Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_60

A case study of integrated remediation and engineering for tailings storage facilities reclamation

Scott Laberge [a,*], **Dale Kolstad** [b]

[a] *Barr Engineering and Environmental Science Canada Ltd, Canada*

[b] *Barr Engineering Co., USA*

Abstract

Tailings storage facilities (TSFs) often remain critical to management of impacted water and soils long after mining operations cease, delaying decommissioning until remedial objectives are achieved. This paper presents a site-specific, phased engineering pathway that prioritises site clean-up and long-term risk reduction while advancing a sustainable and practical closure design for a TSF in Canada. The case study will discuss how early integration and alignment of engineering decisions with the remedial objectives for the site resulted in a closure approach that is both cost-effective and readily acceptable to all parties.

The approach combines traditional site remediation tactics with adaptive, sustainable engineering design practices. Portions of the TSF dam are repurposed to create a smaller, engineered storage cell that maintains necessary containment of site-impacted waters while dramatically reducing the active footprint. The remaining TSF surface is transformed into an engineered landform that isolates residual tailings. Targeted infiltration zones promote natural flushing of impacted soils, accelerating recovery of groundwater plumes and creating soil substrates that can transition towards native ecological communities. These nature-based mechanisms are deliberately integrated to complement, rather than complicate, the engineered system that rehabilitates the site.

Water quality in site water conveyances will be monitored to demonstrate when the flushing period is complete and surface water is suitable for returning to existing waterways. Once the site meets remedial objectives and the TSF is no longer needed within the site water balance, staged dam removal and final landform construction can proceed. Throughout this paper the authors will highlight how long-term closure objectives aligned with the integrated design resulting from the engineering decision-making informed by clean-up timelines, material balances, infrastructure constraints, sustainability objectives and site-specific inputs.

Keywords: *closure, landform, remediation, rehabilitation, reclamation, tailings storage facilities, engineering, design*

1 Introduction

Tailings storage facilities (TSFs) are often long-term liabilities for mine operators and frequently outlive active mining operations. They play an ongoing central role in managing impacted water and soil, which can complicate timely closure. Inevitably, whether it is a legacy site that has not operated for years or an active site nearing the end of operations, areas within the site's footprint often become impacted and will require remedial actions to address chemical instability and return the site to a beneficial land use. As a result of these impacts, both surface water and groundwater captured on the site are often required to be treated and safely released back to the environment, retained onsite for use in operations or stored long term in onsite surface water management facilities. TSFs often form a critical component in a site's water balance and are often the

* Corresponding author. Email address: slaberge@barr.com

'end point' for captured water that cannot be discharged to the surrounding environment. This adds a unique level of complexity to closure of a TSF that is often not present for mine features such as mine rock stockpiles. Owners can often be stuck in a loop from which they cannot decommission their TSF fully because it serves an important role in managing impacted water and/or other materials for the site. As a result, TSF closure is not just an engineering challenge, but a large-scale remediation one. Unfortunately, there is often a disconnect between remediation and typical engineering and design. This disconnect can occur across various organisations due to internal structures that 'silo' different disciplines, making collaboration required to tackle TSF closure more difficult. This challenge, which is not unique to any one geography, commodity, or industry, has relevance to operating and planned TSFs for mine operations around the world.

Conventional TSF closure approaches typically prioritise physical containment and long-term stability, often deferring remediation of impacted soils and water until after major decommissioning activities. In contrast, the approach presented here demonstrates how integrating traditional site remediation objectives as part of engineering and design decisions helps build a more practical approach to TSF closure that is more readily acceptable to stakeholders. The case study discussed in the sections below was first introduced in Laberge et.al. (2023) and follows the sustainable closure principles discussed in that paper and other guidance, such as the Integrated Mine Closure Good Practice Guide published in 2019 by the International Council of Mining and Minerals (2019) and the technical guidance document published by the International Network for Acid Prevention (O'Kane & Baisley 2017). These documents highlight the importance of establishing robust physical and chemical stability of the site to support long-term ecological vitality and community acceptance.

Since that publication, the closure strategy for the site has evolved as remedial objectives, site understanding and design have matured. The sections below discuss the staged approach required to successfully implement this closure strategy as well as how remedial targets informed detailed engineering and design for the facility.

2 Site background

This paper builds on the closure planning framework and initial feasibility-level case study presented in Laberge et al. (2023) and provides a description of the continued evolution of closure design for the TSF as the facility advanced through environmental permitting and detailed engineering and design.

The case study involves a now-inactive TSF at an underground mine in Canada that operated until the 1990s. Following the end of active mining operations, the TSF remained in use to manage process-affected water at the site as well as water from nearby facilities in the region for nearly 2 decades. The process-affected water managed at the site has a high concentration of ions (elevated total dissolved solids [TDS]) that may pose a risk to sustainable ecological restoration and vegetation establishment. No other notable contaminants of concern have been associated with this water.

This paper primarily focuses on the roughly 30-hectare TSF, which is lined with a synthetic geomembrane liner to minimise groundwater interaction with the contents of the TSF. Primary containment is provided by a side-hill earth embankment with a maximum height of approximately 15 m. In addition to process-affected water, the facility also contains residual waste materials left over from mining operations. These waste materials, which are not considered hazardous, are composed of clays, silts and an inert (not acid-generating [NAG]) waste rock. In addition to the TSF, surface water at the site is managed in two synthetically lined water management ponds that can store potentially process-affected water from watersheds outside of the TSF as needed. The site also operates a robust subsurface interceptor drainage system to collect process-affected groundwater and minimise the risk of impacting nearby natural freshwater sources. Management of this water at the site is supported by the remaining infrastructure, including pumphouses associated with the surface water and groundwater management systems, as well as an administration building. The primary process and milling facilities were decommissioned and removed shortly after operations ceased. Figure 1 presents a generalised site layout to illustrate key aspects of the site.

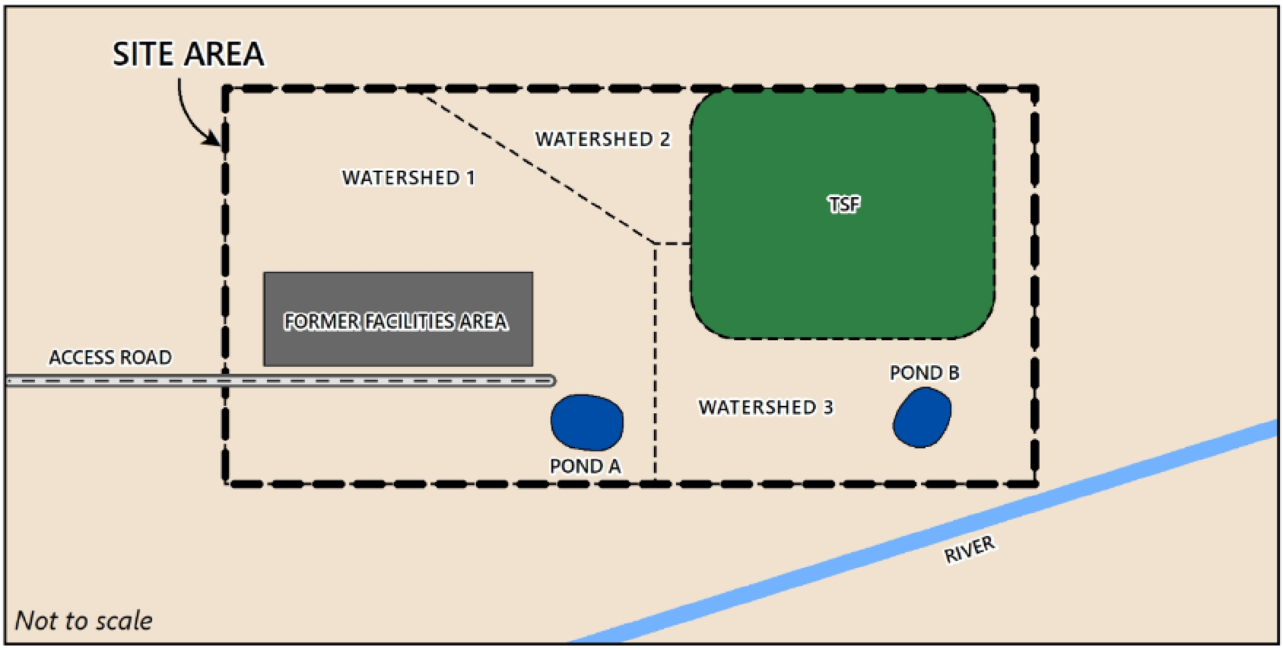

Figure 1 Case study site layout (Laberge et al. 2023)

Water from the 2 surface ponds and the groundwater capture system (GCS) can be returned to the TSF as needed to manage site water. A unique and critical aspect of water management at the site is the ability to transport and discharge process-affected water from the TSF directly to a water body with properties similar to those of the water currently being captured and managed at the site.

Following the end of active operations in the 2010s, focus turned to decommissioning and eventual closure and reclamation of the TSF and other surface infrastructure. The overarching objective is to achieve a 'walkaway' closure outcome following active and passive closure phases for the site. The key challenges the closure strategy needed to address included:

1. long-term management of the residual waste material in the TSF
2. process-affected water from surface watercourses on the site and the TSF
3. existing impacts to groundwater underlying the TSF.

Initial studies, alternatives assessments, beneficial land use selection and a feasibility study were completed. As discussed by Laberge et al. (2023), these studies had to strike a delicate balance between aspiration and realism. For legacy facilities such as this it is not feasible to eliminate all potential liabilities at closure; however, we can significantly reduce them. What is possible ultimately dictates what the site's future land use will be. This work resulted in a strategy that will address all 4 aspects of sustainable closure: physical, chemical, ecological and social stability. This paper is primarily focused on addressing the 2 foundational pillars of physical and chemical stability:

1. physical stability
   a. using a staged approach to transition from an active facility to a natural landform
   b. condition, place and stabilise fine-grained waste materials within the TSF footprint
   c. decommission and remove the TSF dam
   d. create a landform compatible with the regional setting
   e. evolve stormwater management infrastructure from engineered systems to natural drainages

2. chemical stability
    a. using a tiered approach to impacted material management
    b. soils consolidating and isolating higher-risk (impacted) soils from the environment and passive rehabilitation of less-impaired soils for beneficial use
    c. surface waters: enhancing natural recovery of watersheds and staged release to the previous receiving watercourse(s)
    d. groundwater: remediation of existing subsurface impacts currently captured and managed at the site.

Execution of this strategy required a diverse, integrated team to develop the detailed engineering and design for closure of the TSF. This included professionals from various engineering disciplines, including civil, geotechnical, hydrotechnical, environmental and mechanical, as well as scientists (e.g. ecologists, geoscientists) and remediation practitioners, to define a practical approach to closure of the facility. Detailed engineering and design for stage 2 (discussed in the following section) was completed in mid-2025, with construction of stage 2 expected in mid-2026.

3 Staged closure concept

As discussed earlier in this paper, a key challenge of TSFs closure is their importance in managing process-affected materials even after active mining operations cease. For this case study, achieving the site's long-term closure objectives required a staged approach that gradually reduced the need for the TSF. The TSF's current primary purpose at the site is management of the residual waste materials and process-affected surface waters. Instead of approaching closure of the TSF as only an engineering exercise, it is approached symbiotically with remediation and restorative components. In practice, this means having these teams work together to form the design basis and implementation strategy that will ultimately govern the engineering progression for closure of the TSF. This influence led the closure planning team to focus on remedial targets (e.g. the residual tailings material and process-affected surface waters), understanding that if the environmental risks posed by the site are addressed first (or concurrently with engineering design), the need for the TSF to exist will be removed. To achieve this, a staged approach focused on this remedial objective is required. This staged approach was originally introduced in Laberge et al. (2023). As design and site understanding have progressed, the staging has been further refined, splitting the previous stage 3 into 3 distinct substages: 3A, 3B and 3C. If the prior stages 1, 2, and 3 were focused on key engineering and/or construction activities, the substages in stage 3 represent the remedial progress for the site. Figure 2 presents these stages and substages for closure of the TSF. It illustrates the TSF's status during each stage, key activities taking place during each stage and the objective for each.

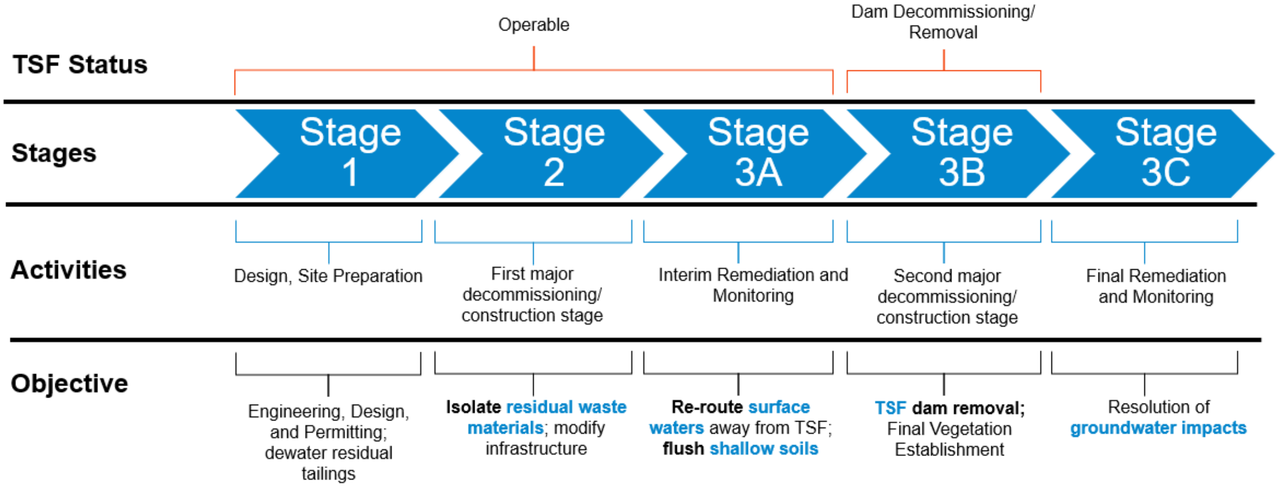

Figure 2 Tailings storage facilities (TSFs) closure staging

The objective defined for each stage can be viewed as a 'checklist' for the purpose of the TSF. At the end of stage 2, the residual waste materials have been placed in a physically stable containment structure which forms an interim landform within the TSF footprint. During these activities, existing infrastructure (primarily the TSF and associated water management infrastructure) is modified to a configuration that better supports the remedial goals for the facility. Given that the site is no longer active and producing new sources of high-TDS material, isolation of these wastes eliminates the remaining source of ions that could further impact water and soil at the site. As a result, the site will begin to recover, with the first remedial targets being shallow soils within the TSF footprint and surface waters at the site. These are targeted in stage 3A, which is largely a passive closure phase focused on remediation. The detailed design process and the integration of this remediation are discussed in later sections of this paper.

Following stage 3A, surface waters captured on the site will be remediated such that they no longer pose an unacceptable risk to the surrounding environment and can be routed directly offsite without needing to be captured and managed in the TSF. Removal of these watersheds significantly reduces the quantities of water that must be managed at the site. During stage 3B, the GCS will be modified to instead discharge to the receiving water body with similar properties (discussed in Section 2), bypassing the TSF entirely. At that point, the TSF containment dam will be removed and the soil used to construct a final landform that supports the future land use of a native ecological restoration for the site. A second remedial stage (stage 3C) will be executed if required until groundwater no longer poses a risk to the natural environment, at which point the GCS will be decommissioned and final closure and reclamation at the site can be completed.

With respect to timing, the total timeline from the present to final reclamation and closure of the facility is determined by the remedial programs in stages 3A and 3C. Construction activities in stage 2 are anticipated to take 2 to 3 years to complete, with remediation during stage 3A requiring 5 to 10 years. Construction during stage 3B is expected to be approximately 1 to 2 years for dam removal, final regrading and seeding. Stage 3C is dependent on the condition of groundwater underlying the TSF at the end of stage 3B and could range from several years to a decade or more. These estimates will be refined through the monitoring programs and numerical modelling described later in this paper.

This paper focuses primarily on stages 2 and 3A. The following sections provide additional detail on the design process and site remediation approach as the TSF prepares to enter stage 2.

4 Stage 2 design – integrated remediation and engineering

The stage 2 design was developed through an integrated, multidisciplinary process that intentionally aligned conventional engineering design with site-specific remedial objectives. Rather than treating the engineering/design process and remediation as separate exercises, care was taken to approach planning and design for stage 2 as a transitional phase that not only established the foundation for long-term physical stability of the site but could create the conditions to accelerate environmental clean-up and gradually reduce dependence on the TSF for site water management.

The design effort depended on close coordination among civil, geotechnical, hydrotechnical, environmental and ecological specialists, supported by regulatory and construction expertise. This multidisciplinary team structure allowed remedial objectives to directly influence geometry, material selection, phasing and operational assumptions embedded in the engineering design. A key advantage is a more cohesive and practical approach that can not only achieve multiple objectives concurrently but also reduce the need for design revisions later in the process and early identification of risks and/or technical gaps in the proposed design. This resulted in a robust design that gave the project team, site owner and regulators confidence that the proposed closure strategy could be effectively implemented.

4.1 Using what we (already) have

Maximising use of existing infrastructure was a guiding principle of the stage 2 design. The existing TSF perimeter dam and internal dyke are retained, with select sections lowered and regraded to provide construction material for key elements of the stage 2 design. This also reduces the total size of the dam structure. The existing pond outlet structure and pumping systems are reused in the reconstructed pond configuration, maintaining established operational controls for impacted water during remediation.

Existing roads, drainage corridors and collection systems were incorporated wherever practical. Future channels to convey non-impacted water offsite are largely aligned with existing or historical drainages, reducing new disturbance and simplifying permitting. Key utilities and site services were largely unaffected in providing operational continuity. Most stage 2 features are contained within the existing TSF footprint. This approach avoids unnecessary creation of additional disturbances that would require reclamation, limits impacts to surrounding wetlands and watercourses, and reduces the need for new borrow areas and access routes. Construction staging, material stockpiling and haul routes were planned to use existing disturbed surfaces, reinforcing the objective of not creating new impacts and/or areas requiring reclamation while addressing the existing closure challenges.

4.2 Designing with the end (of remediation) in mind

The detailed engineering and design for stage 2 took great care to integrate remedial objectives into the core engineering configuration rather than addressing remediation as a separate or downstream exercise. For stage 2, these objectives are centred around shallow soils within the TSF and surface waters at the site. This approach represents a departure from many conventional TSF closure designs, which typically prioritise either environmental containment or physical stability and defer remediation of impacted soils and water until after major decommissioning activities. For this case study, the stage 2 design was configured to simultaneously establish long-term physical stability, reduce environmental risks and permit passive remediation to progress while the TSF remains operable.

At the end of stage 1 (Figure 3), most residual waste materials within the TSF have been excavated and placed in windrowed piles in non-ponded areas inside the TSF footprint to drain and dewater through natural evaporative processes. This will aid in conditioning them to the target moisture content for placement and compaction in the landform within the TSF footprint. Currently, the ponded area in the TSF is a portion of the total area because the quantity of water the TSF is required to manage is substantially less than was required by its original design. This provides an opportunity during stage 2 to modify the TSF to reduce the area within the TSF footprint that must be lined and used to manage impacted water during stage 3A. It involves construction of an additional internal dyke structure that will form a portion of the containment for a 'reconstructed pond' area.

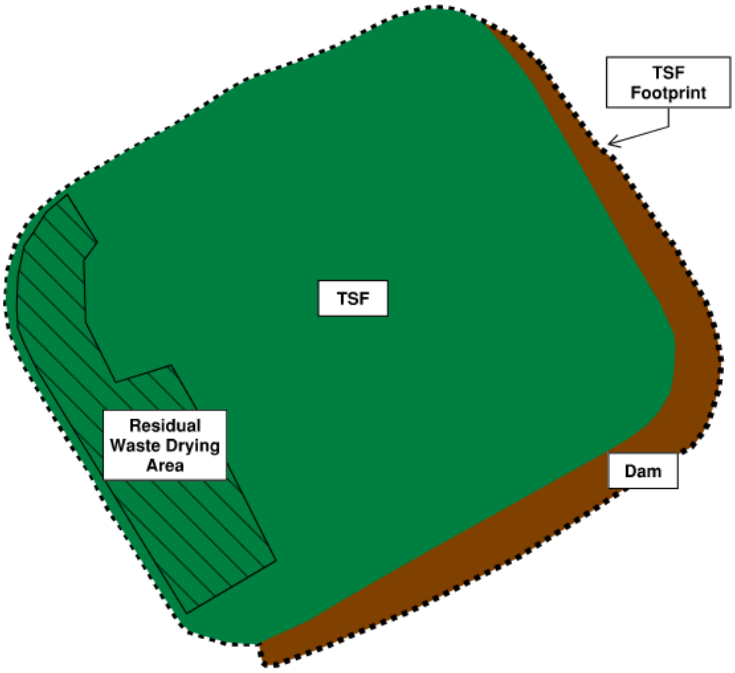

Figure 3 Configuration of the tailings storage facility (TSF) before stage 2 construction

In stage 2, the residual waste materials and highly impacted subsoils are consolidated into the fully encapsulated landform constructed within the existing TSF footprint. The landform is lined on all sides with geomembrane and includes an internal drainage collection system to manage construction-phase water. This configuration allows the containment feature to function as a stable tailings 'stack' rather than a mixed solid-fluid containment cell. The residual waste materials will be conditioned to a target moisture content and compacted within the landform such that they are considered dilative and not anticipated to be liquefiable. This aims to eliminate generating additional process-affected water by preventing contact with these waste materials and also establishes long-term physical stability for the tailings. The surface geomembrane will be covered with an interim cover system (Figure 4) which will provide protection for the surface geomembrane. An interim seed mix of native grasses will be established on the surface to manage erosion and enhance aesthetics during phase 3A. Given the lack of suitable granular drainage material available on the site, a geosynthetic system will provide drainage for the soil cover. The cover soils used to construct the cover system are not considered impacted, and therefore run-off from the surface of the landform will be relatively 'clean' compared to impacted soils and process-affected water at the site.

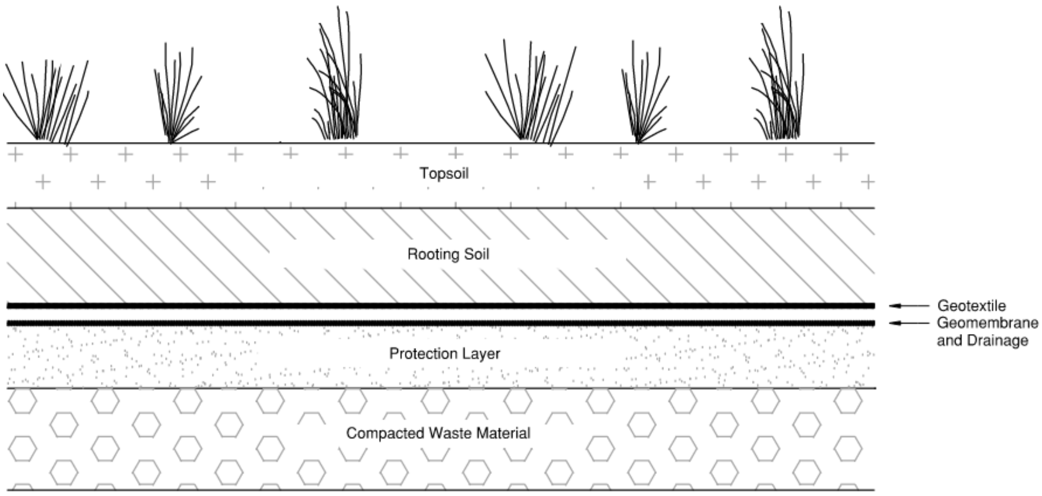

Figure 4 Typical detail – interim cover system

With the waste materials effectively managed and in their final closure location and state, the subsequent approach to water management is designed to support – rather than hinder – remedial goals. A key feature is the infiltration ditch to be constructed along the toe of the landform. This ditch collects the relatively 'clean' run-off from the landform and promotes infiltration of this water into underlying subsoils during typical hydrologic conditions. By increasing downward hydraulic gradients toward existing groundwater collection and interception systems, the infiltration ditch accelerates flushing of residual ions from shallow soils and may contribute to recovery of other groundwater impacts. The infiltration ditch is also designed as a dual-purpose feature that can convey larger storm flows out where required. Initially it will flow to the reconstructed pond area within the TSF but, once the run-off is demonstrated to not pose an environmental risk, it can be conveyed directly offsite to the surrounding environment.

Complementing the infiltration ditch is the soil flushing zone (SFZ) located adjacent to the reconstructed pond in the TSF boundary. In this area the existing geomembrane liner is removed as part of stage 2 construction to allow precipitation and non-impacted surface water to infiltrate and support flushing of the shallow subsoils. The SFZ is graded to encourage infiltration while maintaining gravity drainage back to the reconstructed pond as needed for water-level management. For rare storm events, the SFZ is designed to provide controlled overflow storage for the reconstructed pond, maintaining containment while minimising the risk of re-impacting remediated soils.

Together these integrated features enable stage 2 to function as a transitional closure phase in which engineering infrastructure actively supports remediation rather than constraining it. By reducing the footprint of active water management, consolidating residual wastes into a stable landform, and promoting passive soil and groundwater recovery, the stage 2 design establishes the technical and environmental foundation required for subsequent dam removal and final landform construction in later closure stages. Figure 5 illustrates the configuration of the TSF following stage 2 construction activities.

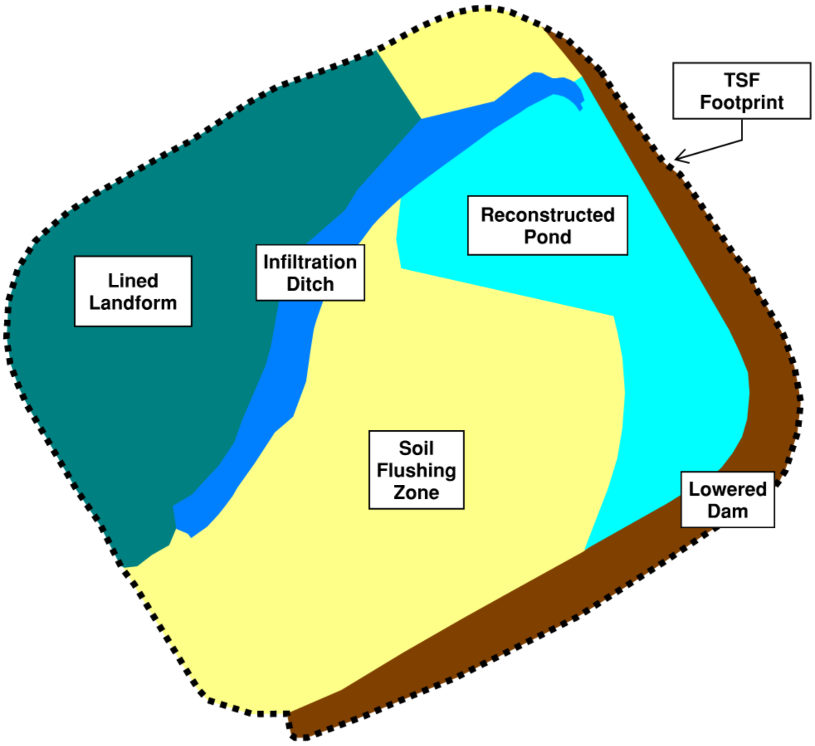

Figure 5 Configuration of tailings storage facility (TSF) following stage 2 construction

Stage 2 primarily focused on modifications to the TSF to support remediation. But with the source of impacts (residual waste materials) effectively isolated in the landform, surface water quality in watersheds outside the TSF is also expected to improve. This is discussed further in the following sections. Once these watersheds have been demonstrated to not pose a risk to the surrounding environment, channels will be constructed to bypass the surface water management ponds and reintegrate these watersheds back into the environment.

5 Stage 3A: remediation part I

Following stage 2, the facility will enter the first passive closure phase (stage 3A), which is focused on remediation of surface waters at the site and shallow soils within the TSF footprint.

5.1 Shallow soils

Elevated TDS in shallow soils within the TSF represents a key risk to long-term vegetation establishment following construction of the final closure landform in stage 3B. These shallow soils will form the foundation for placement of final cover materials and therefore directly influence reclamation success. The magnitude of vegetation risk is governed by the initial TDS of the subsoils and the thickness (and properties) of non-impacted cover soils placed above them. Together these factors control the potential for upward solute migration (wicking) into the rooting zone over time, as well as the duration required for subsoils to flush to levels suitable for final cover placement.

`To manage the risk of wicking to future vegetation, subsoil remediation is explicitly integrated into the stage 2 closure design using a risk-informed, staged approach that combines targeted excavation with passive in situ flushing. Several site-specific simulations were completed using HYDRUS-1D to evaluate TDS reduction over time under varying initial subsoil TDS values, cover soil thicknesses and climatic conditions. Work done by others, including Shaygen et al. (2018), demonstrated the applicability of HYDRUS-1D for simulating TDS (specifically salts) evolution in soil reclamation. The modelling was used to support development of risk-based thresholds that distinguish subsoils requiring removal from those suitable for flushing, assuming an available remediation timeframe of 5 to 10 years before reaching stage 3B. Shallow soils were categorised into 3 types based on their measured TDS:

- type I – highly impacted
- type II – moderately impacted
- type III – marginally to minimally impacted.

Soils classified as type I in the upper 1 m or type II in the upper 0.5 m of the existing soil profile were estimated to pose an unacceptable risk of solute migration within the target time frames for stage 3A and were designated as remediation 'hotspots'. These materials will be excavated during stage 2 and permanently encapsulated within the landform along with the other residual waste materials, isolating them from the surrounding environment. A preliminary classification has been completed based on a 2023 test pit investigation. Final delineation of these hotspot areas will be completed during stage 2 construction activities as the soils become exposed.

Remaining subsoils with lower TDS (type III) will be left in place and remediated through natural flushing processes following partial removal of the existing TSF liner at the end of stage 2. Flushing is driven by precipitation and managed infiltration within the SFZ and along the infiltration ditch. Flushing water either infiltrates towards the existing groundwater collection system or is captured as run-off and managed within the TSF footprint. In addition to improving subsoil conditions for future cover placement, this approach could speed recovery of deeper groundwater impacts by promoting downward hydraulic gradients and dilution. Figure 6 illustrates the typical soil profile in the SFZ at the start of remediation (stage 2) through the end of remediation and removal of the TSF dam (stage 3B).

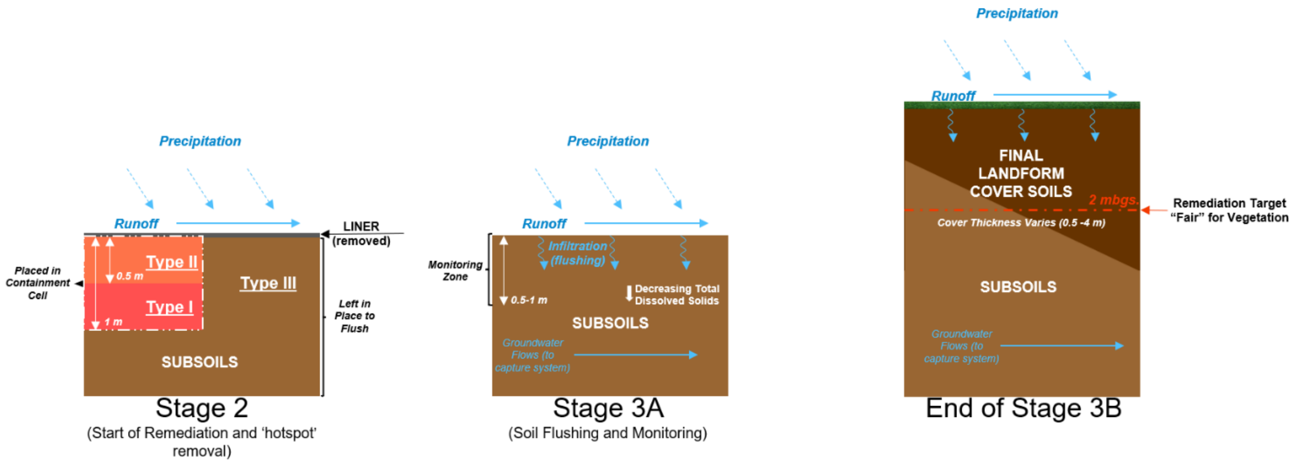

Figure 6 Soil profile in soil flushing zone during and after soil flushing

This integrated subsoil remediation strategy reduces uncertainty about vegetation tolerance and long-term cover performance while avoiding unnecessary excavation of marginally impacted soils. By aligning soil remediation with the overall staged closure framework, the approach supports timely advancement to final landform construction and reinforces the broader objective of achieving a stable, self-sustaining closure condition.

5.2 Surface waters

Remediation of surface water at the facility is split into waters inside the TSF footprint and waters outside of it. Surface water quality at the site is anticipated to improve after the waste materials in the TSF have been isolated in the planned landform and as soil flushing progresses through stage 3A. The subsections below briefly outline the remediation approach for these waters at the site during stage 3A.

5.2.1 Internal to tailings storage facilities

In stage 2, the internal configuration of the TSF will be regraded and subdivided into several sub-watersheds defined by key design elements, including landform, reconstructed pond, infiltration ditch and SFZ (see Figure 5). Surface run-off from the landform and portions of the SFZ will be directed to the infiltration ditch, where it will infiltrate into shallow subsoils, evaporate or flow to the reconstructed pond during larger hydrologic events. The infiltration ditch is designed to promote infiltration of relatively 'clean' run-off to accelerate flushing of impacted subsoils; however, run-off conveyed during early stages is conservatively routed to the reconstructed pond until monitoring confirms its suitability for direct discharge. Precipitation within the SFZ similarly promotes subsoil flushing, with excess water discharged to the reconstructed pond as needed to manage water levels. Remediation of surface water in the TSF relies on natural attenuation and is closely tied to subsoil flushing, with surface water retained onsite until monitoring demonstrates that applicable thresholds for direct release have been achieved, marking completion of stage 3A and readiness to advance to stage 3B.

5.2.2 External to tailings storage facilities

Remediation of surface waters external to the TSF relies on flushing and natural attenuation, with progression towards direct discharge based on monitored water quality relative to defined remedial targets. As surface water quality improves, water currently flowing to the collection ponds or other capture systems will be rerouted via engineered channels to discharge directly to the natural environment. External watersheds are grouped into those flowing to pond A and those flowing to pond B, which are expected to reach suitability for direct release at different times. Watersheds flowing to pond A are primarily associated with former mill infrastructure that has since been decommissioned, and monitoring indicates that these areas have largely recovered through flushing and natural attenuation. In contrast, select watersheds flowing to pond B remain influenced by residual impacts associated with the TSF and are expected to require additional remediation time (relative to pond A watersheds). Completion of remediation for each watershed will be informed by the monitoring program and, while external surface water remediation is independent of remediation inside the TSF, it is expected to be substantially complete prior to initiating stage 3B closure activities. Following diversion of external watersheds offsite, ponds A and B may be retained as operational features to support residual groundwater management (during stage 3C) or other interim site needs.

5.3 Monitoring and remediation targets

The staged construction and remediation approach is designed to maintain the site's existing containment and monitoring systems until they are formally removed after meeting remedial objectives. To support this process, monitoring programs with defined, risk-based remedial targets were developed for both shallow soils and surface waters at the site.

Monitoring of the shallow soils will be conducted through semi-annual soil investigations in the SFZ and other exposed areas of the TSF. These testing programs will be used to assess the effectiveness of the flushing approach and calibrate the numerical solute transport model. Updates to the model will be completed as needed to refine the anticipated flushing timelines and inform the fill thicknesses for the final landform to be constructed in stage 3B.

Instrumentation will continuously monitor the quality and quantity of surface water flowing to the ditches, as well as the receiving watercourse. Site water management and remediation performance are influenced by seasonal variability typical of the regional climate, including spring freshet and typically lower flows during winter. Monitoring programs and release criteria are therefore evaluated across a range of hydrologic conditions (e.g. baseflow, stormflow) to further demonstrate the robustness of the proposed closure approach.

This monitoring will continue until the remedial target has been met and maintained for an adequate period to capture seasonal variations and hydrological events. Most subwatersheds on the site are already actively monitored with between 1 and 3 years of data collected to date.

5.3.1 Risk-informed remedial target values

The remedial targets for shallow soils and surface waters are both focused on limiting risk to site-specific environmental receptors, which follows from criteria-setting-based approaches common in guidance documents such as the Canadian Council of Ministers of the Environment soil quality guidelines (Canadian Council of Ministers of the Environment 1999).

The remedial target TDS for subsoils within the TSF is based on limiting risk to the long-term viability of vegetation on the final closure landform cover in stage 3B. High TDS in soils can impair soil structure, reduce soil fertility by disrupting nutrient uptake, and cause osmotic stress that restricts the water intake by roots. Select federal and provincial guidance documents were used to bracket TDS ranges for management based on the conditions they provide for vegetation growth (e.g. good, fair, poor, etc.). For the site, the final cover soils must provide at least 'fair' conditions to vegetation growth in stage 3B, assuming parkland or agricultural land use. To achieve this, the cover soils cannot exceed the TDS corresponding to 'fair' conditions at 2 m below the final ground surface in stage 3B (see Figure 6). Site-specific modelling (like that described in previous sections) was completed to estimate TDS migration upward out of impacted soils within the TSF into the final cover soils. This guidance and modelling were used to define a target TDS in the top 0.5 m to 1 m of impacted soils within the TSF that is not expected to result in an exceedance of a 'fair' TDS at 2 m below final ground surface. The assumption that 'fair' conditions will be suitable to establish the target ecosystem will be confirmed using the planned cover studies discussed in Section 5.4. The monitoring described above will inform when the TDS in the impacted shallow soils has reached the target remedial value and the site can advance to the next stage of closure.

The risk-informed remedial targets for surface waters at the site are based on demonstrating that the observed water quality and quantity from subwatersheds on the site will not result in an exceedance of an existing TDS threshold value in the receiving watercourse downstream of the site. The TDS threshold is established to protect the health of the river in this region, as an ion imbalance could provide stressors to the freshwater aquatic taxa. Note that this region has naturally occurring sources of high-TDS water, including upstream of the site. As a result, the facility already has an established target TDS in the receiving watercourse downstream of the facility. Using data from the monitoring program(s) described above, an attenuation assessment will be completed to quantify the load that can be discharged from the site without exceeding this target TDS at the existing compliance point. Risk is managed through gradual reintroduction of watersheds to the natural environment with the option to cease and maintain management onsite (if needed). The monitoring program will help verify that loading from the site would not cause an exceedance at the downstream compliance point for a range of representative hydrologic scenarios (e.g. baseflow, stormflow, etc.).

The monitoring program and remedial targets planned for stage 3A are summarised in Table 1.

Table 1 Summary of monitoring plan during stage 3

Media	Remediation target	Monitoring
Shallow soils within Tailings Storage Facility footprint	Total dissolved solids (TDS) in soil to remediation target value to provide 'fair' conditions to vegetation establishment at 2 mbgs	Twice-annual shallow soil investigations to monitor soil flushing progress and revise solute transport model. Expected to include composite and discrete sampling of upper 1 m of soil in soil flushing zone(s).
Surface waters	Maintain TDS in receiving watercourse downstream of site at or below target value	Continuous monitoring at 11 locations (10 in drainages onsite, 1 in receiving watercourse). Monitored until suitable number of hydrological events have been captured to demonstrate suitability to bypass surface collection ponds.

Once remedial targets have been achieved the results will be submitted to the regulator for approval to advance to stage 3B.

5.4 Risk mitigation and adaptive management

The closure strategy leverages the time available during stage 3A to execute trials and studies to de-risk key aspects of the closure plan for the site. This includes a vegetation study that involves constructing 5 approximately 15 × 15 m plots in the TSF footprint. Two will be built on the surface of the landform constructed during stage 2, and 3 in the SFZ. The first two are intended to assess the viability of vegetation establishment on the landform with and without a proper layer of topsoil (see Figures 7a and b). The remaining three (Figure 7c) will be constructed of non-impacted fill material on top of existing subsoils within the SFZ that have different TDS levels (i.e. high, moderate, low). All plots will have 2 native seed mixes to determine which demonstrates the greatest success in establishing a sustainable native ecosystem.

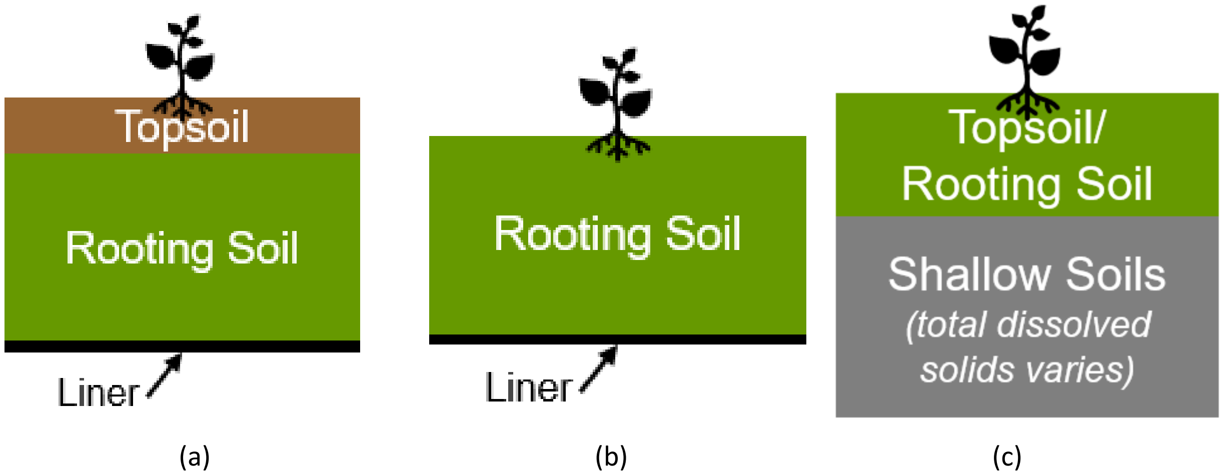

Figure 7 Vegetation cover studies

The 3 plots in the SFZ are the most critical for remediation. Information gathered from those plots will be used to validate the solute transport model and confirm suitability of the defined remedial target threshold.

Adaptive management is used as the decision-making framework for implementing remediation at the site, emphasising iterative learning and progressive reduction of uncertainty through a 'plan, do, check and adjust' approach (see Figure 8). This approach is common in several environmental management systems and is also implemented in the tailings management framework presented by The Mining Association of Canada (2021) for management of tailings facilities. The remediation program is initially developed based on available data and understanding supported by a monitoring program designed to evaluate progress toward remedial objectives and inform adjustments as needed. Key uncertainties include the time required for shallow soils to flush to acceptable levels and for surface waters to recover sufficiently to allow direct discharge without risk of exceedance at the downstream compliance point. If monitoring results indicate that soil or surface water recovery is not progressing as expected, the remediation approach may be modified accordingly. An additional uncertainty is the potential for solute transport into final cover soils following stage 3B and the vegetation's tolerance to these residual impacts. This is complemented by actions to de-risk portions of the closure approach, such as the vegetation studies described above. Actions such as the site-specific vegetation cover study discussed above will provide data to refine soil conductivity thresholds and support long-term reclamation decisions.

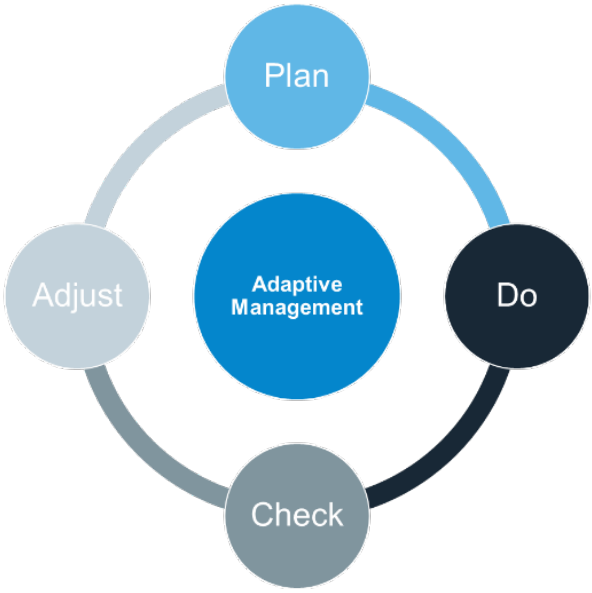

Figure 8 Adaptive management cycle (adapted from Mining Association of Canada 2021)

6 Conclusion

The updated case study demonstrates how early and deliberate integration of remediation objectives into engineering design can provide a practical and defensible pathway toward closure of a legacy tailings storage facility (TSF). By reframing the TSF as an intermediate support to site remediation rather than an isolated, complex challenge to be removed, the staged closure strategy aligns remedial goals with engineering objectives such as the site's long-term physical and chemical stability. Stage 2 serves as a critical transitional phase, consolidating residual waste materials into a stable, synthetically lined landform while supporting passive remediation of shallow soils and surface waters.

Key elements of the approach include targeted excavation of highly impacted soils, risk-informed use of in situ flushing for marginally impacted materials, and deliberate incorporation of features such as infiltration ditches and soil flushing zones to accelerate natural attenuation processes. The strategy minimises additional disturbance by using the existing TSF footprint and infrastructure, reducing long-term liabilities while maintaining regulatory oversight and operational flexibility through adaptive management and performance monitoring.

The applicability of this approach is more favourable at sites where mine impacts are advective contaminants, sufficient hydraulic gradients can be established to promote flushing, and climatic conditions allow for meaningful net infiltration over time. Sites with contaminants susceptible to retardation, limited infiltration potential or extreme arid conditions may require modifications to the approach presented in this paper before implementing it.

While the specific design reflects site conditions and regulatory context in Canada, it demonstrates the value of early alignment of engineering and remediation. The staged removal of containment dependencies and reliance on natural processes supported by targeted engineering applied in the case study are broadly transferable to other inactive and late-life TSFs in Canada and beyond. The approach illustrates how complex closure challenges are best addressed through integrated decision-making, reducing uncertainty and advancing sites toward stable, sustainable closure outcomes that are more readily acceptable to regulators, stakeholders and rightsholders.

Acknowledgement

The authors would like to thank their colleagues Art Kalmes and Billy Dehler for their support of this paper and their leadership through the closure design process for this facility. Thank you to Allison Wedell and Craig

Gustafson for their review and editorial comments. Thank you to the many incredible professionals at Barr Engineering Co. and Barr Engineering and Environmental Science Canada who provided their expertise throughout the site closure planning and design process. Thank you to Barr for its support in the preparation of this paper, and to the site owner for allowing us to present on this fascinating project.

References

Canadian Council of Ministers of the Environment 1999, *Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health*, Winnipeg.

International Council on Mining & Metals 2019, *Integrated Mine Closure Good Practice Guide*, 2nd edn, London.

Laberge, SL, Kolstad, DC, Dehler, WG & Kalmes, AR 2023, 'Evolution of closure planning for an inactive tailings facility', 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_036

Mining Association of Canada 2021, *A Guide to the Management of Tailings Facilities*, version 3, Ottowa.

O'Kane, M, Baisley, A 2017, *Global Cover System Design – Technical Guidance Document*, International Network for Acid Prevention, Mitcham.

Shaygan, M, Baumgartl, T, Arnold, S & Reading, LP 2018, 'The effect of soil physical amendments on reclamation of a saline-sodic soil: simulation of salt leaching using HYDRUS-1D', *Soil Research*, vol. 56, no. 8, pp. 829–845.