial knowledge base serves as a tool to streamline closure monitoring and the assessment of data arising from those monitoring efforts.

Selecting success criteria for closure using the specific, measurable, achievable, relevant and timely (SMART) approach is recommended (ICMM 2025). The application of the SMART framework to a geospatial digital knowledge base can help define the configuration to align with closure objectives and site-specific requirements. It provides a structured and actionable methodology to select, prioritise and implement the data and functionalities that the digital twin should encompass. The following sections will highlight technical advances in the monitoring space – remote sensing and instrumentation that can be applied to mine closure monitoring and how these data sources are only enhanced by the use of, and integration with, a digital knowledge base.

Cambio could improve mine closure monitoring projects by providing real-time data integration and dynamic analysis capabilities. By pairing historical data with closure criteria, and automatically integrating real-time data, owners have a comprehensive and up-to-date understanding of site conditions, facilitating timely and informed decision-making. By enhancing data management and analysis, project efficiency and compliance can be significantly improved, ultimately leading to more effective mine closure outcomes.

4.1 Data accessibility

As the diverse range of datasets accumulate over the life of the mine, effectively navigating, contextualising and leveraging them for decision-making becomes increasingly complex. The Cambio platform addresses these challenges by providing configurable workspaces and integrated dashboards that significantly enhance data accessibility and usability. Configurable workspaces allow project teams to create, save and share customised views of project data, tailored to specific monitoring objectives or stakeholder needs. This capability streamlines collaboration across multidisciplinary teams, supports review meeting preparation and helps convey complex site information to stakeholders with varying levels of technical expertise.

Additionally, configurable workspaces serve as a comprehensive tool for viewing changing site conditions. By regularly updating the data layers and filters, teams can monitor real-time changes in the environment or infrastructure, or other relevant factors. For example, Engineers of Record have used workspaces to organise and present design elements and monitoring data in a way that supports independent review board discussions, improving transparency and clarity. Complementing these workspaces, Cambio dashboards offer high-level summaries of critical parameters such as instrumentation health, threshold exceedances and compliance status. By integrating these metrics with geospatial data, dashboards enable teams to identify spatial trends, prioritise resources and drill down into detailed datasets when needed. This functionality supports not only day-to-day monitoring but also long-term closure, where understanding performance against closure criteria and compliance obligations is essential. Together, these tools offer a unified, accessible platform that simplifies the complexity of mine site data and helps with informed, timely and transparent decision-making throughout the closure process.

4.2 Remote sensing for settlement, erosion and vegetation monitoring

One of the most significant advances in the earth sciences profession has been the evolution and availability of remote earth sensing technologies, including photogrammetry, lidar and satellite-based InSAR. There has been abundant research in the application of remote sensing techniques to mine sites (e.g. Braimbridge et al. 2019; Kelcey et al. 2019; Jones & Franklin 2019; Morel et al. 2021; Sage et al. 2022; Crisp et al. 2024). These technologies have allowed for rapid and accurate assessments of ground movement. Remote sensing data can be used to monitor erosion and settlement, or changes to mining facilities that could be hard (or impossible) to see with the human eye. With fewer people onsite, the use of drone-based photogrammetry or lidar, or satellite-based InSAR, paired with automated processing techniques can identify changes and potential issues sooner, at scales that were previously impossible to achieve. Tailing facilities can be assessed to determine where millimetres of movement may be occurring, and this assessment can be repeated to understand not just the locations of change but also whether it is accelerating or slowing.

4.2.1 Lidar

The use of lidar or photogrammetry data has become increasingly popular at mine facilities (Schmidt et al. 2015). By comparing multiple lidar datasets, the positional change in the datasets can be assessed over time in a process known as lidar change detection (LCD). Changes analysed between lidar datasets are reported as positive or negative relative to the baseline or initial lidar survey. Positive model differences can be interpreted as material accumulation or bulging, and negative model differences can be interpreted as a loss of material, erosion or settlement. Availability of onsite data collection and LCD processing have increased both the efficiency and quality of results. These advancements have enabled high-accuracy LCD to be performed in automated ways. One of the primary advantages of employing a digital knowledge base is the automation of data analysis. Utilising sophisticated algorithms and machine-learning techniques, Cambio can continuously processes incoming data, identifying patterns and anomalies that may not be immediately discernible to the human eye. This automated analysis generates actionable insights, such as issuing triggers based on changing site conditions or deviation from set closure criteria.

The integration of lidar data also provides significant advantages for vegetation management in mine closure monitoring. Unlike traditional imagery, lidar captures detailed 3D structural information about vegetation, including canopy height and density, and overall biomass. By performing repeated lidar surveys over rehabilitated areas, mine operators can accurately track vegetation growth and health over time, confirming compliance with closure criteria related to ecological recovery and vegetation density or height and confirming the function of the cover system or erosion control requiring the vegetative component. Additionally, automated lidar analysis within the digital knowledge base streamlines the monitoring process, rapidly identifying areas that are lagging in recovery and providing precise data that informs remediation activities.

4.2.2 InSAR

In addition to lidar, InSAR provides a valuable complementary method for monitoring settlement and surface deformation during mine closure, particularly for tailings dams and impoundments. InSAR works by transmitting radar signals from satellites towards the Earth’s surface and measuring the phase differences between signals collected at different times. These phase differences indicate slight shifts or movements on the ground surface, enabling the detection of subtle ground movements, often with detection limits as precise as a few millimetres per year over extensive areas. Regularly acquired satellite radar data, such as from the freely available Sentinel-1 constellation (or the upcoming NASA-ISRO Synthetic Aperture Radar mission) enable continuous (sub-weekly) tracking of slow-moving processes like subsidence, creep or settlement across tailings facilities, waste rock dumps and reclaimed mine surfaces. Additionally, commercial InSAR data providers offer higher-resolution imagery and more frequent revisit times, making them preferable for detailed, rapid-response monitoring. A major benefit of spaceborne radar imagery is that since it is continuously collected globally, historical data extending back to at least 2014 is often available for analysis at a mine site.

The potential effectiveness of InSAR is demonstrated by the Brumadinho tailings dam collapse in Brazil. Advanced analysis of satellite data following the failure event demonstrated that ground deformation precursors were detectable months prior to the disaster (Grebby et al. 2021). This highlights how routine InSAR monitoring could have provided a critical early warning; potentially averting the failure or triggering earlier engagement of the emergency response plan. While aerial LCD provides precise, high-resolution 3D measurements ideal for identifying localised changes and quantifying erosion or structural deformation typically greater than a few centimetres, InSAR excels in detecting broader-scale, subtle ground movements over time. Automated InSAR processing within digital platforms facilitates early detection of unexpected deformation patterns, allowing site operators to proactively respond to potential stability concerns. As noted above, availability of historical InSAR data can allow forensic analysis of stability observations made by other monitoring methods. By combining the strengths of both LCD and InSAR, owners gain a comprehensive understanding of site stability. Thus, integrating InSAR into the digital knowledge base significantly enhances the ability to monitor post-mining landforms and infrastructure, promoting long-term safety and compliance with closure objectives.

In addition to monitoring ground deformation, synthetic aperture radar (SAR) can also be used to estimate soil moisture conditions (Kornelsen & Coulibaly 2013). Radar backscatter is sensitive to changes in surface moisture, particularly in the top few centimetres of soil, and variations in moisture content can be observed through time-series analysis. Monitoring soil moisture is especially important in the context of mine closure as it influences vegetation recovery, erosion potential and slope stability (through the identification of seepage zones), and is an indicator of infiltration conditions and other aspects of cover performance. SAR-based soil moisture estimates can support early identification of overly dry or saturated conditions, helping inform revegetation efforts, deviations from drainage design, cover performance and risk assessments related to run-off or slope failure.

A recent addition to the space-based radar toolkit is the Surface Water and Ocean Topography (SWOT) satellite, launched as a joint mission by NASA and CNES. SWOT provides a new capability for monitoring water covers on tailings facilities and pit lakes in mine closure settings. Using advanced radar interferometry, SWOT measures SW extent, elevation and volume changes with unprecedented precision. Its global coverage and ability to measure water bodies as small as 250 m wide make it a powerful tool for large-scale mine closure monitoring. By integrating SWOT data with other remote sensing and onsite hydrological data, mine operators can gain deeper insights into long-term water balance, weather- and climate-driven changes, potential risks associated with water-covered mine closure strategies and other aspect of water management system performance.

4.2.3 Multispectral and hyperspectral imagery

In addition to lidar and InSAR, multispectral and hyperspectral satellite imagery provides important complementary capabilities for remote monitoring of environmental conditions at closed mine sites. These remote sensing technologies capture reflected solar energy across multiple spectral bands, allowing detailed assessments of vegetation health, moisture conditions, seepage, erosion and water quality issues around tailings facilities. Multispectral sensors typically measure reflectance in a limited number of discrete bands (e.g. visible, near-infrared, shortwave infrared), enabling effective monitoring of vegetation health, soil moisture content and erosion patterns. In contrast, hyperspectral sensors measure reflectance across dozens or hundreds of narrow spectral bands, providing detailed spectral signatures that can identify specific minerals, contaminants or subtle variations in vegetation stress, soil conditions and water quality.

Multispectral imagery is widely available from public satellites such as Sentinel-2 (European Space Agency) and Landsat (NASA/USGS), both of which offer free access to regular sub-weekly imagery at resolutions of 10–30 metres. These platforms are highly effective for routine monitoring of vegetation health through indices like the normalised difference vegetation index (NDVI), detecting moisture anomalies indicative of seepage or ponding, and tracking erosion through changes in exposed soil and sediment transport patterns. Commercial providers offer higher-resolution multispectral imagery, often at daily revisit intervals and sub-metre spatial resolution, enabling more precise monitoring of localised issues such as erosion gullies and seepage zones.

Hyperspectral imagery, while less widely available, provides additional capabilities for detailed environmental monitoring. This type of imagery can detect subtle variations in water quality downstream of tailings sites, including elevated turbidity, sediment plumes, acid mine drainage and other contaminants, based on their unique spectral signatures. Additionally, hyperspectral data can precisely differentiate erosion-affected areas from stable soil by detecting specific mineral signatures associated with disturbed or freshly exposed substrates. Public access to hyperspectral data is currently limited, but missions such as NASA's forthcoming Surface Biology and Geology mission aim to improve availability. Meanwhile, commercial providers offer satellite and airborne hyperspectral collection tailored to specific monitoring needs.

4.3 Remote sensing data integration

Integrating remote sensing datasets (such as lidar, InSAR and multispectral/hyperspectral imagery) with other mine closure design and monitoring data significantly enhances the quality and speed of decision-making processes. Each remote sensing method provides unique and complementary insights: lidar delivers high-resolution deformation, erosion and vegetation measurements; InSAR continuously tracks subtle movements; and multispectral or hyperspectral imagery monitors vegetation, moisture conditions, erosion and contaminants. When these diverse data streams are combined and analysed alongside traditional mine closure datasets (e.g. closure design, geological models, hydrogeological data, geotechnical instrumentation readings, climate data, and historical site records including operations and construction records), owners gain a holistic understanding of evolving site conditions.

For example, integrating InSAR-derived ground deformation data with piezometer readings and weather data enables early detection and analysis of potential instability in tailings dams (Figure 2), such as the correlations identified by Grebby et al. (2021) following the Brumadinho tailings dam failure. Similarly, combining lidar-derived vegetation structure measurements with multispectral or hyperspectral vegetation health indices (e.g. NDVI) and weather data provides a comprehensive view of vegetation growth, health and ecological recovery, quickly identifying areas requiring additional rehabilitation or maintenance efforts and potentially identifying distress indicators in the receiving environment. Combining high-resolution digital elevation models derived from lidar surveys with soil moisture and ponding assessments from freely available multispectral imagery enables up-to-date mapping of current drainage paths and ponding areas.

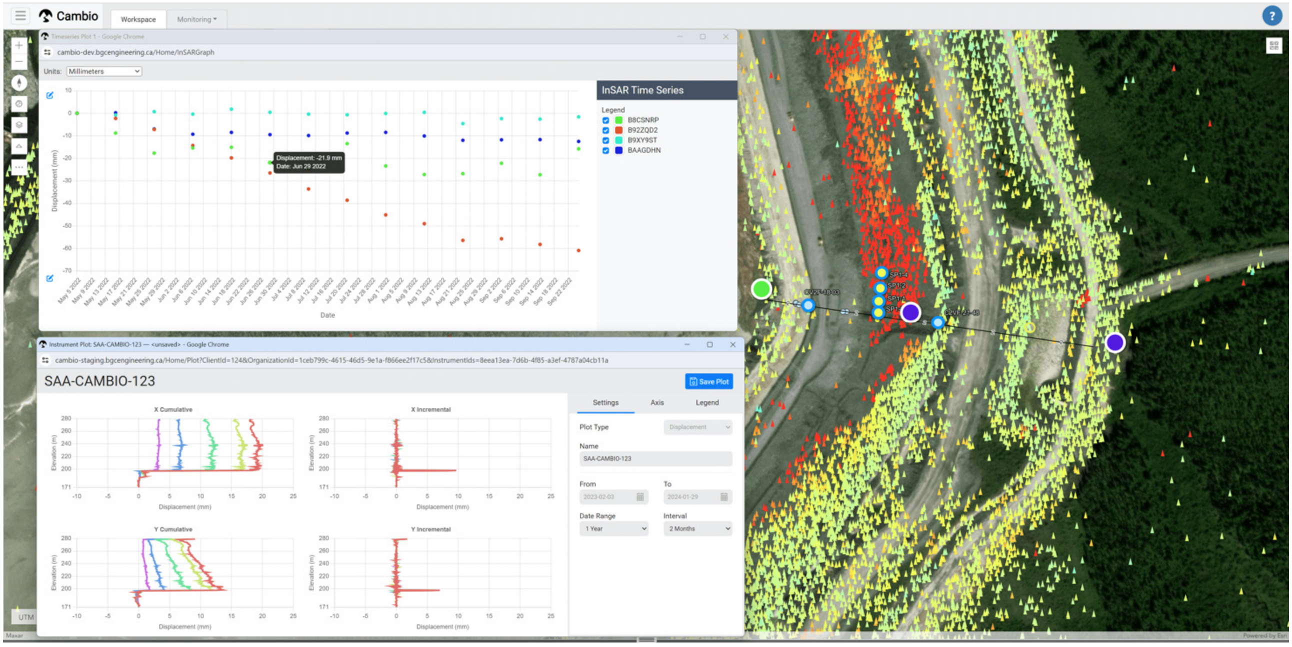

Figure 2 Example of InSAR, instrumentation (shape accel array) data, standard cross-sections and project imagery all viewed together in one platform

Finally, the combination of remote sensing data collection with digital knowledge bases allows for fully remote collection and analysis of data, allowing for more efficient ways of allocating resources. This capability enables experts to monitor and analyse mine site conditions from anywhere so that issues are identified and addressed promptly. When fieldwork is necessary it can be more targeted and efficient as personnel can access project data while in the field without the need for internet connectivity. This approach not only saves time but also enhances the effectiveness of field operations.

4.4 Instrumentation

An integrated monitoring platform that supports a broad range of instrument types could address the challenges associated with disparate monitoring data, and enable centralised management of installation records, spatial context, historical and real-time readings, and associated documentation such as photos or maintenance logs. A system with this level of data integration can improve traceability, support more rigorous quality control, and make it easier to interpret and communicate monitoring results.

The Cambio system has this data integration capability, which is designed to manage detailed metadata associated with each instrument, including configuration parameters, calibration factors, thresholds and maintenance history, alongside geospatial and temporal data. Both manual and automated data acquisition methods are supported, allowing integration of field-collected measurements with real-time sensor feeds.

Visualisation tools within the platform facilitate the interpretation of instrument data by enabling the configuration of plots and dashboards tailored to specific project needs (Figure 3). These can be used to track readings against defined thresholds, supporting early detection of conditions that may warrant further investigation. Visual outputs can be exported in a variety of formats to aid communication with project teams, regulators and other stakeholders.

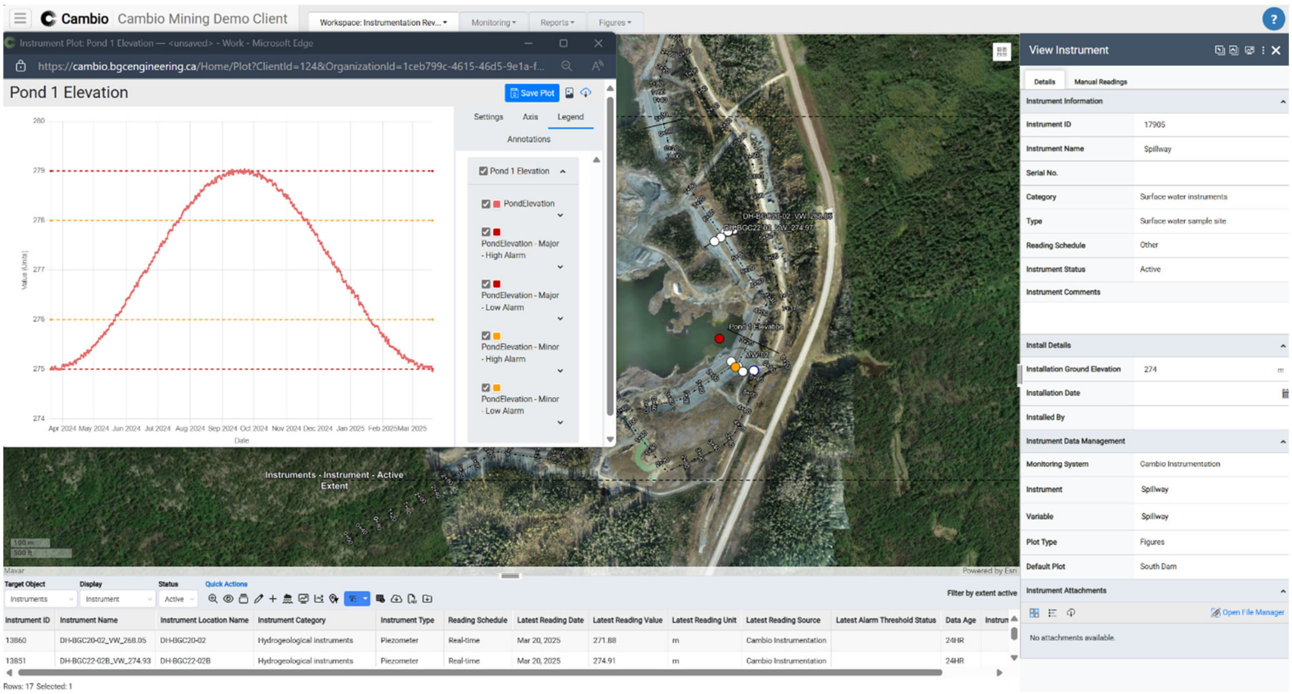

Figure 3 An image of instruments in alarm status can be viewed in summary tables and map views, providing a comprehensive overview of site conditions

The ability to generate cross-sections dynamically, using up-to-date instrument readings, site designs, historical topography, borehole logs and other spatial datasets (Figure 4) reduces the time typically required to produce such visualisations and allows for more iterative, on-demand analysis. A proactive monitoring approach like this helps identify potential issues and enables them to be addressed promptly, reducing the risk of non-compliance and environmental hazards.

The integration of diverse data sources, combined with configurable visualisation and alerting capabilities, supports more efficient and responsive monitoring workflows. For mine closure projects, where maintaining long-term site stability and compliance is critical, this type of system has the potential to improve the effectiveness of closure monitoring programs.

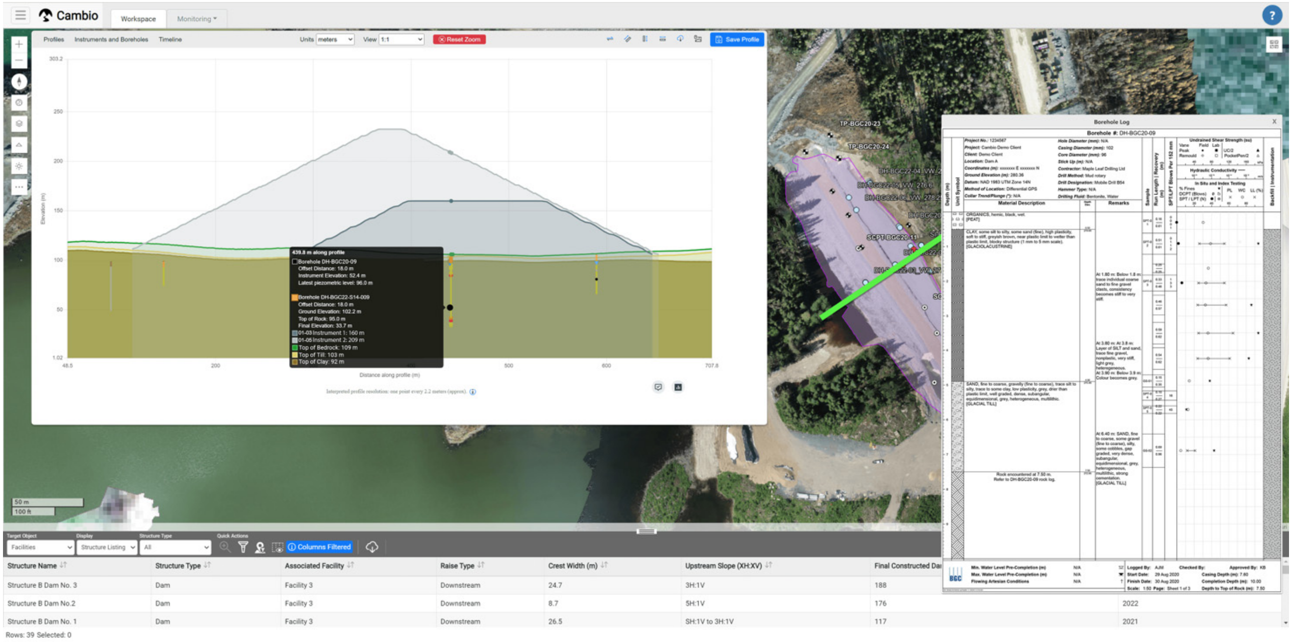

Figure 4 Image of the Cambio platform highlighting the ability to view multiple data sources (borehole location and logs, instruments, cross-sections) at once to better understand site conditions

5 Case studies and application

A previous paper (Burkell et al. 2025) presented several case studies illustrating the application of Cambio to monitoring projects with similar challenges to those of closed mine sites. Applications included two operating tailings storage facilities in Canada, where the use has many similarities to landform monitoring at closure. In addition, examples were presented regarding linear infrastructure compliance inspections and dam reservoir response monitoring, where the monitoring of geohazards has many similarities to the requirements of mine closure settings. Further details are provided within the paper referenced above.

The preceding sections of this paper have described the basics of mine closure monitoring, more recent advances in monitoring approaches, the resulting monitoring datasets, and how a geospatial digital knowledge base could be used to integrate those diverse and complex data sources to allow interpretation of the performance of the closure landscape and, if required, inform responses to performance shortfalls. In this section an example of that application to a hypothetical closed mine landscape will be presented.

5.1 Example facility

A closed tailings storage facility (TSF) landform has been developed with a vegetated low permeability soil cover and landform geometry to promote clean water diversion and mitigated generation of contact water. Diversion channels direct run-off from surrounding areas around the TSF. A low permeability cover has been installed over the tailings, with drainage on the TSF directed to a minimal pond whose level is maintained by a closure spillway. Instrumentation within the tailings dam has carried over from operations, allowing monitoring of the dam performance in closure. Following are some considerations of closure monitoring in this site setting:

- A dataset of the tailings, dam fill and foundation material properties exists from the operations phase.
- Construction records are available for the dam, impoundment, tailings cover and closure landform.
- The dam performance monitoring program during operations was supported by regular inspections and instrumentation monitoring by operations staff, which is not possible by the significantly reduced site presence during closure.

- Site conditions have changed in closure as tailings are no longer being actively deposited and therefore changes in the geometry of the landform are dominated by settlement rather than tailings deposition and dam raises:
  - Ongoing settlement of tailings will result in an evolving TSF surface, likely greater where tailings deposits are thicker.
- Cover components of the landform are new and therefore have no historical dataset describing past performance. Construction records document the actual constructed condition of the cover and landform.
- Vegetation is established across the cover to control erosion and net infiltration of precipitation, as well as to support post-closure land use.
- Seepage controls continue to operate into the active phase of closure as the pore pressure conditions evolve within the TSF to reach a new equilibrium after cessation of tailings deposition and construction of the closure landform (including cover).
- With respect to the closure design:
  - Potentially acid generating materials within the TSF are intended to remain saturated due to ongoing infiltration.
  - As passive closure conditions are reached, mitigated seepage quantities are anticipated to result in site discharge meeting criteria at the compliance point.
- The pore pressure regime within the dam is expected to equilibrate such that pore pressures remain below thresholds for dam stability.
- The landform is suitable for post-closure land use.

Closure monitoring must confirm that the evolving conditions of the landform align with predictions and the closure objectives are being met.

5.2 Monitoring application

The following section will describe how the Cambio platform could be utilised to support closure monitoring at the TSF described above with reduced site presence and evolving landform conditions.

Historical datasets from the operational phase, including material properties, construction records, inspection records and instrumentation logs, can be digitised and imported into Cambio at any stage of the closure process. Cambio can consolidate these diverse data sources into a single geospatially integrated platform. This enables a comprehensive understanding of baseline conditions against which closure performance can be assessed. The platform's configurable workspaces allow for visualisation of dam construction phases and model outputs versus current imagery and topography from photogrammetry, lidar or satellite imagery and instrumentation outputs to monitor changes in landform elevation, settlement patterns and pore pressure regimes. These insights are particularly valuable in understanding areas where thicker tailings deposits may result in greater settlement, which could impact drainage paths or the cover system performance over time.

As site conditions evolve and passive closure conditions are reached, Cambio dashboards can be configured to flag key indicators such as changes in piezometric levels, pond elevation or seepage trends that could affect compliance at the discharge point. Instrumentation data, including readings from operational sensors that remain in place, can be tracked against closure criteria and stability thresholds to provide early warning of deviations. Event-based triggers can be set on open-source datasets or site weather stations to monitor extreme weather or seismic activity and support timely responses. Examples of use cases for the site include:

- A constructed cover system: details can be assessed against mapped erosion features to identify areas with potential degradation of function. Pore pressure monitoring data, seepage interception data and downstream water quality data can be accessed to assess if there are any responses to identified cover degradation or deficiencies in cover performance

- Water balance updates: completed for the facility using traditional approaches but where results within the knowledge base are accessible via Cambio to inform holistic analysis of changes to TSF cover systems, water management features, pore pressure readings and seepage monitoring results
- Water quality trends: monitored and assessed with the incorporation of identified changes in SW control performance, drainage pattern changes or cover system degradation
- Receiving environment ecological conditions, including water quality trends and ecosystem health status, can be assessed against performance indicators of other components to determine the urgency of required responses. Natural attenuation processes and ecosystem resilience inform responses at this level.

The platform's automated remote sensing data integration capabilities are especially beneficial in closure scenarios where onsite staff presence is limited. Cover construction records reviewed with the processed remote sensing results would allow project teams to monitor erosion, vegetation establishment and surface changes without the need (or only a reduced need) for regular physical inspections. In some cases, with Cambio's automated integration of advanced remote sensing datasets, sites can detect changes in near real-time, enabling faster, data-driven responses while also reducing the need for constant onsite presence, delivering both enhanced safety and operational efficiency. SW drainage pattern changes and landform geometry (change detection) results inform assessment to focus inspections, mapping and measurements on areas with a higher risk of reduced performance. Cambio can be used to track development of erosion features at those focus locations. Direct examples of how this could be implemented are:

- Vegetation: site inspection forms input through Cambio are merged with remote sensing datasets (i.e. lidar, InSAR, multispectral/hyperspectral imagery) to assess establishment and the ongoing health of the cover system and erosion control vegetation or receiving environments.
- Landform geometry: site surveys conducted manually, or with photogrammetry, lidar or InSAR, provide input to change detection methods to identify changes in geometry.
- SW controls: site inspection forms for diversion channels, sedimentation ponds and control structures can track any degradation of function.

Cambio also supports stakeholder engagement by presenting complex data in a visual, intuitive format, enabling effective communication of closure performance and stability to regulators and other stakeholders. Ultimately, the platform enhances the ability to track long-term trends, maintain regulatory compliance and support adaptive management strategies throughout the post-closure period.

If variances from expected monitoring results arise, Cambio provides tools that allow engineers to assess those variances holistically and with efficiency. For example, areas of higher settlement than anticipated can be assessed against construction records (to identify if and where variances were accepted) and pore pressure reading trends (to identify if higher than design assumptions exist or are approaching such thresholds) to determine the root cause of the monitoring variances. In addition, responses to any increased settlement can be assessed, such as changes in drainage patterns and infiltration rates or development of erosion features. The evolved landscape can be assessed to determine if it will still meet closure objectives or require remedial efforts.

6 Conclusion

The process of mine closure is complicated, requiring long-term monitoring, adaptive management, and the integration of diverse datasets to achieve compliance with environmental and societal expectations. Maintaining a comprehensive knowledge base and monitoring are crucial components of integrated and effective mine closure (ICMM 2025). The knowledge base contains a broad range of information in many forms, ranging from the domain model to monitoring data, as well as historical information and local/traditional knowledge. Specifically, regarding mine closure monitoring, it can comprise traditional methods (surveys, inspections, instrumentation readings, etc.) with ever-improving automation capabilities as well as new remote sensing technologies such as photogrammetry, lidar, InSAR and multispectral/hyperspectral imagery. An integrated knowledge base that supports holistic assessment and includes automated ingestion, processing and visualisation of the many complex data streams is becoming a necessity, given this growth in the number of data sources and the size of the datasets.

Cambio is a proposed solution that addresses many of the challenges traditionally associated with mine closure monitoring. By providing centralised access to real-time data, configurable workspaces, interactive dashboards and advanced geospatial tools, Cambio transforms the way mine closure data is collected, analysed, shared and acted upon. Future advancements could include the implementation of automated alerting for remote sensing sources like InSAR, similar to that used on instrumentation readings. These alerts and associated trigger response plans can help identify subtle trends before they escalate into major issues, thereby enabling proactive management.

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