Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_038

Clean water by design—The impact of landform design on long-term water stewardship

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Abstract

Mine Rock Stockpiles (MRSs) typically represent the majority of acidity generation potential at a mine site, a multigenerational water quality risk in respect of metal leaching and acid rock drainage (ML-ARD). Too frequently the extent of this risk is unrecognised and underfunded, resulting in a need for increased effluent collection and water treatment capacity after closure, and frequently, in perpetuity. Conventional water treatment options like lime treatment, result in a precipitated waste sludge, which then also requires a long-term disposal and remediation plan.

Mine closure practitioners, when taking a long-term, full-lifecycle approach to design, appreciate that source term control is the highest level of hierarchical risk control in respect of source-pathway-receptor risk management. Applying source term control philosophy to MRS landform design presents an opportunity to reduce ML-ARD risk and the associated water treatment costs. Integration of passive, or semi-passive water treatment solutions into the mine affected landscape can further increase the value of this approach.

This paper compares capital and operating costs using conventional mine rock placement methodologies paired with conventional effluent collection and treatment against an integrated mine closure landform and passive water treatment design. The value of the proposed integrated approach will be demonstrated not just through discussion of costs, but also the value of honouring and respecting water's sacred place in Indigenous knowledge systems.

Keywords: *mine rock stockpile design, water balance, water treatment, indigenous rightsholders, water stewardship*

1 Introduction

Metal leaching and acid rock drainage (ML-ARD) occurs due to the geochemical instability within a range of mine site domains and landforms, such as mine rock stockpiles (MRSs), heap leach pads, tailings storage facilities, open pits, underground mine workings and voids and assorted stockpiles (e.g., slag). ML-ARD results primarily due to oxidation of iron-bearing minerals (reactive sulfides). Weathering and oxidation typically results in complexation, metal mobility and secondary dissolution (Blowes and Jambor 1990).

The International Network for Acid Prevention (INAP 2020) reports that direct and indirect measurements of acidity load from various site domains at more than 40 sites over the past 25 years have revealed that mined sulfidic rock typically contributes to the majority of the total acidity load (60 to 80%) from most mine sites. Examples include the Brunkunga mine site, where MRSs contributed 82% of acidity treated in an active water treatment plant (Scott et al. 2011), and the Equity Silver mine, where 94% of acidity treated over more than 30 years in an active water treatment plant was collected from MRSs.

2 Water

Water is a key welfare security concern in every community worldwide, and water security is intrinsically connected to the security of energy and food (IISD 2022). Concerns regarding freshwater security are often one of the main sources of apprehension for communities adjacent to mining operations. Water security concerns are often divisible into three main categories: water quantity, water quality and social impacts. Although water quantity has operational cost implications, with respect to mining operations, water quality is often of greater concern (IISD 2015).

ML-ARD can represent a multigenerational water quality risk exposure resulting in a need for increased effluent collection and water treatment capacity after closure in perpetuity. Frequently, the extent of this risk is not fully recognised and therefore poorly funded. Further, conventional water treatment options like lime treatment result in a precipitated waste sludge, which then also requires a long-term disposal and remediation plan.

Water has significant cultural importance to Indigenous cultures across Canada and the World. Williams (2021) speaks to the importance of water to Indigenous Peoples:

> *"…it's our life, without water, there is nothing…"*
>
> *" …all the little streams that run into the big rivers, they're the lifeline; those are the laces of the moccasin that hold us together…".*

3 Mine rock stockpiles

Differences in topography, climate, geology, mine rock texture, and geochemistry will significantly influence mine rock placement strategies and therefore final water quality outcomes (INAP 2020). These differences also influence efficacy of mitigation strategies; successful approaches are site specific, and multiple strategies are needed at each site.

Below grade ore is typically referenced in the mining industry as 'waste rock', and the resulting landforms created are referred to as waste rock dumps or waste rock piles. We acknowledge that the mining industry often uses the term 'stockpile' to refer to lower-grade material that is likely to be processed in the future; however, lower-grade stockpiles are most often also a source of ML-ARD.

The term 'waste' implies a material has no value. We contend value requires perspective, and below grade ore may be 'waste' only in the context of the commodity being mined at the time. We argue that having a perspective of lower grade ore as waste represents negative value assignment to a potential asset, the value of which is easily communicated given the multigenerational water quality risk discussed earlier. The benefits of limiting a perceived negative value of mine rock can be leveraged as an opportunity to illustrate the value of planning and implementing progressive closure during mining.

The mine lifecycle starts with disturbance of land during exploration, and transitions from one land use to the next: from exploration, to construction, to operations, and then to the highest value future land use following operations. The highest value land use could be cultural, ecological, or industrial, and will often include a combination of these alternatives. The principles of sustainable mining are core to mine closure planning, as the industry applies mine closure activities as a method, an activity, or tool to ensure social and environmental responsibility in respect of the land being used. Mining projects are frequently located on the traditional territories of Indigenous Peoples whose creation stories are interconnected to the impacted water and land that is being mined. It is insensitive to refer to peoples' creation story as 'waste'.

4 Water stewardship through MRS source term control

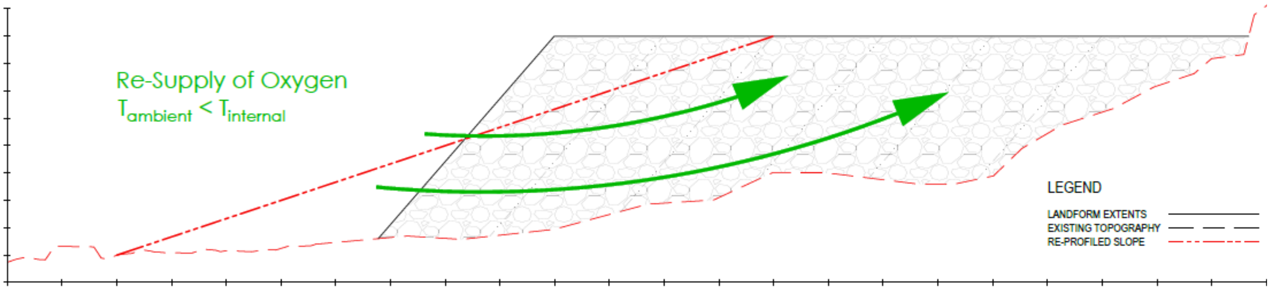
Source term control is the highest level of hierarchical risk control in respect of source-pathway-receptor risk management. INAP (2023) defines source control as a means of ML-ARD prevention; a proactive strategy that obviates the need for a reactive approach to mitigation where the amount of seepage requiring treatment may be reduced if the current source strength is reduced. A focus on MRS source term control may soon represent a requirement to continue mining. For example, if current water treatment with 95% removal of a higher concentration of a constituent of concern may not be sufficient for permit approval, then achieving 95% of an initially lower concentration may be required. Furthermore, there is precedent growing that where the permissible lower concentration limits of a number of constituents (e.g., selenium, nitrogen) are become more stringent. In some instances, the permitting requirements may require concentrations which existing treatment technologies, as currently applied, cannot achieve.

Applying source term control philosophy to MRS landform design presents an opportunity to reduce ML-ARD risk and the associated water treatment costs. Integration of passive, or semi-passive water treatment solutions into the mine affected landscape can further increase the value of this approach.

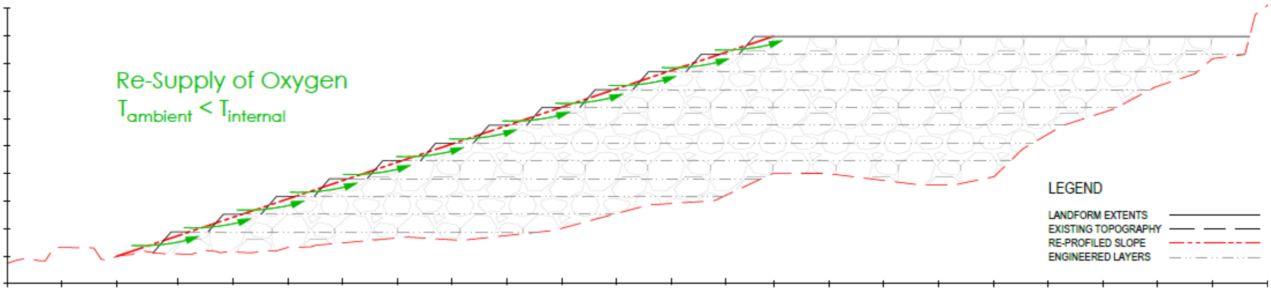
Conventional MRS construction results in high internal MRS airflow capacity given typical mine rock texture, segregation of mine rock material during placement, and relatively drier material as it is extracted. Oxygen concentration in MRS pore-gas will initially be atmospheric following placement of mine rock, and then is reduced as a result of sulfide oxidation (noting that organic carbon oxidation can also consume pore-gas oxygen). Re-supply of oxygen in MRS pore-gas results of diffusion and advection of oxygen from the atmosphere into the MRS. Re-supply due to diffusion is a surface dominated mechanism, influenced by mine rock reactivity, water content, and depth below the surface. Advection results from pressure gradients, such as barometric pressure differences and density, or buoyancy, differences within the MRS in comparison to ambient conditions. Advection leads to re-supply of oxygen deep within an MRS constructed using conventional methods.

For MRSs constructed conventionally, advection as a result of convection (pressure gradients resulting temperature driven density differences) is the dominant mechanism for re-supply of oxygen (O'Kane and Waters 2003; Phillip et al. 2012; INAP 2020).

MRSs constructed with a focus on source term limit re-supply of oxygen deep within an MRS by limiting vertical and lateral airflow capacity, to address the issues of inherent segregation and texture of mine rock as it is being placed. O'Kane and Waters (2003) and INAP (2020) describe mine rock placement methodologies to limit vertical and lateral airflow capacity within an MRS, the value of which can be evaluated at all stages of the mine lifecycle. Figure 1 illustrates, conceptually, difference in airflow capacity and re-supply deep into an MRS through construction of an MRS that limits vertical airflow capacity.



(a)



(b)

Figure 1 **Conceptual illustrations of airflow capacity for a conventional Ridgeline Valley Fill MRS (a), as compared to a Ridgeline Valley Fill MRS constructed by limiting vertical airflow capacity for source term control (b), assuming ambient temperature is less that MRS internal temperature**

5 Water treatment

5.1 Active treatment versus passive treatment

Active and passive treatment are the two generally recognised categories of treatment approaches used for treating ML-ARD. Active treatment involves the addition of alkaline chemicals to neutralise acidity, while passive treatment relies on natural processes to remediate the water.

Passive treatment is driven by processes that couple geochemical/biogeochemical transformations, such as biological, chemical, and biogeochemical reactions, with physical transfers such as sorption, filtration and settling (when applicable), to treat water. Where a treatment system makes use of minimal use of chemicals or power to support or improve the performance of a passive treatment system the term semi-passive is used. The objective with passive and semi-passive treatment systems is for a design to be relatively self-sustaining, operationally passive, and/or remotely operated, with minimal periodic maintenance or management.

The transformations in passive and semi-passive treatment systems are often catalysed by biogeochemical reactions driven by microbes. Different microbes perform different reactions, and passive and semi-passive treatment systems (PTSs) can be specifically designed to encourage the establishment and activity of the desired types of microbes.

Active treatment methods often involve the use of lime or limestone to raise the pH of the water and precipitate metals. This can be done through various processes such as limestone beds, chemical dosing, or lime precipitation. Active treatment systems are typically more expensive to operate and maintain than PTSs, requiring ongoing chemical inputs and frequent monitoring. One of the most common treatment systems for treating acidic mine waters containing metal contaminants is the hydroxide precipitation process (Figure 2) that can be implemented either as a Low Density Sludge or a High Density Sludge (HDS) configuration.

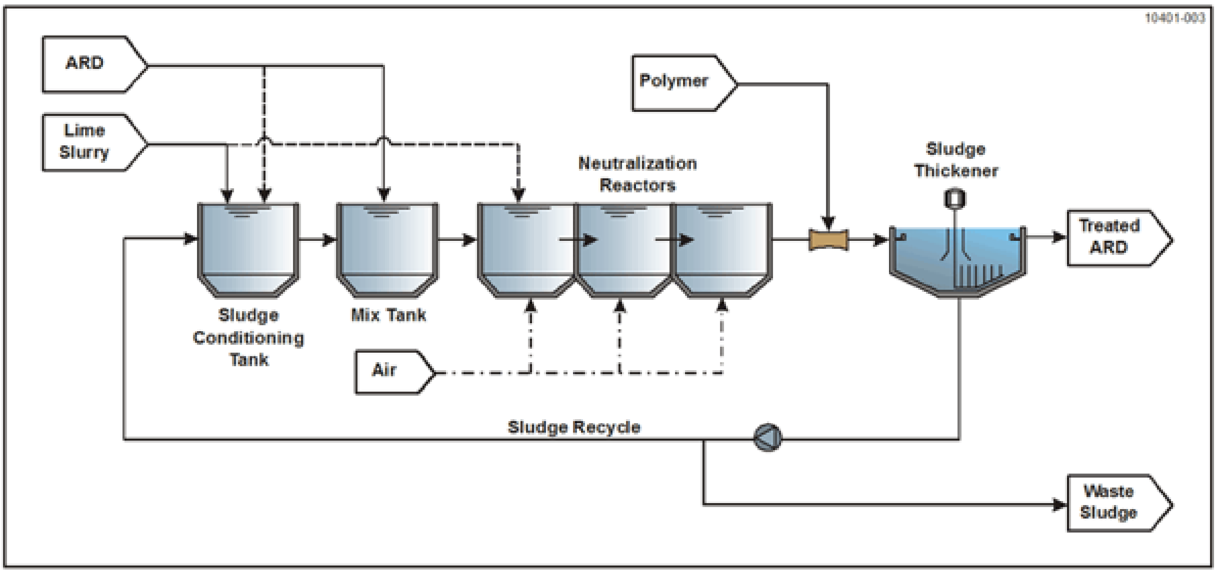


Figure 2 **Schematic representation of a typical HDS process configuration**

In contrast, PTSs utilise natural biological, chemical, and physical processes to treat ML-ARD. These systems are designed to mimic natural wetlands or ponds and require minimal ongoing maintenance once established. They rely on naturally occurring processes such as microbial activity, oxidation, and precipitation to remove metals from the water.

Selection of active or passive treatment systems depends on various factors such as water quality, flow rate, site characteristics, and available resources. Active treatment methods are often preferred in cases where immediate treatment is required. Passive treatment systems are suitable for low to moderate flow rates and can be cost-effective in the long run. The choice between the two water treatment approaches depends on site-specific factors and project goals.

There is an array of different passive treatment systems that have been developed and used to treat mine water around the world. The following are a few of the most common systems used (Figures 3 and 4):

- Open/oxic limestone channels
- Anoxic limestone drains
- Successive alkalinity producing systems
- Biochemical reactors (BCRs)
- Constructed wetland treatment systems (CWTSs)

Since BCRs and CWTSs form the central technologies used in analysing PTS costs for this paper, we describe them in more detail in the following paragraphs.

5.2 Biochemical reactors (BCRs)

Treatment of mine-affected water using biochemical reactors (BCR) has successfully been demonstrated at various mine sites around the world (AEG 2012; Blumenstein et al. 2008; Duncan 2004; Ettner 2007; Gallagher et al. 2012; Germain 2003; Harrington et al. 2015; Kuyucak 2006; Tassé et al. 2003; USEPA 2006; Zamzow and Miller 2017). Passive and semi-passive BCRs are primarily reducing systems (i.e., operate in absence of oxygen) that can be used to treat water containing Contaminants of Concern (CoCs) such as metals, metalloids, nitrate, and sulphate. They are constructed of a permeable material (e.g., gravel) that is either incorporated with or supplemented with organic carbon sources that drive treatment through microbial reactions. The permeable material can also be supplemented with reactive materials such as iron, sorptive materials, or additional nutrients. One of the advantages of BCRs is the opportunity for year-round treatment, and a relatively fast commissioning period (weeks to months). Additional strengths for BCRs are they can have a small footprint (depending on CoCs and flow rates) and are easy to decommission.

Depending on the solid-phase carbon source (e.g., straw, wood chips) integrated into a passive BCR and the load of constituents for treatment, the design life has the potential to be as short as a few or as long as 30 years before the substrate requires replacement; however, short-circuiting and/or clogging is frequently encountered much sooner, decreasing hydrological and treatment capacity. The selected solid-phase carbon source and substrate for the BCR requires rigorous testing at a pilot or field-scale to inform subsequent full-scale design. BCRs with liquid carbon sources (e.g., ethanol, glycerol) are slightly less passive (i.e., semi-passive) and will require pumping systems, but can be operated by solar power with remote operation. Liquid carbon sources are more effective as they can be adjusted according to changes in chemistry and flows and are less prone to clogging.

Solid-phase organic carbon BCRs are often followed by oxidizing cells to facilitate aeration and treat any excess biochemical oxygen demand (BOD) generated by the system, while providing filtration and removal of suspended solids generated in the reducing environment of the BCR. Conversely, liquid carbon dosed BCRs may or may not require this (depending on design), as the carbon dosing can be adjusted to prevent an excess of BOD in the outflow.

BCRs can be used at locations where treatment of year-round flow is required, as a BCR can be insulated underground and with soil covers (Harrington et al. 2015). At locations where very high concentrations of CoCs are a concern to wildlife, a BCR is also favourable as it is a contained system.

5.3 Constructed wetland treatment systems

Treatment of mine-affected water via constructed wetland treatment systems (CWTSs) has successfully been demonstrated at various mine sites as stand-alone treatment systems or as part of a treatment train paired with other technologies such as BCRs (e.g., Contango 2019; Duncan 2010; Ettner 2007; Gammons 2000; Hedin 2020; Kadlec 2009; Kuyucak et al. 2006; Martin et al.; 2015; Nelson 2010).

CWTSs can be designed to promote either aerobic (oxidizing) or anaerobic (reducing) conditions, both of which are facilitated by microbes within the CWTS that act as catalysts for reactions. Reducing or oxidizing CWTS designs are applicable for treatment of various CoCs and can be implemented in a treatment train if both reducing and oxidizing conditions are needed to treat CoCs. CWTSs could be used at sites where water is targeted for seasonal treatment and where adequate land area is available. CWTSs generally require the greatest land area and can have lower treatment effectiveness in freshet, where high flows may need to be diverted around the CWTS.

While CWTSs can be aesthetically pleasing, they are distinctly different from wetlands (natural or constructed) that provide habitat for wildlife or are intended to compensate or reclaim and restore impacted wetlands. Instead, a CWTS is designed to remove CoCs from water, using natural microbiological processes to sequester them into the soils, rendering them less bioavailable (i.e., minimising plant uptake). Organic carbon from decomposed plant material is used as food by microbes.

CWTSs are the most passive and long-term treatment option, requiring minimal amendments with organic carbon regenerated through plant decomposition once the wetland has matured. Depending upon treatment needs and site-specific water chemistry, CWTSs can also be supplemented (passively or semi-passively) with amendments such as solid or liquid phase carbon sources (e.g., straw, wood chips, methanol), alkalinity, nitrogen, phosphorous, and/or iron sources. Construction lead time can be longer than other treatment options because of necessary piloting and longer commissioning periods. Long-term management and maintenance can be minimal and periodic and may involve manual correction of hydrology and removal of certain plants.

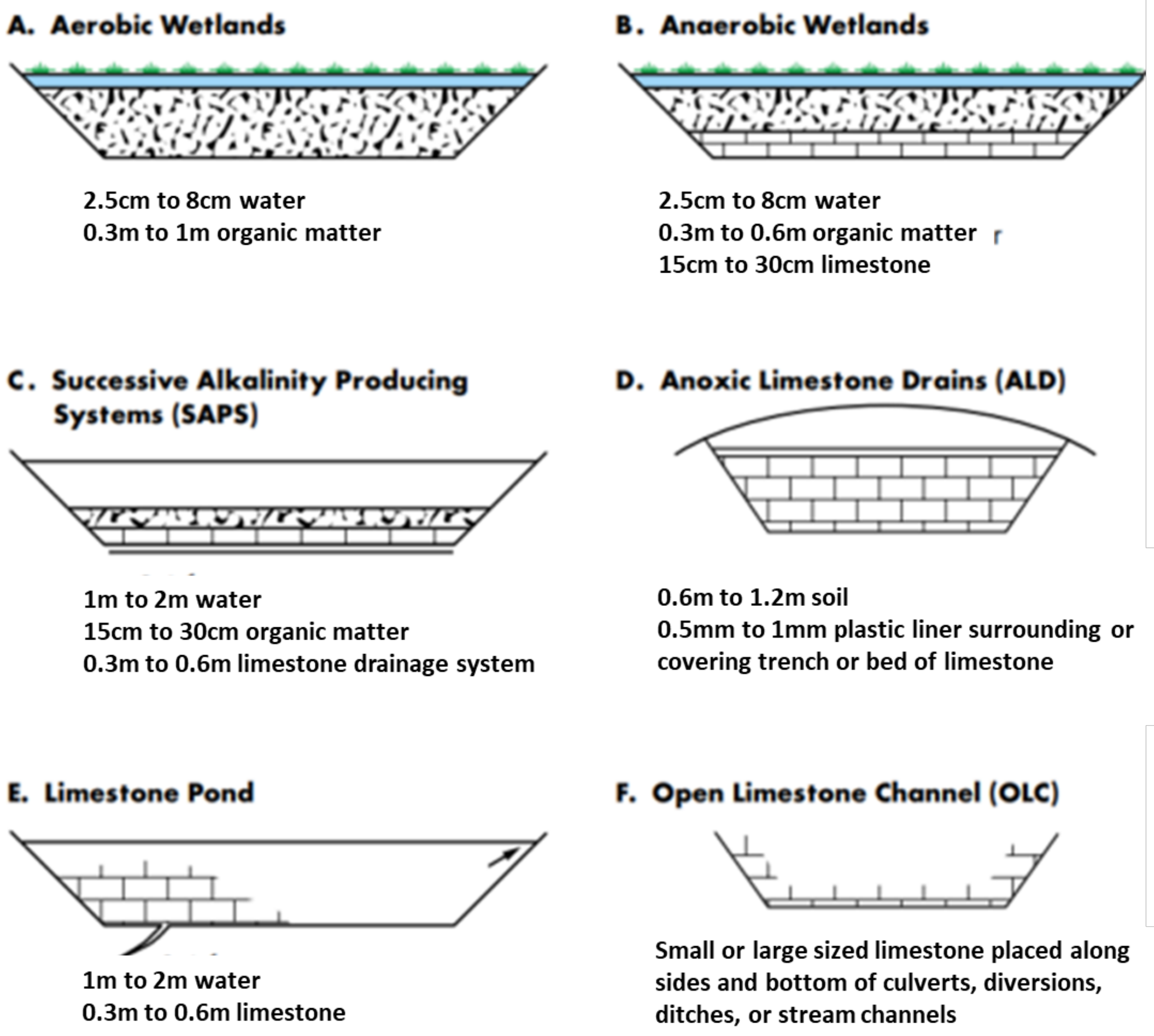


Figure 3 Schematic representation of common passive treatment systems (Reproduced with approximate metric units from the original imperial units published by Ford 2003)

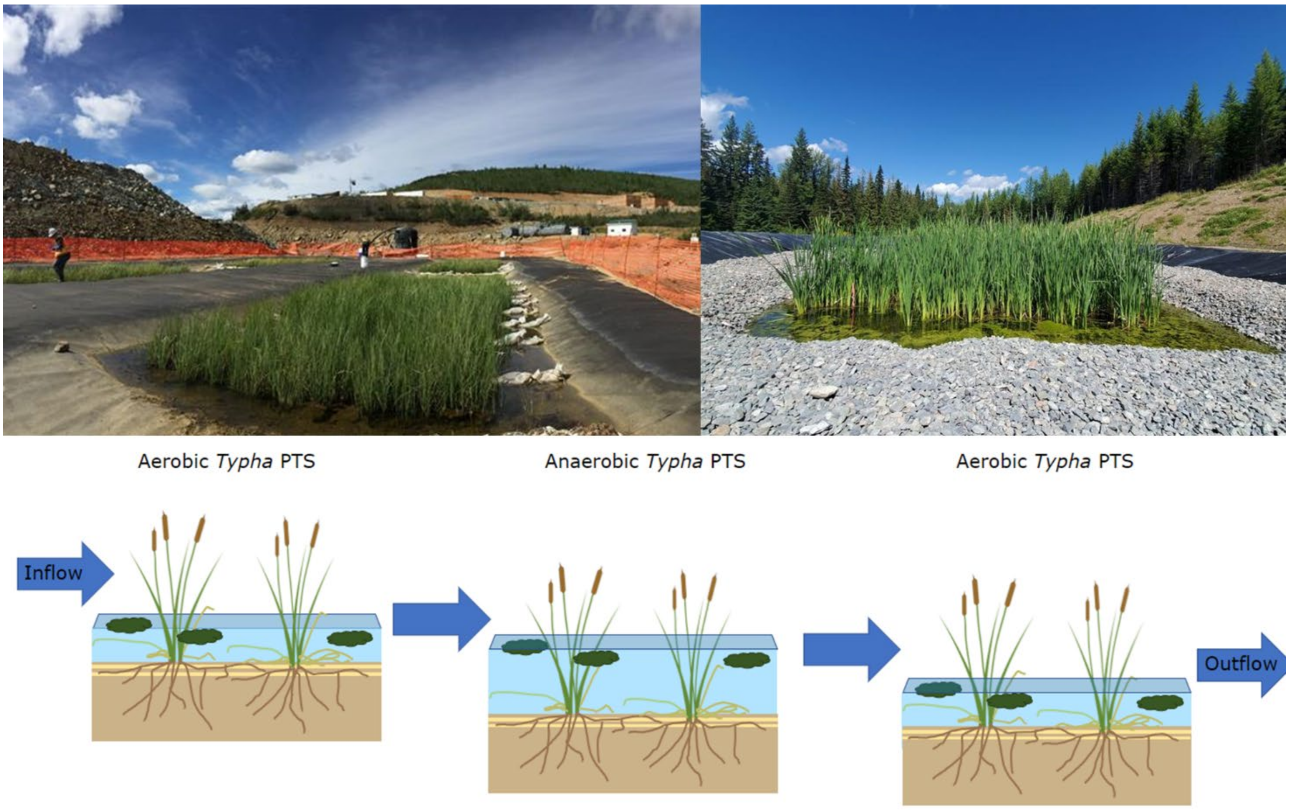


Figure 4 **Examples of CWTSs during installation and testing (courtesy of Ensero Solutions 2023)**

6 Clean water by design

Discussion on 'clean water by design' in the context of this paper includes i) the recoverable-unrecoverable ratio, ii) wetting up of an MRS, and iii) acidity mobilised. Figure 5 conceptually illustrates four generic MRSs constructed conventionally for ridgeline valley fill and open pit flat terrain conditions, as well as with a focus on source term control.

6.1 Recoverable-unrecoverable ratio

The recoverable-unrecoverable MRS seepage ratio, illustrated in Figure 6, is a key concept for evaluating and communicating benefit of an MRS constructed with a focus on source term control, compared to an MRS constructed with conventional methods. The ratio defines the percentage of seepage from an MRS that is collected, for the purposes of managing potential adverse impact to the receiving environment, as compared to seepage that will eventually move unimpeded to environmental receptors. Villeneuve et al. (2017) determined that the recoverable-unrecoverable MRS seepage ratio for a ridgeline valley fill MRS to be ~65%-35%. The authors state that basal and toe seepage, as described in Figure 6, are strongly influenced by watershed hydrology outside the footprint of the MRS, and hence the ratio of the MRS's footprint to the valley's watershed as the MRS is constructed. McKeown et al. (2017) discuss the importance of evaluating the timing of MRS seepage from the footprint of the landform, the resulting influence on groundwater conditions, and toe seepage quantity, quality, and timing for an open pit flat terrain MRS. More simply McKeown et al. (2017) illustrate the influence of the location of the groundwater table under an MRS, and mounding of this groundwater table in response to MRS seepage.

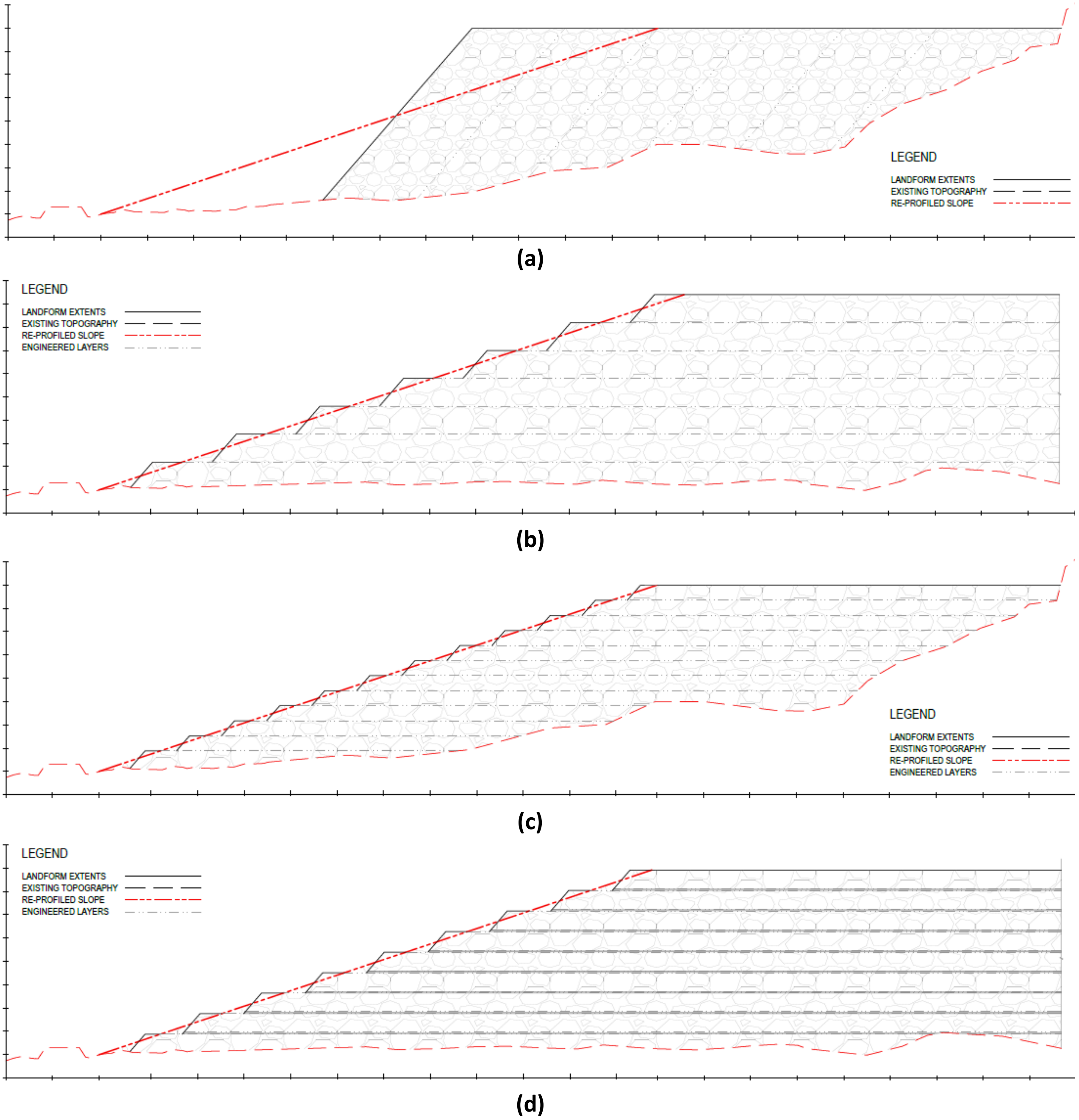


Figure 5 Conceptual illustrations of four generic mine rock stockpiles constructed conventionally for (a) Ridgeline valley fill conditions, (b) Open pit flat terrain conditions and constructed with a focus on source term control for (c) Ridgeline valley fill conditions, (d) Open pit flat terrain conditions

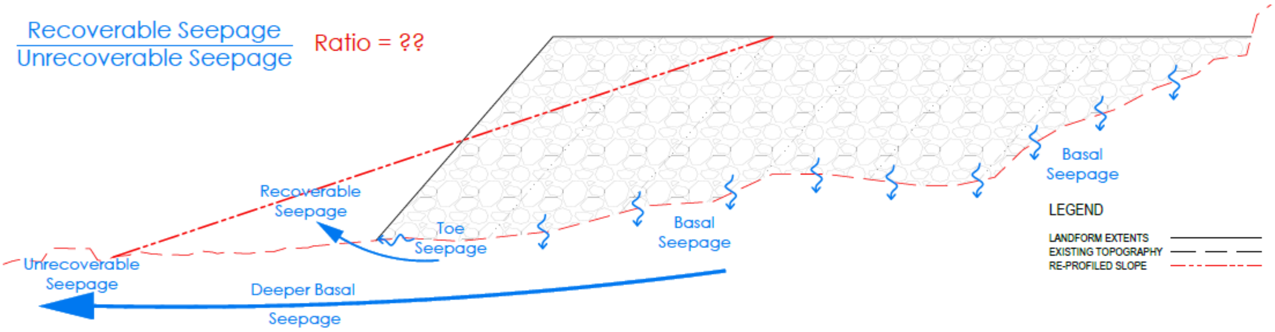


Figure 6 **Conceptual illustration of recoverable – unrecoverable ratio for MRS seepage water management**

6.2 Mine rock stockpile wetting up

Groundwater mounding under an MRS is strongly influenced by the 'wetting up' characteristics and behaviour of an MRS. This is where a 'wetted up' condition is defined in this context as the condition where a drop of water at the surface of an MRS results in a pressure response at the base of the MRS to 'push a drop of water' out the base. Noting that this does not represent pore-water velocity (the time for the 'drop of water' to move through the full height of the MRS). In addition, different areas of an MRS 'wet up' faster / slower due to material thickness, all other facets controlling wetting being the same; also, the material will drain due to gravity before the system is 'fully wetted up'. Hence, seepage from the base of an MRS will occur before the entire MRS is 'fully wetted up'. Finally, a 'wetted up condition' does not necessarily imply saturated conditions; it simply describes the steady-state volumetric water content of the material for the given surface infiltration (or net percolation) rate, depth of material, and texture of material.

Bring these two concepts together, the recoverable-unrecoverable ratio, and the time to 'wetted up' conditions as the MRS is being constructed and following construction, are key aspects of clean water by design. For an MRS constructed with a focus on source term control, it is our perspective that it will be less complex to increase the MRS recoverable-unrecoverable ratio through simple engineering means as the MRS is built, and that enhancing the need for a higher recoverable-unrecoverable ratio can be adaptively managed to a greater extent. In addition, constructing an MRS with source-term control leads to substantial reduction in the risk of adverse effects arising from the unrecoverable component of seepage to the receiving environment. In summary, by constructing an MRS initially to the full extent of its planned footprint, and continuing to focus on limiting re-supply of oxygen, the required recoverable-unrecoverable ratio is likely to be lower (because the unrecoverable seepage component will be of much better quality). Further, if required, it will be simpler to increase the recoverable-unrecoverable ratio because monitoring of toe seepage will already be located at the ultimate extent of the MRS.

6.3 Quantifying acidity mobilisation for an MRS

Hey et al. (2022) report a comparison of stored acidity for an MRS constructed using conventional methods to one constructed with a focus on source term control. The authors state that an order of magnitude difference in stored acidity was accumulated over 100 years. The conventional MRS has stored acidity being generated at a rate of 1 x 10^{-2} kg of H_2SO_4 equivalent per tonne of rock placed (kg/t), whereas when constructing an MRS with a focus on source control, as illustrated in Figure 5c, stored acidity was reduced an order of magnitude to 1.7 x 10^{-3} kg/t of rock placed.

Calculation of the cumulative mobilised acidity generated for the two MRS construction methods by Hey et al. (2022) predicted a 98% decrease in lime requirements for ML-ARD treatment over 45 years. This equates to 11,800 tonnes of lime per year (t/y) under the conventional MRS construction method compared to 250 t/y for the MRS constructed with a focus on source term control.

7 MRS construction and water treatment costs

The differences between mining and water treatment costs associated with constructing an MRS using conventional means and with a focus on source term control are discussed using Figure 7 as the basis for discussion. An MRS constructed with a focus on source term control substantially increases opportunity to apply passive water treatment solutions, which is otherwise not typically available, by improving MRS seepage water quality and reducing the volume of water requiring treatment.

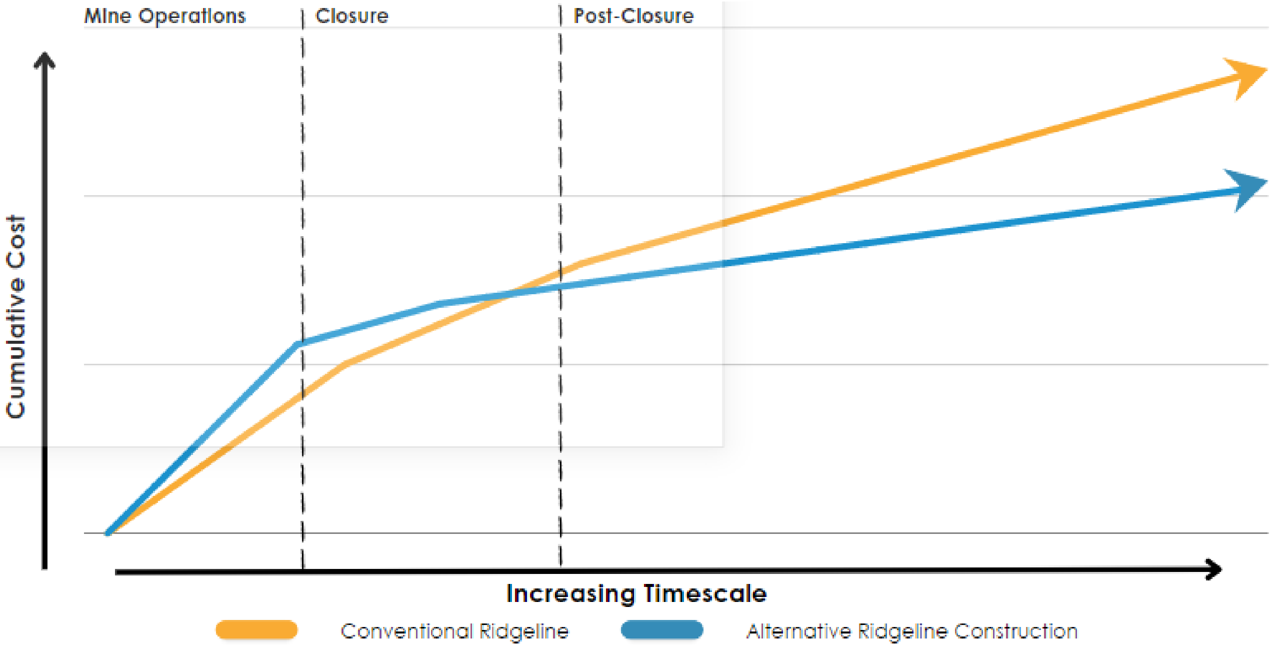


Figure 7 Conceptualisation of cumulative costs for mine operations, closure, and post closure for an MRS constructed for ridgeline valley fill conditions using conventional methods and with a focus on source term control

Figure 7 purposefully does not discount future costs from 'time 0'; rather, cumulative annual costs are presented for three periods strongly influencing MRS construction and management; operations, closure, and post closure. This approach is indicative of a Value Driver Tree (VDT) approach to communicating value. A VDT approach allows for inclusion of a comparison of differing mine rock placement methods, as well as MRS effluent collection and treatment. Hence, a combination of operational and financial performance in respect of construction and performance of an MRS is developed, which allows for disaggregation of higher-level financial evaluations into key lower-level operational elements / aspects that truly drive performance when constructing, operating, and closing an MRS.

7.1 Mining costs for conventional and source term control generic MRS construction

A key assumption for evaluating costs for the different MRS types and construction methods was the same volume of mine rock placed into the MRS. For a ridgeline valley fill MRS, the footprint increases when constructing the MRS with a focus on source term control, as shown when comparing Figure 5a and Figure 5c, because of the need to place rock from the base of the valley and back up within the valley. The footprint for the open pit flat terrain MRS was assumed to be consistent for conventional and source term control MRS construction. For this condition, individual lift height was reduced, and a layer of material with higher density and finer-textured was included on top of each lift.

A comparison of incremental costs associated with construction of an MRS constructed conventionally and with source term control, for ridgeline valley fill and open pit flat terrain conditions (shown in Figure 8) are in Table 1. A key assumption for the ridgeline valley fill condition is that mine rock is being placed into a valley that extends 100m vertically from its base to the ridgeline. Resloping is assumed to take the outer batter slope of the MRS from overall, or inter-bench, angle of repose conditions, to a final slope of 3H:1V.

Table 1 Summary of incremental mine rock placement costs for source term control MRS construction vs conventional MRS construction

MRS conditions	**Incremental cost of source term control (by comparing $/tonne)**	
Ridgeline valley fill: Source term control vs. conventional	Mine rock placement:	+51%
	MRS resloping:	-96%
	Total:	***+37%***
Open pit flat terrain: Source term control vs. conventional	Mine rock placement:	+5%
	MRS resloping:	-77%
	Total:	***-5%***

Overall, mine rock placement for ridgeline valley fill conditions is incrementally higher due to the cost of placing rock at the base of the valley initially for an MRS constructed with a focus on source term control; this is largely influenced by mine rock placement costs (load, haul, place). The incremental cost increase in this case is strongly influenced by the height (or extent) of the valley in which the mine rock is being placed. The increase of ~50% in costs, on a $/tonne of rock placed, will be greater for larger and deeper valley fill conditions. In contrast, the incremental cost of MRS resloping a source term control MRS for ridgeline valley fill conditions will be further reduced in comparison to conventional MRS construction because dozer costs (push and hours) will be that much less as slope lengths and heights increase.

For open pit flat terrain conditions, mine rock placement costs are only 5% higher for a source term control MRS vs a conventional MRS. This is because the inter-bench lift height for a source term control MRS, while lower than for a conventional MRS, does not strongly influence mine rock placement cost. The cost incremental increase is primarily a result of load, haul, place, and compaction of the horizontal layer to manage vertical airflow capacity in the MRS. These incremental cost increases are offset by the reduction in MRS resloping costs (77%), resulting in a reduction of overall mine rock placement costs of ~5%. In this case, dozer push distance is the same; however, the volume of rock that is required to be pushed is less because of the reduced lift height.

Note that for both ridgeline valley fill and open pit flat terrain conditions, the incremental costs shown in Table 1 include a difference in swell factor for placing mine rock in differing lift heights. We have not accounted for the benefit of the additional tonnage of rock that can be placed, for the same 'air-space' volume and footprint as a result of a lower swell factor for placing mine rock is short lifts.

7.2 Water treatment costs for conventional and source term control generic MRS construction

Water treatment costs are strongly influenced by site-specific climate and geochemistry conditions. For this paper, we present indicative relative costs for water treatment resulting from conventional vs source term control MRS construction. These cost ranges are presented in Table 2 and were developed based upon the following broad assumptions:

- The application of conventional MRS construction results in elevated metals and acidity load and a higher, and more variable, treatment flow rate compared to the alternative construction method. As a result, the application of a PTS is not feasible, and an Active Water Treatment Plant (AWTP) is required.
- The application of alternative construction methods results in a reduction in flow and contaminant load to the degree that a PTS, based upon BCR and CWTS unit operations become viable and delivers the required treatment. Acidity and metals load is reduced through the exclusion of oxygen thus minimising pyrite oxidation.
- For the AWTP case, conventional hydroxide neutralisation and precipitation process was used as a model flowsheet, costed and compared to case studies from various recent projects the authors participated in. In addition to these case studies, industry standard HDS capital cost curves were used as a reference (MEND 2014).
- Various model flowsheets were considered for costs of PTS options and recent project examples and published literature cases were compared to arrive at the cost ranges summarised in the table.
- Costs are relative to arbitrary base unit costs for CAPEX (denoted by C_X in the table) and OPEX (denoted by C_O in the table). 1Cx is the CAPEX for 100% of total installed cost for an Active Water Treatment Plant at the lower end of the range of treatment options required for the Conventional MRS Construction case while 2Cx represents the upper end of the range. Similarly, 1Co represents the operating cost per unit time for the same AWTP solution. Cost ranges presented in the table are illustrative for a broad range of applications and will vary significantly from site to site.

Table 2 Summary of relative water treatment costs ranges for source term control MRS construction vs conventional MRS construction

MRS conditions	Estimated cost range
Conventional MRS construction	AWTP CAPEX range: $1C_X$ to $2C_X$ AWTP OPEX range: $1C_O$ to $1.5C_O$
Source term control MRS construction	PTS CAPEX range: $0.1C_X$ to $0.8\ C_X$ PTS OPEX range: $0.05C_O$ to $0.2C_O$

7.3 Results and discussion

The results show that an MRS constructed with source term control can have significant impacts on water treatment costs. The capital costs for the active treatment systems are higher due to the materials of construction (e.g., concrete, structural steel and process control equipment) required. Passive treatment systems are limited in their applicability in that feasible treatment is possible at the lower end of the range of flow rates encountered in mine water treatment applications. The ability to lower the rate of flow by applying alternative construction methods allows for increased use of passive treatment to treat water originating from MRSs. The resulting savings in capital cost observed in this analysis ranged from 10% to 80% of the cost of an active AWTP that would be needed for water originating from the same WRS constructed using conventional designs. For operating costs, the difference is more pronounced ranging from as little as 5% to 20% of the costs for the conventional case.

Figure 7 is illustrative of the cumulated annual costs during operations, closure, and post-closure periods over a general timeline for a ridgeline valley fill MRS. Conventional MRS construction and active water treatment implies a lower cost profile, as compared to an MRS constructed with a focus on source term control, where a passive water treatment approach would be feasible; until the capital and operating costs for the active water treatment system result in a cross-over of the two curves, shown near the end of the closure period. This 'cross-over' would occur later if the height from the base of the valley to the ridgeline were greater than as shown in the data from Table 1 (i.e., in excess of 100m). However, the slope of the curve would increase as there would be incrementally more requirement for active water treatment (higher capital expenditure and operation costs). Wetter climate conditions would result increase active water treatment costs due to higher flow rates. In drier climate conditions, wetting up of the MRS in a ridgeline valley fill setting using conventional methods would take longer, and it is likely the largest risk in respect of active water treatment costs would be water within the watershed, but from outside of the MRS footprint, running through the base of the MRS. Also, in the case of an MRS in a ridgeline valley fill setting, resloping costs would substantially increase cumulative cost during the closure period if the height from the valley bottom to the ridgeline increased compared to that shown in Table 1.

As shown in Table 1, the difference in cost between an MRS constructed in an open pit flat terrain setting using conventional methods or with a focus on source term control is nominal. Higher costs will be incurred for an MRS constructed using conventional methods for both resloping and active water treatment. Hence, we hypothesize that for most climatic settings, and MRS constructed in an open pit flat terrain setting would have cumulative cost curves being similar during operations, and then diverge, with the costs for the conventional MRS construction and water treatment being much higher in closure and post-closure. This would be exacerbated for wetter climate conditions; noting that for very wet and tropical conditions the issue in respect of resupply of oxygen as a result of convection does reduce because the variation in ambient temperature is minimal.

8 Conclusion

We have purposely presented indicative costs for generic MRS construction and water treatment conditions and made several broad assumptions in developing these cost comparisons, because costs are highly site-specific. With the approach presented herein, we focus on key value drivers to illustrate that constructing an MRS with a focus on source term control is not necessarily 'more expensive'. Capital and operating costs are highly dependent on the timeframe applied to the evaluation, site-specific conditions, CoCs, and water treatment requirements.

Furthermore, source term control is the highest level of hierarchical risk control. A focus on MRS source term control may soon represent a requirement to continue mining, if active water treatment is required to remove CoCs with a very high efficiency, which may still not be sufficient to meet permit conditions. In this scenario, which will likely become more prevalent as concentration limits on CoCs become more stringent, achieving high treatment efficiency of an initially lower concentration may be required.

The value of this MRS design approach goes beyond financial. Water has significant importance to Indigenous people across Canada and the world, and ML-ARD can represent a multigenerational water quality risk. Source term control is reflective of a comprehensive water stewardship approach. The value in a 'clean water by design' approach becomes apparent when taking a long-term, full lifecycle, inclusive stakeholder and Indigenous rightsholder perspective.

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