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Mine waste disposal in pit lakes: a good practice guide

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Abstract

Pit lakes are formed through the inundation of empty mine voids and can be a significant legacy landform for mine closure when complete backfill is not possible. Increasingly, mine wastes are disposed into pit lakes to reduce post-closure land disturbance and integrate two final landforms into one with consequent cost savings. Subaqueous storage of mine wastes that present potentially acidic and/or metalliferous drainage (AMD) hazards is considered best practice for geochemical stability and through hydrogeologic containment (where inward gradient is permanently maintained). Subaqueous storage also reduces wind and water erosion rates compared to subaerial deposition in waste rock dumps or tailings storage facilities.

However, subaqueous mine waste disposal can also introduce closure risks, such as contamination of pit lake, surface and groundwaters. Accordingly, planning for mine waste disposal requires a detailed characterisation of mine wastes and their behaviour in the particular pit lake environment, in addition to a cost-benefit analysis of other waste disposal options. This information allows for waste placement that can be implemented during operational phases and into closure. Knowledge of this information early in the mining process, or pre-mining, allows for a wider range of options that can improve the success of the pit lake.

We summarise the state of knowledge and practice for mine waste backfill into pit lakes and identify key benefits, issues and strategies that have led to successful mine closure outcomes globally. Based on these findings, we provide guidance for mine waste disposal into pit lakes.

Keywords: *closure planning, pit lakes, tailings, mine waste, repurposing, waste rock dump, tailings dam*

1 Introduction

Mine closure is the practice of planning and executing closure of the mining-disturbed landscape. This landscape includes the project area and may also entail consideration of the broader region. Leading mine closure practice seeks to holistically reduce total project closure risk and maximise total project closure benefit by considering landforms interdependently of each other (Asia Pacific Economic Consortium [APEC] 2018; International Council on Mining and Metals [ICMM] 2019). This holistic practice recognises the implications of closure options for each landform on other landforms and how these options affect the primary aim of a successful site closure. Such closure planning then begins at conceptual levels of understanding with identification of final landform risk and management of this risk, achieved through increasingly more detailed studies through the life of mine towards closure.

Pit lakes are closure features of most open pit mines with a positive water balance (i.e. net precipitation and/or groundwater inflow into the pit void). As legacy landforms at closure, pit lakes must be explicitly considered in mine closure planning: in particular, how pit lakes will fit within broader mine closure objectives. Like all mine landforms such as tailings disposal facilities and waste rock dumps, pit lakes cannot

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be independently closed without a broader context of the overall mine site (Vandenberg et al. 2022) and, indeed, regional landscapes (McCullough & Van Etten 2011).

Pit lakes usually cannot be rehabilitated back to a previous terrestrial environment and therefore represent a significant change in land use values (and consequent company and stakeholder planning) for closure strategies, with consequent different post-mining land use (PMLU) opportunities (McCullough & Van Etten 2011; McCullough et al. 2020). Nevertheless, pit lakes also form the aforementioned interdependent components of holistic mine closure outcomes by interacting with regional and local surface and groundwaters, contributing to project area geotechnical stability and functioning as waste storage repositories (Vandenberg et al. 2015a).

Huge amounts of mine waste are generated during open cut mining as overburden and interburden, tailings, etc. Solid wastes are typically minerals of varying sizes and chemical/mineralogical composition ranging from inert (e.g. non-acid forming, NAF) to potentially acid forming (PAF). Solid mine waste is typically placed in a closure landscape either as a terrestrial landform (subaerially) or below either surface or groundwater (subaqueously). At mine completion, the waste in a disposal facility (in-pit or above-ground) is typically covered with either a ‘dry’ or a ‘wet’ cover to create a terrestrial or aquatic closure landform. The decision to use dry or wet covers depends on numerous site-specific factors and waste characteristics, and must be evaluated on a case-by-case basis (INAP 2009).

One option for a wet cover is disposal of mine waste in mined-out pits or in pit lakes. A study conducted by the Mine Environment Neutral Drainage (MEND) Program in 1995 (MEND 1995) identified over 40 sites around the world where open pits have been used for mine waste disposal, including Canada, the USA, Australia and Germany. Additional case studies have been published since 1995 as cited herein. These case studies show that completed open mine pits often provide stable environments for the disposal of wastes including:

- tailings and waste rock
- industrial process residue
- municipal refuse
- excavation spoils (e.g. overburden).

This review summarises fundamental knowledge and good practice for placement of waste rock and tailings backfill into pit lakes. The review also identifies key benefits, issues and strategies that have led to successful mine closure outcomes globally. Although mine waste can consist of many different materials, both solid (e.g. waste rock) and liquid (e.g. site-treatment water), this paper focuses primarily on solids.

2 Benefits of in-pit backfill

2.1 Eliminate geotechnical risks

Storage of mine waste in completed mine pits is considered best practice for geotechnical stability (Morgenstern et al. 2015) because it reduces the amount of material stored in above-ground facilities. Although pit wall failures can occur in pit lakes with subaqueously stored mine waste, an inward failure toward the pit void would nearly always lead to less environmental impact compared to a geotechnical failure of an above-ground landform containing mine waste. One of the major advantages of in-pit disposal is that it does not rely on an elevated impoundment structure (such as a dam) to physically contain the mine waste. The wastes are confined below final grade within the confines of the pit. Filling a pit with mine wastes has the additional benefit of stabilising the pit walls (Skousen et al. 2012).

In addition to large-scale geotechnical failures, erosion of mine wastes can be considered a hazard for dry and wet covered wastes. Wastes that can be eroded are normally covered with waste rock or a layer of inert sand and a water layer that is sufficiently deep to prevent wave erosion and resuspension of fine particles

(McCullough et al. 2019). Shoreline features can also be engineered to minimise wind-wave erosion, though not all pit geometries and water levels are conducive to such engineering.

2.2 Reduced closure costs

In-pit backfill can remove the need for another waste management landform by combining two landforms into one as an integrated landform, such as an integrated waste landform (Williams & Minard 2010). This reduction further reduces the site footprint and therefore reduces the overall mining land disturbance footprint. A smaller land area to rehabilitate requires less topsoil and revegetation, and offers a flatter surface with lower erosion risk. A key driver for mines with multiple voids is that completed pits provide a cost-effective opportunity to store mine waste rather than constructing a new engineered structure for the purpose (Puhalovich & Coghill 2011). Placement of waste and completion of the combined waste landform and pit simultaneously also assist with progressive rehabilitation goals. While the backfilling of exhausted open pits is less technically challenging, concurrent open pit backfilling and mining is common in aggregate, coal and oil sands mining, and is becoming increasingly common in metal mining (Williams 2006; Testa & Pompy 2007). For the mine operator, pit backfill can also mean shortened and potentially less costly downhill haulage routes (Johnson & Carroll 2007).

However, some operational situations will present where mine waste cannot be placed into a pit and must be stored until the pit becomes available for waste deposition. Transferring such intermediately dumped material into a pit/pit lake will eventually very likely produce considerable extra handling costs and might be technically challenging when trying to minimise the interaction with oxygen and the mobilisation of contaminants.

2.3 Achieving terrestrial final landforms

Few mines can be rehabilitated to replicate their pre-mining state (Doley & Audet 2013). Open cut mining creating pit lakes converts a terrestrial landscape to a post-mining aquatic landscape (McCullough & Van Etten 2011). Creation of such a de novo landscape will result in significantly different landscapes with differing landforms and, consequently, differing levels of overall risk and opportunity (McCullough & Lund 2006) than those experienced previously to mining. However, complete backfill with waste is often undertaken to completely realise the storage potential of the pit, which, when accounting for settlement, can achieve near original topography. For example, NAF in-pit tailings were disposed in the Perch pit (Plutonic mine) and Fisher pit (Jundee mine) (Figure 1), and in the K1SE pit (Marymia mine), all in Western Australia, (Johnson & Wright 2003) to the original ground level, followed by terrestrial revegetation. Mine wastes have also been backfilled to near the watertable to achieve wetland revegetation (Flambeau Mining Company 2009) and even reinstatement of original creek lines can be possible (Kozak et al. 2021).

Figure 1 In-pit tailings disposal at the Perch pit (Plutonic mine, Pilbara, Western Australia) (CD McCullough)

2.4 Geochemical stabilisation

Operating mines create wastes and can expose materials that pose risks to the environment, e.g. oxidation of sulphide minerals within mine waste can result in the generation of sulphuric acid, which reduces the pH and greatly increases the dissolution of metals present in the waste solids. This is important because the potential rate of release of metals to the groundwater and surface water will be directly proportional to the concentrations of metals in the porewater (Watson et al. 2016, 2017). Acidification can directly cause metal leaching, but metal leaching can also occur at neutral or basic pH when redox conditions change during mining and processing.

Saturating PAF mine waste with water is an effective method for reducing the rate of acid generation. The rate-controlling process is the diffusion of oxygen through the water in the pits of the flooded waste, which is at least 10,000 times slower than the oxygen flux in mine wastes that are exposed to air (Gammons 2009). In practical terms, the placement of waste in a saturated environment essentially eliminates acid generation.

Placing reactive waste underwater through backfilling into a pit lake is recognised internationally as good practice to cover or encapsulate these materials cost-effectively (Jones & McCullough 2011). Accordingly, mine pits can be used as sites for disposal of geochemically reactive or contaminated tailings, waste rock and overburden (Schultze et al. 2011). Storage of PAF mine waste under a water cover is considered best practice for permanent storage of PAF waste because it mitigates against production of acidic and/or metalliferous drainage (AMD) in addition to preventing transport of either waste or waste contaminants to sensitive receptors (INAP 2009; Verburg et al. 2009; Department of Foreign Affairs and Trade [DFAT] 2016).

Consequently, one of the main reasons for the use of subaqueous mine waste disposal globally is that it is an effective method for preventing AMD, especially when there is a potential that the waste may generate AMD. Maintaining PAF mine waste below a watertable (subaqueous placements) and with upper pit levels (subaerial) filled with benign waste may also be advantageous over a simple water cover (DFAT 2016; Australian National Committee on Large Dams Incorporated [ANCOLD] 2019). Additionally, lime or some other additive can be used to initially neutralise or buffer acidic porewater that could migrate from the waste to the water cover over time. This neutralisation should then prevent further AMD production under anaerobic subaqueous conditions. For example, at the Barite Hills Superfund site's pit lake in South Carolina, USA, around 38,000 m^3 of high-pyrite waste rock with some lime addition was backfilled into subaqueous pit lake storage (Interstate Technology & Regulatory Council [ITRC] 2010).

Other contaminants besides geochemical may present as constituents of potential concern (COPC) in pit lakes e.g. nitrate (McCullough 2024). However, nitrate may also be remediated in groundwater under backfilled conditions (Weilhartner et al. 2012; Margalef-Marti et al. 2020).

2.5 Removal of pit lake water as a contaminant transport mechanism

Open pit lakes are potential transport mechanisms of COPC to environmental receptors such as wildlife, livestock and humans through direct contact, drinking and feeding (McCullough & Sturgess 2020). Although dry climate pit lakes may act as passive hydraulic sinks, resulting in no discharge to the surrounding aquifer or surface waters, these lakes are still subjected to evapoconcentration which further degrades water quality and presents the aforementioned COPC transport pathways. Backfilling open pits above the local groundwater level is one method of mitigating these pit lake environmental issues (Johnson & Carroll 2007).

2.6 Hydrologic/hydrogeologic containment

Surface water flow is a prime driver of closure risk as water is responsible for pit lake failure hazards such as geotechnical instability, erosion and contaminant transport (McCullough 2015). Hydrological containment can limit impacts to surface and groundwaters from waste disposed as an in-pit backfill closure strategy. Surface water management preventing excessive water ingress and consequent discharge is usually reasonably achievable with pit lakes as they have inherently small catchments (Schultze et al. 2010; Schultze et al. 2013). However, regardless of catchment size, a good understanding of long-term water balance is required to ensure sufficient freeboard remains during storms e.g. annual exceedance probability 0.1% events (McCullough & Schultze 2018).

However, even with good surface water management it can still be hard to detect and control pit lake water exchange with regional groundwater. The ideal pit for mine waste disposal is surrounded by unfractured rock having very low hydraulic conductivity/permeability and a minimal groundwater gradient across the pit so that contaminant transport by groundwater advection is inconsequential. It is also beneficial if the upper part of the aquifer surrounding the open pit is more permeable than the lower part (i.e. below the level of the waste deposit) and that the waste is relatively less permeable so that most of the flow across the pit occurs above the level of the waste, with minimal infiltration through the waste, and is discharged into the regional groundwater.

If necessary, the hydrogeology surrounding the pit can be engineered to manage contamination through preferential flow paths around the pit void. This approach has been practised at uranium mines in Saskatchewan, Canada, as ‘pervious surround’. This has become internationally recognised as the best practice for containment and storage of milled uranium tailings (International Atomic Energy Agency [IAEA] 2004). In addition to PAF wastes, other solid mining wastes that contain high concentrations of contaminants have also been used for backfilling material subaqueously to restrict exposure pathways.

Historically, some pit lakes, e.g. Berkeley Pit lake (Gammons & Duaine 2006; Gammons & Tucci 2013), were developed in poorly characterised, high-permeability settings, and hydrogeological containment was not adequate. This could potentially lead to seepage that could migrate offsite if not actively treated, and is a major disadvantage. However, if hydrogeological conditions are well characterised during mine permitting and operations, the likelihood and consequence of seepage out of backfilled pit lakes can be detected and mitigated in backfill strategies.

2.7 Create pit lake habitat

Even complete backfill can still create pit lakes as seasonally inundated voids surcharge sufficiently to give rise to ephemeral freshwater wetlands. Semi-arid regions are often characterised by few and typically seasonal water bodies of relatively short hydroperiods, and regional ecology is adapted to utilise shallow, short-lasting water bodies. In these climatic regions, backfilled pit voids might provide pit lakes that mimic non-permanent pit lakes and therefore benefit the regional ecology. Pilbara iron ore majors have been investigating such opportunities since 2010, e.g. Hamersley Iron — Yandi Pty Limited (2014).

3 Challenges of in-pit disposal

This brief review of mine waste backfill as an option for pit lake closure provides the following lessons for mine closure generally and pit lake development specifically. Under circumstances when backfill risk exceeds that of the option of no backfill, a pit lake may be the best outcome for mine closure.

3.1 Pit hydrogeology

Pit hydrogeology is often the most critical factor for determining the suitability of a pit for waste disposal and will dictate the engineering controls necessary to develop an acceptable disposal option. A good understanding of regional flow gradients offers useful context, but the key will be understanding how the pit lake water interacts with local groundwater. Hydrogeological changes to groundwater flux from blast zone damage should also be considered at pit completion (Rousseau & Pabst 2023). These key factors include the:

- bulk permeability of the rock around the pit — the presence of extensive hydraulically transmissive features such as karst, faults and fracture zones that may connect with other mining areas, groundwater aquifers or surface waters
- location and gradient of regional groundwater and interaction within the backfilled pit
- pit water balance and resulting final equilibrium water level in the open pit
- stratigraphy and permeability of the overburden and bedrock
- hydrogeology and sensitivity associated with any downgradient receiving water body.

The hydrology of the pit lake will be strongly affected by the regional climate (Niccoli 2009). In a very dry climate, evaporation from the surface of the pit lake can exceed the pit inflows (i.e. runoff, precipitation and groundwater inflow). In such a case, the equilibrium pit lake water level may be below the regional watertable and the pit lake can act as an evaporative sink, resulting in inward groundwater flows (McCullough et al. 2013; McCullough & O'Grady 2022). By contrast, in wet climates the pit lake may have a positive water balance and is likely to continue to fill until it overflows to surface or groundwaters (McCullough & Schultze 2018). In such a case, the flow direction (into or out of the pit) will depend on the relationship between the pit overflow elevation and the pit void's discharge and regional watertable levels. In many jurisdictions, closure plans for a pit acting as a likely long-term potential source for mine-influenced waters will not likely be approved.

The backfilled pit may also act as a local surface water sink and infiltration source. Over time, these attributes may potentially create a locally mounded watertable beneath the pit which may promote increased recharge and hence recovery. However, this sink may provide a path for water from backfilled waste to groundwater. Partial backfill can lead to poor water quality if mine waste has sufficient hydraulic conductivity in a climate and catchment that permits leaching of COPC down through the backfill and into the pit lake.

3.2 Water-waste interactions

Subaqueous disposal of mine waste is likely to alter the physical, chemical and biological character of the pit lake through the processes described below. While these processes themselves may not pose a risk to the environment, the main challenge associated with them is to accurately understand how they will interact to affect the lake so that the closure plan can be iteratively modified to optimise outcomes.

3.2.1 Tailings consolidation and porewater release

Most subaqueously disposed tailings will consolidate over time, increasing the solids density of the tailings and releasing porewater upward to the water column. Tailings consolidation thereby decreases the lake bed elevation over the first few years after filling, and increases both the water depth and water volume of the lake. Depending on the physical properties of the tailings and the chemical make-up of the porewater, this process may materially alter the physical and chemical characteristics of the pit lake. For example, a lake that becomes deeper over time is also more likely to become meromictic. In addition, most mine waste porewaters are more saline than natural groundwater or surface waters (Oggeri et al. 2023), and the saline porewater released to the water column at the lake bottom further increases the strength of vertical density gradients and the likelihood of meromixis.

3.2.2 Vertical stratification and oxygen inhibition

Vertical densities within the water column can cause seasonal or permanent stratification of layers within the lake. Lakes that are sufficiently deep or that have sufficiently saline waters at depth will tend to stratify permanently and are termed meromictic lakes. Because the deeper layer of such lakes is essentially isolated from the atmosphere, there is no transport mechanism to replenish oxygen that is consumed in biochemical reactions, so the lower layer will tend to become anoxic and the environment will be reducing (Boehrer & Schultze 2006; Schultze et al. 2016).

3.2.3 Sediment diagenesis

Over the long-term, mine waste deposited into pit lakes may undergo a process of diagenesis, which is a collection of biogeochemical reactions that convert in situ materials into forms that are geochemically stable in their immediate tailings environment (Oldham et al. 2009; Read et al. 2009). For example, if materials and minerals that were chemically stable in a subaerial environment are placed underwater, they will, over time, be transformed to chemical forms that are stable in oxidation-reduction state, pH and pressure of the underwater environment. The main change that will occur will be that most chemical species will be converted from their oxidised form to reduced forms at the sediment-water interface, and throughout the entire bottom layer of water in the case of meromictic lakes (Vandenberg et al. 2015b).

For some metals, sediment diagenesis will result in the permanent sequestration of insoluble minerals. For example, in an anoxic environment, conditions favour insoluble metal sulphides that will remove copper, zinc and other metals. Reducing conditions also prevent the oxidation of PAF materials, so this environment is ideal for disposal of PAF mine wastes. Conversely, under the same conditions, manganese and phosphorus will be released, potentially degrading water quality.

3.2.4 Sediment-water exchange

Ideally, mine waste that is disposed in a pit lake will be permanently sequestered with little or no release of contaminants to the water column. However, depending on the geochemical conditions set up by the processes listed above, disposed mine waste can be a source or sink of contaminants. Hence, understanding which contaminants are of interest (Section 3.5) and their solubility under future pit lake conditions is critical for managing the waste over the long-term.

In additional to the soluble release of metals and ions, disposed waste can be a source of suspended sediment to the water column that will cause turbidity, decreasing the lake’s aesthetic and aquatic habitat value. The potential for resuspension of waste is a function of the waste’s particle size and density, and the strength of water currents at the sediment-water interface. Therefore, in general, the finer the sediment the deeper it will need to be covered to avoid resuspension. Under most settings, 5 to 20 m of water cover is predicted to be sufficient to avoid resuspension in many circumstances (Hamblin et al. 1999; Lawrence et al. 2016). However, depth will be highly site-specific, and on the deeper end of this range for lakes with larger surface areas and finer sediments (Håkanson & Jansson 2002). Consequently, deposition of fine material should be in the deepest pit lake locations and, regardless, always deeper than wave activity. Usually the hypolimnion is acceptable, but location-specific considerations are required because of diverse influencing factors including local wind conditions, maximal wind fetch, lake basin morphology, grain size, density of particles and the cohesive characteristics of particles (Bloesch 1995). MEND (1998) provides a thorough guide for the design of subaqueous impoundments.

3.3 Resource sterilisation of the ore resource

Resource sterilisation, which means rendering an underlying ore resource difficult or infeasible to extract in the future, can be a major disadvantage of backfilling a pit with mine wastes. Generally, ores are not mined to the point of complete removal but to the point the ore:waste ratio no longer results in economic gain. That ratio may change in the future with improved commodity prices, rendering a currently uneconomic ore economic in the future. While water can be readily pumped from a pit to allow for re-mining, removal of tailings or waste rock from a pit lake can be expensive, challenging and time-consuming; essentially rendering the remaining ore sterilised.

3.4 Delayed rehabilitation

A number of consolidation issues may delay the final rehabilitation of a backfilled pit landform. These include trafficability, where an unstable or unconsolidated surface can impede vehicle access for final profiling and cover placement, including topsoil. Revegetation and monitoring will also be delayed if trafficability is poor, with the consequent achievement of a stable and even surface to revegetate delayed. Finally, determining long-term backfill height, especially against the groundwater level within the backfilled pit, may mean additional backfill is required, with consequent delays in the final cover. Determination of the bulking or swell factor for material used to backfill prior to the minimum waste level being achieved is an important consideration here.

3.5 Problematic geochemistry must be understood and managed

Global case studies show that most unsuccessful pit lake closures resulted from misunderstood and/or mismanaged enriched geochemistry within the pit void shell or in-pit waste materials, or by altering the conditions (e.g. redox, moisture) to which mine waste is exposed without understanding the implications of those alterations. As noted above, a common outcome of this misunderstanding or mismanagement is AMD leading to low pH and elevated metal concentrations and salinity. Case studies show that the major disadvantages of pit lakes are that they create or increase legacy liabilities if improperly planned or if conditions and mine waste characteristics are not well understood. This caveat equally applies to poorly understood and executed pit backfill.

Fully understanding the mine waste geochemistry requires a battery of laboratory-scale tests and, ideally, field-scale tests prior to full-scale mine waste disposal. The tests should replicate the future conditions that the waste will be exposed to, whether that be under a wet or dry cover. Both solids and porewaters should be tested for leachability and the soluble contents of metals, ions, nutrients and other substances that are relevant to the specific mine being closed (see Table 1 for examples).

Once the potential leachate and porewater have been adequately characterised they should be incorporated into water and mass balance models to understand potential environmental impacts to groundwater and surface waters, including impacts to humans and biota that rely on those waters.

Table 1 Potential mine waste issues for different commodity types: ✓ indicates likely; ? indicates a possible issue

Commodity	Aluminium	Coal	Heavy minerals	Iron ore	Metals	Oil sands	Uranium
Acid		?	?	?	✓	?	✓
Metalliferous		✓	✓	?		?	✓
Alkaline	✓						
Saline	✓	?	?	?	✓	✓	✓
Nitrogenous	✓	✓	?	✓	✓	✓	✓
Organics						✓	
Radionuclides	?	?	?		?		✓
Cyanide	✓						

4 Timing and methods for waste placement

4.1 Backfill waste placement

Waste can be backfilled to different extents:

- nil
- partial
- complete.

Figures 2A and 2B represent extremes of fill, whereas partial backfill can be realised in many different ways, including combinations of Figures 2C and 2D.

Complete backfill must consider that groundwater levels increasing regionally or even just within in-pit backfill can lead to a pit lakes forming. This might be due to:

- inaccurate equilibrium pit groundwater level predictions
- a lack of contingency in backfill above this predicted level
- the groundwater level rising due to long-term climate change or following extreme rainfall events.

Figure 2C can often be undertaken during operations through hauling and paddock dumping into a dry pit. This placement is ideal for co-mingling or even PAF cell creation to reduce AMD production until the rising pit lake water level covers PAF materials. Figure 2D represents a common approach to completed pits, where waste is highwall dumped into the open pit. Following careful planning to ensure highwall stability and access safety, highwall dumping can be made into filling or even fill a pit lake through haul truck placement and then dozer-pushing into the pit.

Complete backfill can be used to prevent a pit lake from forming and associated potential surface water expressions of poor-quality pit lake water. However, complete backfill may then lead the pit lake to become through flow, transporting poor-quality water into downgradient aquifers.

Partial backfilling with a reduced pit lake surface area can reduce net evaporation losses from the lake, thereby preventing groundwater loss and depression around the lake, and pit lake salinisation (Hall 2004), and may cause the pit lake to function as a through flow rather than a terminal sink.

However, the partial backfill afforded by Figure 2D can lead to poor water quality if mine waste has sufficient hydraulic conductivity in a climate and catchment that permits leaching of COPC down through the backfill and into the pit lake. Where the pit lake is a through-flow type, neighbouring aquifers, and potentially surface waters, may also be impacted.

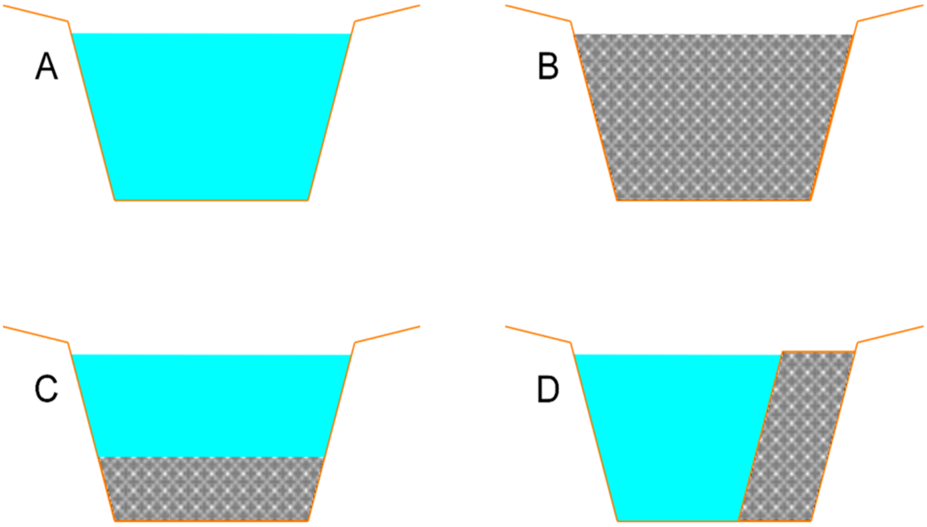


Figure 2 Typical solid mine waste backfill placement in pit lakes: (A) pit lake without direct contact with mine waste; (B) complete backfilling; (C) partially backfilled pit across pit floor; (D) partially backfilled pit across pit highwall

4.2 Timing of backfill

Backfilling timing will have effects on both water balance and water quality for either the groundwater or the pit lake (Table 2). Material free of leachable contaminants can be placed largely whenever so long as the final form is geotechnically stable so as not to preclude long-term PMLU. Further, the method and timing of such benign waste placement does not matter under these non-polluting circumstances. However, when waste material contains leachable contaminants, the typical closure objective is to manage environment contamination.

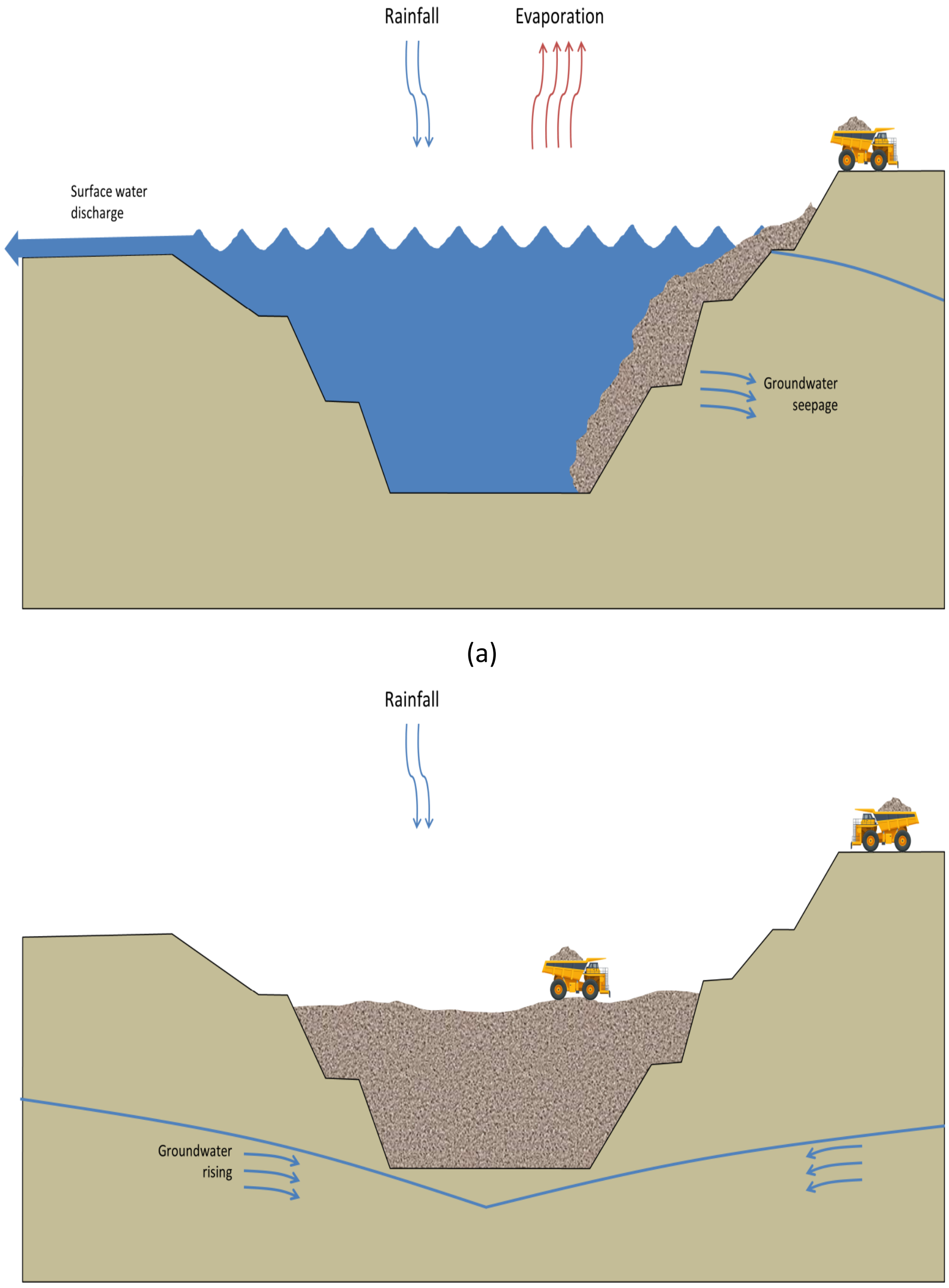
Table 2 Opportunities and risks of different backfill timings

Timing	Opportunities	Risks
After filling	Backfill does not need to be prioritised in the mining schedule and can be delayed	Leaching is likely to be increased Geotechnical and erosion-protected placement is not achieved Lake might surcharge, discharging to the surface and groundwaters
Before	Backfilling before placing water allows for heavy equipment to access the pit directly and achieve encapsulation, lower waste placement and compaction Lake starts as a terminal sink, containing water	Operational constraints may delay backfill until a lake has formed

Backfilling into a pit lake that is already full of water is typically achieved by highwall tipping. However, in addition to vigorous mixing and the consequent contaminant leaching of waste into lake water, placing more material into a full lake can cause surcharging of the water level, leading to a positive water balance and seepage into groundwaters and/or discharge into surface waters (Figure 3a). Dumping highly leachable waste into an existing pit lake can therefore sometimes only be done by transporting the material to the lake bottom via a pipeline. Otherwise, excessive leaching would take place during downslope and down-water column transport.

However, backfilling before the pit lake fills reduces evaporation of inflowing groundwater, leading to faster groundwater recovery (Figure 3b). Material containing leachable contaminants can also be placed at the bottom of the (future) pit lake to reduce erosion. A further opportunity can then also be taken to compact waste through paddock dumping and trafficking. PAF cells could also be incorporated in this strategy. Deposition before pit flooding is usually not too complicated. However, flooding without the considerable mobilisation of contaminants via erosion, resuspension and leaching is a substantial challenge. Special inflow structures for water, e.g. from rivers, are needed and (partial) capping with inert materials can be an option.

As a further strategy, active recharge through mine/surface or distant groundwater pumping to the lake can result in faster pit lake equilibrium and groundwater recovery. This will slow weathering of pit geologies and cover backfilled wastes faster. However, the fastest pit lake equilibrium and groundwater recovery are achieved by combining pit lake active recharge (e.g. mine dewatering/sumpage pumping) with backfilling.



(a)

(b)

Figure 3 Backfilling: (a) After pit lake fills; (b) Before pit lake fills

5 Conclusion

With potential benefits, although not without risks (Table 3), the option of returning mine wastes such as waste rock, tailings and sludge as mine pit backfill is appealing to the mining industry and, with some exceptions, generally well received by stakeholders and regulators globally. In many cases, subaqueous mine waste disposal is seen as returning the materials to the non-oxidising environments from which they came, albeit with a different surface feature (i.e. water rather than land). Mine closure guidelines and regulator feedback on mine closure plans are consequently showing a greater recognition of pit backfilling with mine waste to reduce closure risk and achieve agreed post-closure land use (INAP 2009; Ramsey & Martin 2009; Department of Mines, Industry Regulation and Safety [DMIRS] 2020).

Table 3 Opportunities and risks of backfill extents

Opportunities	Risks
Geotechnically stable and safe	Discharge to surface or groundwater
Pit lake water quality risk removed	Resource sterilised
Terrestrial habitat reclaimed	Increased closure costs
PAF geochemistries stabilised	

Overall acceptance of a pit for waste disposal and the type of cover to use are determined by the geologic, hydrogeologic, climatic and geotechnical conditions at a site, the dimensions of the pit, the geochemistry of the waste, availability of alternative disposal methods, contaminant transport pathways, and the presence and sensitivity of social and environmental receptors. Each of these factors requires detailed study so that alternate disposal and cover methods can be evaluated comprehensively within the broader mine closure plan.

Successful pit lake closures using backfill have typically been well-planned in advance and with consideration of other post-mining landform elements across the closure landscape. Such holistic planning may improve overall mine closure outcomes (reduced risk and liability). We therefore recommend that mine closure landforms be closed in accordance with the full catchment scale (which includes the entire mine and the natural watershed in which it is located) and also with consideration of each element within the catchment. This includes pit lake landforms. The closure of any individual landform will affect the design, construction and performance of other closure landforms. This integrated mine closure across the project area catchment considers:

- long-term stability and overall risk to safety
- availability of construction materials
- mine waste material types requiring storage and their volumes
- connection with surface and groundwaters and pathways to receptors
- climate and climate change
- timing of individual processes and overall mine closure.

Increasingly, the closure of pit lakes is being evaluated more holistically as the assets can reduce post-closure land disturbance while minimising both operational and closure risks and costs for both environmental and business drivers. However, this strategy necessarily involves trade-offs when considering where and how to dispose of waste, and the option of disposing of waste in pit lakes must be weighed against the pros and cons of disposing elsewhere on site. We recommend that backfill be considered as a closure option in all pit lake closure planning, along with the associated rigorous assessment of relevant costs and benefits for both backfill and no-backfill closure strategies.

References

ANCOLD 2019, *Guidelines on Tailings Dams – Planning, Design, Construction, Operation and Closure*, revision 1.

APEC 2018, *Mine Closure Checklist for Governments*.

Bloesch, J 1995, 'Mechanisms, measurement and importance of sediment resuspension in lakes', *Marine and Freshwater Research*, vol. 46, pp. 295–304.

Boehrer, B & Schultze, M 2006, 'On the relevance of meromixis in mine pit lakes', RI Barnhisel (ed.), *Proceedings of the 7th International Conference on Acid Rock Drainage*, American Society of Mining and Reclamation, St Louis, pp. 200–213.

DFAT 2016, *Leading Practice Sustainable Development Program for the Mining Industry - Preventing Acid and Metalliferous Drainage Handbook*, Department of Foreign Affairs and Trade, Canberra.

DMIRS 2020, *Mine Closure Plan Guidance - How to Prepare a Mine Closure Plan in Accordance with Part 1 of the Statutory Guidelines for Mine Closure Plans*.

Doley, D & Audet, P 2013, 'Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites', *Ecological Processes*, vol. 2, pp. 1–11.

Flambeau Mining Company 2009, *Annual Report*.

Gammons, CH 2009, ‘Subaqueous oxidation of pyrite in pit lakes’, D Castendyk & T Eary (eds), *Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability*, Society for Mining, Metallurgy, and Exploration, Littleton, pp. 77–90.

Gammons, CH & Duaine, TE 2006, ‘Long term changes in the limnology and geochemistry of the Berkeley Pit Lake, Butte, Montana’, *Mine Water and the Environment*, vol. 25, pp. 76–85.

Gammons, CH & Tucci, N 2013, ‘The Berkeley pit lake, Butte, Montana’, in W Geller, M Schultze, RLP Kleinmann & C Wolkersdorfer (eds), ‘Acidic pit lakes - legacies of surface mining on coal and metal ores’, Springer, Heidelberg, pp. 362–376.

Håkanson, L & Jansson, M 2002, *Principles of Lake Sedimentology*.

Hall, J 2004, ‘Excess saline mine water management in the Goldfields – a case study (White Foil and Frog’s Leg gold mines)’, *GEMG Proceedings – 2004 Workshop on Environmental Management*, Goldfields Environmental Management Group, Kalgoorlie, pp. 27–40.

Hamblin, PF, Stevens, CL & Lawrence, GA 1999, ‘Simulation of vertical transport in mining pit lake’, *Journal of Hydraulic Engineering*, vol. 125, pp. 1029–1038.

Hamersley Iron – Yandi Pty Limited 2014, *Yandicoogina Mine Closure Plan*.

IAEA 2004, *The Long Term Stabilization of Uranium Mill Tailings: Final Report of a Co-ordinated Research Project: 2000–2004*, Report IAEA-TECDOC-1403 IAEA.

ICMM 2019, *Integrated Mine Closure: Good Practice Guide, International Council on Mining and Metals*.

INAP 2009, *Accessed, Global Acid Rock Drainage Guide*, viewed 18 February 2024, http://www.gardguide.com

ITRC 2010, *In Situ Treatment of Mine Pools and Pit Lakes*.

Johnson, B & Carroll, K 2007, *Waste Rock Backfill of Open Pits – Design Optimisation, and Modelling Considerations*, *Mine Closure 2007: Proceedings of the Second International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 701–708.

Johnson, SL & Wright, AH 2003, ‘Mine void water resource issues in Western Australia’, *Hydrogeological Record Series*, Report HG 9, Water and Rivers Commission, Perth.

Jones, H & McCullough, CD 2011, ‘Regulator guidance and legislation relevant to pit lakes’, in CD McCullough (ed), *Mine Pit Lakes: Closure and Management*, Australian Centre for Geomechanics, Perth.

Kozak, W, Atkinon, S & Pearson, B 2021, ‘Creek reinstatement over backfilled mine pits’, *Life of Mine*, Australasian Institute for Mining and Metallurgy, Melbourne, pp. 103–105.

Lawrence, GA, Tedford, EW & Pieters, R 2016, ‘Suspended solids in an end pit lake: potential mixing mechanisms’, *Canadian Journal of Civil Engineering*, vol. 43, pp. 211–217.

Margalef-Marti, R, Carrey, R, Benito, JA, Martí, V, Soler, A & Otero, N 2020, ‘Nitrate and nitrite reduction by ferrous iron minerals in polluted groundwater: isotopic characterization of batch experiments’, *Chemical Geology*, vol. 548.

McCullough, CD 2015, ‘Consequences and opportunities of river breach and decant from an acidic mine pit lake’, *Ecological Engineering*, vol. 85, pp. 328–338.

McCullough, CD 2024, ‘The importance of nitrate dynamics in mine pit lakes of drier regions’, *Mine Water and the Environment*, vol. 43, pp. 231–254.

McCullough, CD & Lund, MA 2006, ‘Opportunities for sustainable mining pit lakes in Australia’, *Mine Water and the Environment*, vol. 25, pp. 220–226.

McCullough, CD & O’Grady, B 2022, ‘Closure of an Australian pit lake with AMD using a terminal water balance as an evaporative sink’, J Pope, C Wolkersdorfer, R Rait, D Trumm, H Christenson & K Wolkersdorfer (eds), *Proceedings of the International Mine Water Association (IMWA) Conference*, International Mine Water Association, pp. 247–252.

McCullough, CD & Schultze, M 2018, ‘Engineered river flow-through to improve mine pit lake and river water values’, *Science of the Total Environment*, vol. 640–641, pp. 217–231.

McCullough, CD, Marchand, G & Unseld, J 2013, ‘Mine closure of pit lakes as terminal sinks: best available practice when options are limited?’, *Mine Water and the Environment*, vol. 32, pp. 302–313.

McCullough, CD & Sturgess, S 2020, ‘Human health and environmental risk assessment for closure planning of the Argyle Diamond Mine pit lake’, J Pope, C Wolkersdorfer, A Weber, A Sartz, K Wolkersdorfer (eds), *Proceedings of the International Mine Water Association Congress*, International Mine Water Association, pp. 187–192.

McCullough, CD, Schultze, M & Vandenberg, J 2020, ‘Realising beneficial end uses from abandoned pit lakes’, *Minerals*, vol. 10, pp. 133.

McCullough, CD & Van Etten, EJB 2011, ‘Ecological restoration of novel lake districts: new approaches for new landscapes’, *Mine Water and the Environment*, vol. 30, pp. 312–319.

McCullough, CD, van Rooijen, A & van Maren, DS 2019, ‘Process-based erosion modelling for shoreline rehabilitation design of a coal mine pit lake’, in AB Fourie & M Tibbett (eds), *Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 75–88, https://doi.org/10.36487/ACG_rep/1915_07_McCullough

MEND 1995, *Review of In-Pit Disposal Practices for the Prevention of Acid Drainage - Case Studies*, MEND Report 3.43.1, Report No. 2.36.1, Canadian Centre for Mineral and Energy Technology, Ottawa.

MEND 1998, *Design Guide for the Subaqueous Disposal of Reactive Tailings in Constructed Impoundments*, Report 2.11.9, Canadian Centre for Mineral and Energy Technology, Ottawa.

Morgenstern, NR, Vick, SG & Van Zyl, D 2015, *Independent Expert Engineering Investigation and Review Panel*, *Report on Mount Polley Tailings Storage Breach*, Government of British Columbia, Vancouver.

Niccoli, WL 2009, ‘Hydrologic characteristics and classifications of pit lakes’, in D Castendyk & T Eary (eds), *Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability*, Society for Mining, Metallurgy, and Exploration, Littleton.

Oggeri, C, Vinai, R, Fenoglio, TM & Godio, A 2023, 'Large scale trials of waste mine burden backfilling in pit lakes: impact on sulphate content and suspended solids in water', *Sustainability*, vol. 15, https://doi.org/10.3390/su15097387

Oldham, C, Salmon, SU, Hipsey, MR & Ivey, GN 2009, 'Modelling pit lake water quality - Coupling of lake stratification dynamics, lake ecology, aqueous geochemistry and sediment diagenesis', in D Castendyk & T Eary (eds), *Workbook of Technologies for the Management of Metal Mine and Metallurgical Process Drainage*, Society for Mining, Metallurgy, and Exploration, Littleton.

Puhalovich, AA & Coghill, M 2011, 'Management of mine wastes using pit/underground void backfilling methods: current issues and approaches', in CD McCullough (ed.), *Mine Pit Lakes: Closure and Management*, Australian Centre for Geomechanics, Perth.

Ramsey, D & Martin, J 2009, 'Subaqueous disposal of sulfide tailings - reclamation of the Sheriddon orphan mine site, Manitoba, Canada', *Proceedings of the International Mine Water Conference*, International Mine Water Association, Pretoria, pp. 746–755.

Read, DJ, Oldham, CE, Myllymäki, T & Koschorreck, M 2009, 'Sediment diagenesis and porewater solute fluxes in acidic mine lakes: the impact of dissolved organic carbon additions', *Marine and Freshwater Research*, vol. 60, pp. 660–668.

Rousseau, M & Pabst, T 2023, 'Blast damage zone influence on groundwater fluxes through backfilled open-pits', *Canadian Geotechnical Journal*, vol. 60, no. 3, pp. 1–14, http://dx.doi.org/10.1139/cgj-2021-0462

Schultze, M, Boehrer, B, Friese, K, Koschorreck, M, Stasik, S & Wendt-Potthoff, K 2011, 'Disposal of waste materials at the bottom of pit lakes', in AB Fourie, M Tibbett & A Beersing (eds), *Mine Closure 2011: Proceedings of the Sixth International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 555–564, https://doi.org/10.36487/ACG_rep/1152_58_Schultze

Schultze, M, Boehrer, B & Geller, W 2013, 'Morphology, age, and development of pit lakes', in W Geller, M Schultze, RLP Kleinmann & C Wolkersdorfer (eds), *Acidic Pit Lakes - Legacies of Surface Mining on Coal and Metal Ores*, Springer, Berlin.

Schultze, M, Castendyk, D, Wendt-Potthoff, K, Sanchez-Espana, J & Boehrer, B 2016, 'On the relevance of meromixis in pit lakes – an update', C Drebenstedt & M Paul (eds), *Proceedings of the IMWA Conference 2016*, International Mine Water Association, pp. 199–200.

Schultze, M, Pokrandt, K-H & Hille, W 2010, 'Pit lakes of the Central German lignite mining district: creation, morphometry and water quality aspects', *Limnologica*, vol. 40, pp. 148-155.

Skousen, J, Ziemkiewicz, P, Yang, JE, Skousen, J, Ziemkiewicz, P & Yang, JE 2012, 'Use of coal combustion by-products in mine reclamation: review of case studies in the USA', *Geosystem Engineering*, vol. 15, pp. 71–83.

Testa, SM & Pompy, JS 2007, 'Backfilling of open-pit metallic mines', *National Meeting of the American Society of Mining and Reclamation*, vol. 1, pp. 816–830, http://dx.doi.org/10.21000/JASMR07010816

Vandenberg, J, Schultze, M, McCullough, CD & Castendyk, D 2022, 'The future direction of pit lakes: part 2, corporate and regulatory needs to improve management', *Mine Water and the Environment*, vol. 41, pp. 544–556.

Vandenberg, JA, McCullough, CD & Castendyk, D 2015a, 'Key issues in mine closure planning related to pit lakes', A Brown, L Figueroa & C Wolkersdorfer (eds), *Proceedings of the Joint International Conference on Acid Rock Drainage ICARD/International Mine Water Association Congress*, International Mine Water Association, pp. 1852–1861.

Vandenberg, JA, Prakash, S & Buchak, EM 2015b, 'Sediment diagenesis module for CE-QUAL-W2. Part 1: conceptual formulation', *Environmental Modeling & Assessment*, vol. 20, pp. 239–247.

Verburg, R, Bezuidenhout, N, Chatwin, T & Ferguson, K 2009, 'The Global Acid Rock Drainage Guide', *Mine Water and the Environment*, vol. 28, pp. 305–310.

Watson, A, Linklater, C & Chapman, J 2016, 'Backfilled pits – laboratory-scale tests for assessing impacts on groundwater', *Life of Mine*, Australasian Institute for Mining and Metallurgy, Melbourne, pp. 113–117.

Watson, A, Linklater, C, Chapman, J & Marton, R 2017, 'Weathered sulfidic waste – laboratory-scale tests for assessing water quality in backfilled pits', *9th Australian Workshop on Acid Metalliferous Drainage*, Sustainable Minerals Institute, The University of Queensland, St Lucia, pp. 57–65.

Weilhartner, A, Muellegger, C, Kainz, M, Mathieu, F, Hofmann, T & Battin, TJ 2012, 'Gravel pit lake ecosystems reduce nitrate and phosphate concentrations in the outflowing groundwater', *Science of the Total Environment*, vol. 420, pp. 222–228.

Williams, DA & Minard, TE 2010, 'An environmentally and economically attractive integrated landform for the storage of tailings and waste at the Randalls Gold Project in Western Australia', R Jewell & A B Fourie (eds), *Mine Waste 2010: Proceedings of the First International Seminar on the Reduction of Risk in the Management of Tailings and Mine Waste*, Australian Centre for Geomechanics, Perth, pp. 129–143.

Williams, RD 2006, 'Pit backfill: yea or nay, a Montana example', in RI Barnhisel (ed.), *Proceedings of the 7th International Conference on Acid Rock Drainage*, American Society of Mining and Reclamation, pp. 2397-2410.