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Toward integrated mining landform design: recent tailings project examples from Canada

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Abstract

This paper explores the current state of integration between operational mining needs and post-closure legacy for mining landform design at operating mines. The exploration uncovers opportunities to efficiently integrate short-term and long-term considerations using tools already in common use, such as more rigorous closure planning and expanded landform design basis. Mining landforms include tailings storage facilities, stockpiles, waste rock dumps, open pits, drainage networks, and block cave craters. These landforms persist on the landscape long after mining ends. Mining landforms have historically been designed with a short-term operational focus to meet immediate mining needs. Reclamation and closure have historically been considered near the end of the operational life of the landform. Site-wide closure plans may lack the detail and rigour required to meaningfully contribute to operational landform designs, while site-specific experience gained during operations can inform better performing landform designs. Recent project experience in Canada with operational landform design across a variety of mining projects has revealed a spectrum of current practice. Closure plans at some mines exist primarily to meet regulatory submission requirements, while at others closure plans are more closely integrated with operational mine planning. The landform design process requires clearly stated performance objectives and design criteria to succeed. Short-term operational needs are typically well defined. Long-term post-closure needs may or may not be clearly defined in closure plans. Mine operators can maintain operational performance while improving long-term outcomes by more closely linking closure planning, mine planning, and landform design. This paper presents recent tailings storage area landform design project examples from different operating mines in Canada, with some key lessons learned and suggestions for more integrated mining landform design.

Keywords: *closure, planning, integrated design, landforms, landform design, TSF design*

1 Introduction

The history of mine closure in Canada has been mixed, with some mines generally meeting regulatory and local community closure expectations, and other abandoned mines negatively impacting local ecosystems and communities. For example, the International Council on Mining and Metals (ICMM) (2019) highlighted the Sullivan Mine near Kimberley, British Columbia, as an example of successful mine reclamation where the mine operator "started engaging with communities as early as the late 1960s to co-create strategies that would mitigate the economic impact of the pending closure" ICMM (2019, p. 22).

The British Columbia provincial government recognised the Gibraltar Mine near Williams Lake, British Columbia, for a "forward-looking approach to reclamation by utilizing research trials to determine best methods in order to set the stage for future reclamation success" Government of British Columbia (2012).

The Canadian Land Reclamation Association awarded the Detour Lake Mine near Cochrane, Ontario, for "progressive reclamation effort, supported by a long-term multidisciplinary research program" CLRA (2021).

Conversely, Giant Mine near Yellowknife, Northwest Territories, was abandoned in 2004 without an effective closure plan (CIRNAC 2018); Brittania Mine, near Squamish, British Columbia was abandoned in 1975, leaving a legacy of acid rock drainage and environmental degradation (O'Hara 2007); and the Faro Mine, near Faro, Yukon, once the world's largest open pit lead–zinc mines, is now "the site of one of the most complex abandoned mine remediation projects in Canada" CIRNAC (2021).

At these mines, expensive ongoing remediation programs are underway to mitigate significant negative impacts from historic mine operations.

This paper discusses the current state of integrating immediate operational objectives with closure objectives in landform design practice through some examples of how integrated mine planning and landform design tools are used at select mine sites across Canada. The paper provides case studies of successful and unsuccessful integrated landform design with the intention of supporting landform designers in their future successful application of these common design tools. The landform design examples draw from the authors' experience on teams engaged in tailings storage facility (TSF) design at operating mines.

1.1 Canadian historical context

The Teck Sullivan Mine near Kimberley, British Columbia (population 8,000), and Giant Mine near Yellowknife, Northwest Territories (population 20,000), provide illustrative case studies for the range of historical mine closure management in Canada.

The Teck Sullivan Mine is an example of successful mine operation, reclamation, and closure (ICMM 2019; NRCAN nd; Teck nd). The Sullivan Mine orebody was discovered in 1892 and the mine operated from 1909 until 2001 (NRCAN nd). For closure planning, "Teck focused on the inclusion of the local community and Indigenous Peoples in planning for post closure land use" (ICMM 2019, Page 22) with community engagement starting in the 1960s. Reclamation research began in 1972, with progressive reclamation beginning in 1990. The waste rock dumps and TSF were recontoured, capped with reclamation material, and vegetated (Teck nd). Water treatment began in 1979, is ongoing, and is planned to continue indefinitely. Collaboration was key to successful mine closure, including supporting the town of Kimberley's transition from a mining to a tourism economic base:

> *"The development of a partnership between the municipality and the mining company was critical to the success of the project. The strong and collaborative relationship that emerged between the City of Kimberley and Teck enabled them to team up, creating a unified voice and a shared vision when seeking support from the province, investors or the community." NRCAN (nd)*

Success was achieved through openness and collaboration among the mine operator, community leaders, Indigenous peoples, and community members (NRCAN n.d.). Teck continues to operate in the region and maintains a presence in the community.

The Giant Mine has left a legacy of contamination (Mackenzie Valley Review Board 2013). Gold was discovered by prospectors in the Yellowknife area in 1896. Underground and open pit mining occurred from 1948 to 2005 by a succession of mine operators, with some of the transitions between operators resulting from bankruptcy. The mine was abandoned in 2005 and is currently the responsibility of Canada (CIRNAC 2018). The mine was abandoned with over 100 buildings, 237,000 tonnes of water-soluble arsenic trioxide, and 13.5 million tonnes of contaminated tailings spread over 95 hectares (Mackenzie Valley Review Board 2013). Arsenic contamination extends beyond the mine site as a result of mineral processing, "releasing tonnes of airborne arsenic daily out of the roaster for years" Mackenzie Valley Review Board (2013, Page 9).

Limited progressive reclamation began after 1999. Current expectations are that 'perpetual' care will be required following active reclamation. Relations between the mine owner and workers were acrimonious for at least part of the mine life, with a deliberately ignited underground explosion killing nine people during labour unrest in September 1992 (CIRNAC 2018). Even after Canada took responsibility for the mine, the Mackenzie Valley Review Board (2013) agreed with community members that engagement and consultation were inadequate.

These two former mines were selected to illustrate a range of historical practice. Decades of reclamation research and extensive community involvement created good closure outcomes at Sullivan Mine. Lack of foresight, inadequate financial strength, and acrimonious community relations contributed to poor closure outcomes, requiring expensive remediation at Giant Mine. The modern Canadian mining industry and mine regulators have learned from these good and poor examples. Today, there is a greater push towards integrated mine planning and effective closure design at operating mines.

1.2 Tailings storage facilities

The case studies presented in this paper are drawn from the authors' work with TSFs. TSF design, construction, and operations commonly occur over 5 to 20+ years. Typically, the full height ultimate dam design is completed to a conceptual, pre-feasibility study, or feasibility study, level of design as part of mine planning. Detailed design for the starter dam and each subsequent dam raise is typically completed sequentially over many years, and detailed raise designs are completed in line with the ultimate dam design. Additional site investigation and performance observations completed through operations inform the detailed designs and support the end-of-operations and reclamation design, which may evolve over time. Progressive reclamation before a TSF reaches its ultimate crest elevation is rare, given that dam slopes and tailings surfaces are typically buried as construction progresses. Large mines may have several TSFs over the mine life, with each TSF landform reclaimed shortly after the end of its operational life.

McKenna & Van Zyl (2020) describe the typical tailings landform design team as 40% engineers, 40% biologists, and 20% other specialists. This distribution of expertise reflects the multidisciplinary nature of tailings landform design, particularly from the perspective of communities who will inherit these landforms after mining ends. In practice, this is the team needed to design the ultimate TSF landform. In contrast, the team completing the detailed design for each raise tends to be weighted toward engineering expertise, with a focus on physical stability, tailings deposition, water management, geochemistry, and constructability.

1.3 Design service life and perpetual care

Many reclaimed mines, such as the Sullivan Mine and the Giant Mine, require 'indefinite' or 'perpetual' active care. For a TSF, long-term care may be required to inspect dams, manage process-affected seepage, and monitor and maintain covers, slopes, drainage channels, and spillways, for example. With or without active care, a reclaimed TSF is expected to persist on the landscape for thousands of years. McKenna & Van Zyl (2020) suggest considering a 1,000-year TSF landform service life, based on ICOLD (2013) and Slingerland (2019). This design service life is much longer than the design service life of 20 to 100 years typically specified in other civil engineering disciplines.

Future civilisations, social structures, geological processes, ecosystem evolution, climate conditions, and world events over the span of many centuries are difficult to imagine, let alone design for in a traditional engineering sense. The communities surrounding the Giant Mine expressed "significant public concern" regarding the ability for engineering designs to stand up to the extreme levels of uncertainty inherent in designing for perpetuity (Mackenzie Valley Review Board 2013, Page 70). Social and institutional breakdown, technological progress, unpredictable climate change, opportunities to benefit from future technological advances, and a desire for reversibility were offered as arguments against a very long design life. In response to these community concerns, the Mackenzie Valley Review Board (2013) required that the Giant Mine remediation design proceed only as an interim design with a 100-year service life, with a commitment to review the remediation approach every 20 years.

While it is a useful exercise to contemplate potential trajectories for mining landforms over many centuries, engineering designs that outlive the service life of elements such as pipes, pumps, internal drains, geomembranes, and geotextiles may be difficult to produce. A shorter engineering design service life of up to perhaps a century or so, combined with a commitment to care for the landform until it has been demonstrated to be benign, is probably a more pragmatic approach.

2 Methodology

This paper reviews the current state of mine closure practice in Canada through an exploration of landform design tools in common use as a part of the integrated mine planning approach. Integrated mine planning combines mining operational and closure planning into a single coordinated process that explicitly considers closure objectives in operational designs (Ansah-Sam et al. 2019; McGreevy et al. 2018). The value of integrated mine planning is widely recognised throughout the mining industry. The ICMM (2019) provides guidance for incorporating mine closure considerations into integrated mine plans and poses some key questions for life-of-mine (LoM) planning:

> *"Has a multidisciplinary team provided input to the short, medium and LoM planning processes? Is there integration between the closure, mine engineering/planning, environment and community teams in planning for closure?*
>
> *Has the closure vision been clearly communicated to the LoM planners? Do LoM planners understand the potential added value of designing for closure?*
>
> *Are the roles and responsibilities of teams clearly defined in achieving the overall closure vision?*
>
> *Is there a platform/system in place to ensure integration between teams and incorporation of closure into the mine business plan?" ICMM (2019, Page 14)*

The following sections discuss landform design tools and case studies showing effective and ineffective use of these tools. The examples and cases have been anonymised, except where previously published. The list of tools is not comprehensive, and the tools presented have been selected to show a cross-section of the state of practice in Canadian closure design. The following tools and processes are highlighted:

- Knowledge base.
- Landform design basis.
- Tailings deposition design.
- Consolidation and settlement.
- Water balance.
- Geochemistry and water quality.

3 Tools and case studies

3.1 Knowledge base

The guide for integrated mine closure identifies the knowledge base as a key closure planning element (ICMM 2019). The Global Industry Standard on Tailings Management identified maintaining an integrated knowledge base as a part of the framework for safe TSF management (ICMM 2020). The integrated knowledge base topic includes two principles:

> *"Develop and maintain an interdisciplinary knowledge base to support safe tailings management throughout the tailings facility lifecycle, including closure.*
>
> *Use all elements of the knowledge base – social, environmental, local economic and technical – to inform decisions through the tailings facility lifecycle, including closure." ICMM (2020, Pages 8 to 9)*

During the mining process, significant amounts of data are generated, including, but not limited to, geological information, ore grades, geochemistry data, precipitation records, snowfall records, streamflow records, geotechnical testing information, groundwater levels, hydraulic conductivity testing, site investigation information, vegetation surveys, wildlife surveys, regulatory commitments, First Nations commitments, community commitments, construction records, and instrumentation readings. The quantity of data created is likely to increase as mine sites become more heavily instrumented, data collection technologies become more integrated into mining operations, mine approvals become more complex, and the number of involved stakeholders grows. As an example, construction records now often include terabytes of data encompassing photographs, drone imagery, drone and LiDAR survey scans, and satellite imagery. A knowledge base is often required to store these structured and unstructured data in a way that is accessible and can be manipulated by multiple users. When made accessible broadly to mine operator staff, consultants, communities, and regulators, the knowledge base provides a powerful tool for building alignment. For landform designers, the combination of a knowledge base and design basis memorandum provides a powerful tool to prepare designs that meet the principles of integrated mine planning and reduce future rework by explicitly considering all available data.

Knowledge bases and other methods of managing these data are not new in the mining industry; however, methods and technologies for storing and presenting the information must become more sophisticated with the rapid increase in the quantity of data being produced. In the past, knowledge bases for landform designs have been captured using constraints maps that identify the various constraints that influence a specific landform (Ansah-Sam et al. 2019). More recently, constraints tracking has moved to online platforms, often with integrated instrumentation portals, that can be accessed widely by mining operator employees and their consultants. Mine operators may elect to provide varying degrees of access to regulators and interested stakeholders to facilitate open, transparent collaboration.

At one mine site, the mine operator developed a custom GIS-based web application tracking site-wide instrumentation, site-wide pond water levels, weather, dam breach analyses, impacted properties, emergency response plans, and footprint constraints. This web application allows for the coordinated alignment of mining staff and consultants with the mine commitments. However, even in this impressive case, significant portions of the mining data remain inaccessible through the platform, including regulator commitments and construction records information. These data gaps highlight the effort entailed in developing a coordinated knowledge base platform, which extends both to developing (or purchasing) a platform for the knowledge base, and to spending the effort reviewing and distilling the site data into a format that can be stored and easily accessed and interpreted in the knowledge base. Without these steps, the knowledge base may have limited utility, and collected data may not be effectively used by the intended users of the knowledge base.

3.2 Landform design basis

Mining landforms must meet short-term mine operational needs, such as storing mining materials (e.g. waste rock, tailings, low-grade ore, and reclamation material), managing water (e.g. flood containment or routing, drainage, reclaim, compensation habitat, collection, and treatment), and producing ore (e.g. pits and underground workings). As a result, landform designs are subject to myriad operational constraints, such as material specification and availability, haul distance and elevation change, mineral processing and waste production rates, seasonal water availability, seasonal high and low temperatures, energy costs, construction management and constructability, physical stability, geochemical stability, and water quality. Regulatory and permitting requirements further constrain landform designs. Long-term reclamation and closure goals inform the location, morphology, and design of mining landforms.

The landform design basis memorandum (DBM) captures the design objectives, and operational and closure constraints and criteria (Ansah-Sam et al. 2016). The DBM forms the key linkage between the integrated mine plan and landform designs (Ansah-Sam et al. 2019). The DBM includes specific and measurable design criteria for each design basis. Where the closure plan lacks engineering design rigour, the landform DBM cannot effectively define specific and measurable design criteria, and a design gap is identified.

To effectively implement the design basis approach, integrated mine teams with a culture of strong collaboration are required. Community expectations, regulatory requirements, economic constraints, engineering design limitations, orebody properties, and immediate operational needs must be integrated into a DBM, and ultimately into a successful mine with a positive long-term legacy. Where mine departments and various technical consultants operate in silos, collaboration cannot occur, important closure considerations may not be communicated, and opportunities to adjust landform designs to simultaneously meet short-term and long-term mining objectives will be lost. In these cases, landforms may be designed to meet immediate mine operational needs without considering the longer-term impacts. DBMs must be updated regularly to account for changes or additions to the site's knowledge base.

At the Muskeg River Mine in Alberta, Canada, landform designers used a coordinated site-wide landform DBM, allowing for designs that explicitly integrated mining operational needs and the site-wide site closure commitments (Ansah-Sam et al. 2019; McGreevy et al. 2018). The use of the integrated landform DBM resulted in design decisions that included widening ramps to allow for the establishment of closure drainage channels, and the incorporation of roughed in closure geometry during construction to reduce closure grading requirements. These designs would have been cost prohibitive if not included during the initial design stages, which would have resulted in poorer long-term landform performance.

At another mine, the TSF landform design was completed to a conceptual level of design for the ultimate dams and reclaimed landform. The conceptual reclamation design considered physical stability, revegetation, drainage, and geochemistry. Tailings porewater and seepage were assumed to be acceptable for eventual discharge after closure based on available geochemical characterisation. Detailed designs for the starter dam and initial raises have focused on tailings deposition capacity, physical stability, operational water balance, and seepage management, and have been designed to be aligned with the conceptual TSF ultimate dam design. In parallel with the starter dam and initial raise designs, ongoing geochemical characterisation and water quality monitoring have suggested that long-term water quality may be worse than previously expected. Based on this new understanding, there is an opportunity to update the DBM and ultimate TSF landform design to reflect the current geochemical understanding. The updated ultimate landform design, supported by additional characterisation data and operational experience, will allow for better annual raise designs, and for the final TSF landform design to meet post-closure performance objectives. This case demonstrates the importance of using an iterative design approach, where ongoing monitoring and characterisation leads to updates to the DBM and ultimate landform design, and design improvements as the TSF is constructed over a period of many years.

3.3 Tailings deposition design

The use of three-dimensional tailings deposition modelling has become standard for tailings deposition design in the mining industry. The tools allow for the rapid development and iteration of tailings plans and dam design geometries, allowing engineers and mine planners the opportunity to assess many options (Cunning et al. 2011; Ketilson & Treinen 2018). When deployed as part of an integrated planning approach, tailings deposition modelling allows realistic future projections of tailings basin topography, allowing for cover and closure grading planning, including flood routing. Tailings deposition modelling requires estimates of tailings beach slopes, tailings density, and the expected tailings pond levels. The development of these parameters can be challenging before tailings deposition begins. Additionally, tailings beach slope and density are prone to change through the mine life as milling processes or the ore feed changes. As a result, tailings deposition modelling requires regular calibration to bathymetric and topographic surveys.

In the authors' experience, and as discussed in the literature (i.e. Cunning et al. 2011; Ketilson & Treinen 2018), tailings deposition modelling has been well integrated into operational planning at most mines; however, the authors still see a gap in the use of the operational tailings deposition models to support closure planning. As a result, at these mines, integrated planning is not being effectively implemented.

At one mine where the operational tailings deposition model was not used to support closure planning, it was discovered that the mine was underestimating closure cover material requirements. At the site, the tailings facility is planned to include a permanent water cap, with a soil cover required to be placed over the top of the subaerial beach and in water shallower than 2 metres. The closure plan assumed that the soil cover would be required to cover 200 metres of beach to meet this requirement. However, the tailings deposition modelling, which was based on observed site beach slopes, indicated covers would be required to cover 600 metres of beach to meet the stated requirements and the projected closure pond geometry. As a result, closure construction planning, soil stockpile planning, and closure cost estimates were all based on a cover material quantity lower than what may be required. Earlier integration of the operational tailings deposition modelling and closure planning efforts would have avoided these discrepancies and may have allowed changes to the operational tailings plan to better meet closure objectives.

Conversely, the authors have experience with many cases where annual operational tailings deposition modelling has been integrated into the closure planning process. At one mine, the closure plan for the tailings facility was to establish a locally common sagebrush ecosystem. A landform DBM was prepared and a closure criterion identified: a trafficable surface would be required to establish the sagebrush ecosystem. Two options were determined that would be practicable for providing a trafficable surface: waste rock backfilling, and thickened whole tailings placement. Tailings deposition modelling was performed that was aligned with the operational constraints; the modelling indicated that it was feasible to deposit thickened whole tailings in a way that would simultaneously meet operational constraints (i.e. tailings storage volumes, placement rates, operational constraints on pumping and pipe distribution) and the closure requirements. The design was iterated as part of the annual operational tailings deposition modelling, and the design was modified as required to meet operational and closure constraints.

3.4 Consolidation and settlement

Tailings consolidation and settlement are critical to successful TSF landform design. During operations, tailings consolidation and the associated settlement increase tailings bulk density, providing additional storage volume and tailings strength. Ongoing consolidation after the end of TSF operations may affect drainage from the TSF plateau. Closed lows that pond water may form over time, which may or may not meet the landform performance objectives. Tailings porewater released during consolidation may migrate upward into cover systems, degrading shallow groundwater and surface water quality on the reclaimed landform. Consolidated tailings may remain liquefiable, which has implications for dam decommissioning and long-term monitoring requirements.

Consolidation and settlement models are in common use to support operational design. Most models are one-dimensional spreadsheet models or more sophisticated finite-strain consolidation models, such as FSConsol (GWP Geo Software 2021). The use of consolidation and settlement models for closure design can be more challenging. Operational consolidation and settlement models are often focused on TSF basin scale volumetric changes to manage tailings storage. Conversely, closure consolidation and settlement models are more often focused on understanding the distribution of settlement beneath a TSF basin, and the impacts of the settlement on long-term landform design performance.

To meet these long-term performance objectives, closure consolidation and settlement models typically require more extensive representative sampling to characterise deposit variability than is required for operational consolidation and settlement models. Tailings deposits will also change over time with ongoing tailings deposition and during final tailings backfilling operations that typically entail backfilling some or all of the tailings water ponds. As a result, representative sampling for a closure consolidation and settlement model typically cannot be completed until the TSF is very near the end of the TSF life. Landform designs often manage this uncertainty by making consolidation and settlement estimates based on the operational consolidation and settlement models. If the expected magnitude of settlement is low and the deposit is expected to be relatively homogenous, these estimates may be suitable for landform design. For TSFs where the magnitude of settlement is expected to be high, and the deposit is expected to be heterogenous, landform designs may be required to be overly conservative to accommodate settlement.

3.5 Water balance

TSFs are integral to the operational mine water balance. Conventional tailings deposition involves pumping a slurry of tailings solids and process water through pipes into a containment structure. As the solids settle, a process water cap develops as a tailings operating pond. Process water is reclaimed from the operating pond for re-use in mineral processing. The TSF water balance components include tailings water input, reclaim water output, precipitation input, evaporation output, water storage as tailings porewater, release from tailings storage due to consolidation, seepage losses, and inputs from contributing watersheds (runoff and seepage).

Climate exerts a strong influence on the TSF water balance through precipitation, evaporation, and inputs from contributing watersheds. In Canadian mining regions, the climate typically ranges from semi-arid to humid. Summer maximum temperatures between 20°C and 30°C are common, with winter temperatures ranging from below −40°C at northern mines to −10°C in more temperate regions. Average annual temperatures range from below freezing in regions with permafrost to a few degrees above freezing elsewhere.

Mines require freshwater input at start-up and early in mine operations. As operations continue, mines in arid to sub-humid regions typically require an ongoing freshwater supply to offset losses to evaporation and storage in tailings porewater. In sub-humid to humid regions, mines may need to release water offsite to offset excess precipitation. Mine operations may require freshwater makeup to maintain ore processing water quality requirements, even if the water balance does not produce a deficit. Seasonal and multi-year climate variability may drive mines through cycles of water excess and water deficit during operations.

A site-wide water balance model (WBM) is a key mine water management tool, ranging from a spreadsheet approach to probabilistic WBMs, such as GoldSim (GoldSim Technology Group 2021) in common use. For a TSF, climate data, mine throughput and process details, tailings consolidation rates, and seepage rates are critical inputs. Operational water input and reclaim often dominate the TSF water balance during operations, masking some of the other inputs and outputs. At closure, tailings slurry deposition and reclaim stop, and the other TSF water balance components, such as consolidation, seepage, and climate projections, control the post-closure landform water balance. For TSF landforms with a vegetated cover, precipitation, actual evapotranspiration, net percolation, and runoff are the key long-term water balance components. Of these, only precipitation can be directly monitored during operations. Water balance is intimately connected to water quality, which will be described in the next section.

Tailings consolidation and seepage through tailings are important to the post-operation's TSF landform water balance. Tailings consolidation and the associated landform settlement are also important to reclaimed landform design and performance. Physical tailings properties, which may vary across the deposit, are required inputs to develop consolidation and seepage water balance components. Laboratory consolidation testing provides consolidation properties and estimates of hydraulic conductivity. Cone penetration testing (CPT) measures in situ tailings properties and can be completed from wheeled or tracked rigs on tailings beaches and otherwise trafficable deposits, or from barges on tailings ponds. Consolidation parameters and hydraulic conductivity parameters, among others, can be derived from CPT data. Pumping tests, ranging from days to months, have been completed directly in tailings deposits at a few Canadian mines to evaluate bulk hydraulic conductivity and hydraulic storage properties as part of active tailings dewatering trials.

TSF foundation hydraulic properties also strongly influence the post-operational landform water balance with respect to seepage from the facility. Tailings deposits commonly occupy several square kilometres, and foundation characterisation efforts typically focus on the dam footprint to support dam design. Foundation characterisation by site investigation across the TSF footprint prior to TSF landform construction is rare. Two-dimensional and three-dimensional groundwater flow modelling is typically used to estimate seepage rates and hydraulic head distribution. Overall seepage rates from a TSF can be greater than a factor of 10 or more for a TSF overlying a highly transmissive foundation compared to a TSF overlying a poorly transmissive foundation. Limited basin-wide foundation characterisation can result in a wide range of uncertainty in seepage rates.

For one mine, the presence of highly transmissive aquifers under the dams and tailings deposits, more permeable tailings, and a slightly drier actual climate than initially assumed, resulted in the realisation that potentially acid-generating (PAG) tailings being deposited in the facility would not remain saturated after the end of operations. The closure plan and closure landform design required saturated PAG tailings to prevent acid generation and associated metal leaching. In this case, a more rigorous sensitivity and uncertainty analysis and more comprehensive site investigation at an earlier stage of design would have provided valuable insight and may have fundamentally changed the tailings deposition plan and landform closure design.

In general, the operational WBM is a powerful tool for landform post-operational design. The operational period provides data to calibrate and refine the WBM. Probabilistic models are commonly developed to recognise uncertainty and variability associated with climate inputs. Climate change considerations are routinely incorporated into models with a longer-term (e.g. greater than 10 years) time horizon. Because operational WBMs can be dominated by process water inputs and outputs, seepage and consolidation may be highly uncertain in an operationally calibrated WBM. Thus, the design team must explicitly consider the range of uncertainty associated with these water balance components that are critical to understanding the post-operational water balance. Climate change, while helpful during operations, becomes critical for long-term designs, where the design life is commonly 100 years, or perhaps even longer.

3.6 Geochemistry and water quality

From the perspective of post-operational landform design, water quality is typically managed in a source-pathway-receptor risk framework. Key receptors, such as groundwater resources and surface water bodies, are typically identified during mine development and closure planning in consultation with regulators and local communities. While the details of water quality regulation vary by Canadian province, water quality permit requirements for discharge typically consider provincial and/or federal guidelines, background water quality, science-based environmental benchmarks, and potential effects on aquatic life. Mines with a long operational history may have been permitted under less stringent water quality requirements than would be permitted today. In some jurisdictions, regulators are requiring mines to meet current discharge water quality requirements for legacy landforms as a condition of permitting mine expansion. Local community members and other stakeholders are generally interested in maintaining and enhancing water quality, particularly for surface water resources.

Geochemical characterisation is required to predict tailings porewater quality, and interactions between meteoric waters and tailings, dam construction materials, and cover construction materials. Orebody mineralogy, mineral processing methods, and storage conditions (e.g. subaqueous versus subaerial) influence tailings porewater quality. Tailings dams at legacy mines and other mines with limited geochemical characterisation may include waste rock that is PAG and/or with metal leaching potential. Even with comprehensive geochemical characterisation, interactions between materials, upscaling effects from laboratory-based or bench scale testing to operational scale, and variations in waste rock used in construction and orebody geochemical characteristics may lead to differences between predicted and actual performance.

During operations, water quality is monitored at seepage collection systems and groundwater monitoring wells surrounding the TSF landform. Seepage pathways during operations are through tailings, dam shells, and foundation materials. In some cases, water quality changes may manifest soon after operations begin. In others, water quality changes may develop after many years of operations because of lag times from deposition to the onset of acid generation and time required for seepage migration along flow paths from sources to observation locations. Water quality along seepage paths typically continues to evolve over decades. Water quality is commonly predicted to continue to evolve over decades to centuries following the end of operations as tailings porewater is flushed by meteoric water and meteoric waters interact with tailings and dam construction materials. Geochemical modelling with software, such as PHREEQC (Parkhurst & Appelo 2013), and water quality modelling, supported by WBMs using software such as GoldSim (GoldSim Technology Group 2021), are used to improve the understanding of geochemical reactions and mechanisms controlling water chemistry and to predict long-term water quality trajectory.

At one Canadian mine, a previous closure plan assumed up to five years of post-operations water treatment, based on limited characterisation that led to uncertainty in water quality model predictions. More recent water quality source term development and water quality modelling, based on more comprehensive characterisation and monitoring data, were completed to support landform closure design. The use of better constrained source water quality terms for the water quality model and a calibrated WBM indicated that water treatment would be required for the full 100-year post-operational design period. The results were consistent across a range of uncertainty and future climate scenarios.

Passive closure with no active care (i.e. 'walk-away scenario') is a common objective of mine operators. In practice, poor water quality resulting from the reservoir of process water stored in tailings deposit pores and geochemical reactions leading to metal leaching associated with acidic or neutral drainage conditions is nearly ubiquitous across operating and legacy mines across Canada. Strategies to limit mobilisation include limiting infiltration rates through low-permeability cover systems, for example, and limiting contact with oxygen by maintaining saturation. These and other passive landform design strategies may reduce the volume of water requiring treatment prior to release or delay the onset of migration. Few Canadian mines with significant TSF landforms have achieved walk-away closure with seepage water quality acceptable for direct release.

4 Conclusion

A suite of standard landform design tools is in common use at operating Canadian mines. The knowledge base is critical to develop and maintain institutional memory for a mine. The landform DBM articulates performance objectives, design criteria, and design constraints. When used effectively, the DBM links operational and closure performance objectives. Observed performance monitored during the multi-year TSF construction and operational phase, ongoing site characterisation, and reclamation research results are stored in the knowledge base and contribute to regular DBM updates and corresponding design modifications. Beyond these two critical overarching tools, core tools that support TSF landform design in common use at Canadian operating mines include tailings deposition models, consolidation and settlement models, water balance and water quality models, and geochemical models. Appropriate site investigation and interpretation are required to define model inputs and constitutive relationships that drive model outputs. Rigorous uncertainty analysis is required to explore a range of potential outputs and characterise risks associated with design assumptions. Developing closure landform designs to feasibility level, with the associated supporting site investigation, may be required to adequately characterise long-term performance for TSF mining landforms.

At a minimum, the landform design team must review the most recent mine closure plan to provide input to the landform DBM. Similarly, mine planning teams, including closure planners, must review each landform design across a mine site to integrate operational designs into closure plans. The design and planning teams need to communicate to address gaps and inconsistencies, where practicable, and track them to address in the next design and planning iteration otherwise. Mines should work toward creating a culture of collaboration, with ongoing, open communication among technical disciplines and the various operations, planning, reclamation, regulatory, and community relations teams. Where possible, mines should extend this open communication to communities and regulators to create a shared vision for post-closure success, grounded by technical realism. As knowledge-base tools have developed, it is now possible to expand partial or full access to the mine knowledge base to regulators and communities while maintaining data integrity and security.

Existing and emerging tools provide ever-increasing technical sophistication, knowledge management, and risk management. Even more importantly, fostering a culture of openness and collaboration at the mine, with technical consultants, with regulators, and with local communities is critical to successfully integrate short-term operational and post-closure performance objectives for mining landforms.

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