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TECHNICAL COMMUNICATION

The Future Direction of Pit Lakes: Part 2, Corporate and Regulatory Closure Needs to Improve Management

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Abstract

Pit lakes may present significant risks to ecological and human receiving environments but can also provide beneficial end use opportunities. The understanding of many processes that influence the magnitude of these risks and opportunities remains limited, and even where our understanding is adequate, the application of that knowledge is not consistently applied. From initial planning to long-term closure, regulation and corporate management of pit lake closure can be improved to realise more sustainable pit lake legacies. In this two-part manuscript, we recommend focus areas for future research by academics (Part 1), and strategies to structurally improve the practice of pit lake closure for mining industry regulators, corporate sustainability officers, global practice leads, and site mine closure planners (Part 2). Here we identify barriers that often limit the understanding of pit lake processes and closure practices and suggest ways that corporate leaders, closure practitioners, and regulators can improve pit lake management. Recommended corporate changes include: conducting risk assessments at an early planning stage; funding pit lake research and trials; allowing data sharing and case study publication; avoiding the simplifying assumption of a fully mixed pit lake when making predictions; integrating climate change into pit lake predictions; improving the quality of technical reporting; generating industry guidance for pit lake rehabilitation; maximizing opportunities for subaqueous, in-pit disposal of mine wastes; creating a positive legacy through beneficial uses of pit lakes; and verifying predictions using long-term monitoring. Recommended regulatory advancements include: raising expectations of corporate pit lake closure planning and execution; acknowledging good pit lake closure examples; balancing the need to simulate long closure periods with expectations of model reliability; considering the value of pit lakes as future water resources during permitting; and requiring closure costing and bonding commensurate to closure risk.

Keywords Mine closure planning · Regulatory change · Sustainability · Beneficial end use · Expert commentary

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Introduction

Globally, pit lakes remain as final landforms of the post-mining landscape at many surface mines. Poorly planned pit lakes often present legacy risks to the environment and human health and safety (Doupé and Lymbery 2005; McCullough and Sturgess 2020), such as slope instability, drowning, entrapment, falls hazards, and poor water quality (McCullough and Lund 2006). Poor water quality may result from the addition of acidic and metalliferous drainage (AMD) with low pH and/or elevated element concentrations associated with sulfide mineral oxidation (Eary and Castendyk 2013; Friese et al. 2013), saline conditions resulting from evapoconcentration (Eary 1998), and/or elevated nutrient concentrations from the dissolution of nitrogen-based blasting agents leading to eutrophication

(Roman-Ross et al. 2005). Conversely, pit lakes that are well-planned and managed have the potential to become beneficial end-use resources (McCullough and Lund 2006). Such end uses include: ecological reserves, recreation areas, water supplies for irrigation or stock water, reservoirs for thermoelectric energy production, and treatment facilities for contaminated mine water (McCullough et al. 2020).

In Part 2 of this two-part series, we highlight key institutional barriers to the advancement and application of pit lake knowledge and research. The authors of this paper represent a cross-section of experienced pit lake researchers, managers, and closure planners from around the world (Canada, Germany, Australia, and USA) who have worked in and across academia, government, and private industry. Based on our collective experiences and recent literature, we discuss corporate barriers to pit lake closure that currently limit the global mining industry's ability to mitigate risks and realize closure opportunities. We then suggest improved corporate practices to reduce future risk and improve opportunities for beneficial outcomes.

We also identify areas where regulatory policy is not commensurate with pit lake understanding and societal expectations. In some instances, policy has become prescriptive "check a box" exercises that provide little management value or predictive accuracy. Such issues likely require collaborative resolution among government, industry and academia (McCullough 2016). Many of the solutions will involve legal changes as well as a paradigm shift in how society and industry view pit lakes.

Our intent with this paper is to encourage the transformation of pit lakes into post-mining assets with acceptable risks that become beneficial to societies and environments, and that promote the social license to mine. This change will require applying the knowledge gained through research (see Part 1; Schultze et al. 2022) and modernizing the approach to pit lake management at the corporate and regulatory level.

Improved Corporate Practice

Mining companies have the greatest opportunities to improve the outcome of pit lakes through early closure planning and execution. Improved closure practices may reduce risks to the mining companies while providing benefits to the local communities that will remain after mining ceases. Though the benefits may require long time periods to accrue, the social licence generated through the application of these improvements is necessary to sustain the industry. The following practices can be improved by mining companies and their contractors.

Conducting Risk Assessments at an Early Planning Stage

Risk can be a nebulous concept, even for experienced mine closure planners. Characterizing and addressing pit lake risks requires expertise in a range of relevant hazard categories and an understanding of the interactions of pit lakes with environmental and social contexts (McCullough and Schultze 2018a). Although risks may be localized (often to the pit lake catchment or pit lake proper) they may be long-term and may worsen over time e.g. through evapoconcentration of contaminants (Eary 1998).

Risk categories include environmental risks (especially from contaminant hazards) and safety hazards. There can also be a long-term or even perpetual financial liability in mitigating these risks. To complicate the matter, risks can manifest decades after the end of mine operations, when the mine is no longer generating revenue and when filling, erosion, and water quality trends have created hazards that were not apparent during mining. Risk mitigation may not be feasible if the closure budget has been expended, the site has been relinquished to another landowner, or if the time between the end of operations and the final lake level is very long (i.e. centuries). Understanding the hazards that might result in ongoing risks and the magnitude of these risks should be a key component of pit lake closure planning (Commonwealth of Australia 2016; Government of Western Australia 2020).

General pit lake risks should be evaluated in all assessments, including:

- depletion and/or salinization of regional groundwater or surface water resources;
- use of lake by wildlife for drinking and foraging (Sampson et al. 1996);
- development of plant and animal habitats, some of which may be considered pests;
- development of chronic health risks to aquatic or aviary biota (including bioaccumulation);
- hunting, foraging and eating of wildlife from pit lake catchments (biomagnification risks) (Lawrence and Chapman 2007; Sampson et al. 1996) ;
- access by public resulting in falls from high walls and/or drownings from sudden depth increases around pit lake margins (Ross and McCullough 2011);
- health impacts on people recreating near, in or on the pit lake (Hinwood et al. 2012);
- collapse of unstable highwalls and beaches and excessive erosion (McCullough et al. 2019); and.
- formation of surge waves within and downstream of pit lakes (McCullough and Diaz 2020).

A source-pathway-receptor model is a useful tool to transparently assess the source and fate of pit lake water contaminants and how they might present as water quality hazards. However, this tool is inappropriate to the assessment of non-contamination related risks such as safety. In such cases, Failure Modes Effects Analysis (FMEA) may be more useful for assessing risks with and without controls and mitigations (Vick 2002).

Fund Pit Lake Research and Trials

Sound closure planning relies on foundational research of many key pit lake processes (see Part 1; Schultze et al. 2021). However, funding is typically low for pit lake research, particularly reliable funding for long-term studies that allow for iterative research opportunities. In many countries, pit lakes fall into the realm of applied sciences, which national funding agencies may view as having less academic merit than pure ("blue sky") scientific endeavours. These agencies also consider applied research to be the responsibility of industry to fund, while mining companies with low research budgets and concerns about data confidentiality tend not to fund research other than studies directly related to short-term financial return or specific regulatory requirements. Too often, the results of industry research go unpublished.

Without funding, the advancement of remediation practices by the mining sectors achieved to date would not have been possible. Such advancements have been supported by sector-wide investments that promote sharing of funding, resources, and data. For example, the German government spent millions of Euros in the 1990s and beginning of the 2000s, funding research on mining, mine closure and post-mining issues on lignite pit mines located in former East Germany. This attracted many researchers and resulted in an enormous step forward in understanding the relevant processes (Gläßer 2004).

Similar outcomes can be achieved by a voluntary consortia within a given mining sector. For example, oil sands mines in Canada have formed the Canada's Oil Sands Innovation Alliance to pool research funding to address regional and sector-specific environmental issues. The consortium has promoted several research programs and generated many publications with pit lakes being one focus area, such as the pilot-scale pit lakes described by Vandenberg et al. (2014). There is an opportunity for the international mining industry or individual mining sectors to establish a similar pit lake research consortium on a global or sector-based level.

Allow Data Sharing and Case Study Publication

Access to long-term, post-mining monitoring data is essential for generating reliable, long-term development trajectories for future pit lakes and to thereby improve the understanding of pit lake liabilities and opportunities. The limited availability of pit lake predictions and data collected from completed pit lakes is an enduring issue for researchers, closure planners, and regulators seeking to understand fundamental pit lake processes and improve physical/chemical/ecological outcomes.

The primary obstacle to data sharing is the potential legal or reputational liability companies may face should data be used in opposition against them. Consequently, most companies contractually prevent publication of water quality monitoring data, predictions and related research results. The resulting lack of publicly available data is a hindrance to consultants working on permitting projects in the interest of mining companies. Treating monitoring data as confidential increases the cost of permitting, erodes public trust, and limits the industry's ability to learn from successes and failures.

A related consequence of hesitancy to publish pit lake case studies is that publicly available datasets can be heavily skewed to positive outcomes (e.g. pit lakes with good water quality or realised social values). However, many of the most important lessons related to pit lake management were derived from observing unique and challenging pit lakes, such as the Berkely Pit Lake in Montana, USA, and the novel approaches used to improve these systems over several decades (Davis and Ashenberg 1989; Gammons and Icopini 2020).

While a growing number of studies have been published over the past four decades, there remains a global need for comprehensive monitoring and publication of pit lake data, especially for long-term pit lake water balances and quality. To encourage data sharing at a corporate level, site names, locations, and owners could be anonymised with only fundamental parameters shared (e.g. water quality, climate, commodity, mining method). These "sanitized data" would retain considerable value to improve subsequent predictions while protecting the anonymity of companies.

We are encouraged by the development of an international database of pit lake water quality by the International Network for Acid Prevention (INAP) (Johnson and Castendyk 2012). Yet, even this industry-sponsored tool has suffered from a lack of data contributed from the world's largest metal mining companies. Finding innovative approaches that encourage corporations to contribute unpublished datasets will help advance the field of pit lake research, planning, and management.

To shift the prevailing corporate mindset, each pit lake closure or management project could be viewed as an important case study from the outset. Making more monitoring data publicly available can have positive consequences for the industry. Predictions, monitoring reports, and management plans can be summarized and published as case studies with datasets of hydrology and water quality provided in supplemental information. Publishing more complete datasets in accessible journals will improve public trust, foster research, and, most importantly, allow predictions to be verified. Accurate predictions make subsequent predictions more efficient and reliable, reduce the cost of future predictions and permitting, and build public confidence in corporate commitments, all of which are in the interests of the companies who own the data.

Avoid the Simplifying Assumption of a Fully Mixed Pit Lake in Predictions

It has long been recognized that simple, dimensionless, analytical equations (i.e. relative depth and Froude number) are incapable of accurately representing the complex physical structure of a pit lake (Schultze et al. 2016). Although easy to calculate, the numerical answers produced have no consistent application to observed conditions in lake systems due to an oversimplification of variables. For example, outdated literature suggested that lakes with high relative depths should be stratified, and pit lakes with low relative depth should mix, without accounting for density gradients or local wind patterns. Yet, as more limnological observations have been collected from existing pit lakes, researchers have been unable to consistently connect relative depth and the potential for whole-lake mixing. To the contrary, we now have many examples of pit lakes with high relative depth that completely mix, and pit lakes with low relative depth that are perennially stratify.

Similarly, treating a dynamic, seasonally stratified system such as a lake as if it is a well-mixed system will tend to yield inaccurate geochemical predictions compared to actual pit lakes that exhibit concentration gradients along a vertical profile. This particularly applies for meromixis (i.e. permanent chemical stratification), but also for seasonal thermal stratification. In both cases, part of the water body, often the majority by volume, has no contact to the atmosphere and, thus, no exchange of dissolved oxygen, carbon dioxide, hydrogen sulfide, and other dissolved gases.

The depletion or accumulation of these dissolved gases will affect redox state, pH, and other driving variables that affect metal and mineral solubility. They also influence the composition and abundance of all biological organisms within a lake, from microbes to primary producers to fish. Therefore, incorrect assumptions about vertical mixing or stratification may negate biogeochemical prediction goals, such as water quality and ecological habitat suitability.

Although limnologists have urged pit lake modellers to avoid such simplifying assumptions in favour of more accurate hydrodynamic modelling, both mining clients and geochemical modelers still often select the least expensive, simplest approach to physical assumptions at the cost of physical and chemical accuracy. Prominent geochemists still rationalize this neglect of physics on the grounds that "prefeasibility predictions do not require this level of detail." Thus, a disproportionate effort is often placed on the accuracy of lake geochemistry while fundamental lake physics is neglected, even though the former relies on the latter.

Options are available for simulating lake physics and geochemistry within fully-coupled model packages (Hipsey et al. 2019; Mueller 2021; Prakash et al. 2015; Salmon et al. 2017; Wells 2021), although these complex models carry a considerable burden of extensive input data requirements and program-specific training. Nonetheless, there are relatively simple approaches that can advance predictions from fully-mixed models to more vertically representative models. These begin with using 1-D or 2-D hydrodynamic models to understand basic vertical dimensionality (e.g. maximum depth of mixing and frequency). Such predictions can also then be used to construct two- or three-layer geochemical models with different chemical properties within each layer, and possibly with intermittent mixing as predicted by the hydrodynamic model. This process replicates the basic vertical structure of density and oxygen within a pit lake and will lead to stepped improvements in geochemical model predictions. We contend that such an approach should constitute the minimum level of effort expended to replicate vertical stratification, unless there is an alternative line of evidence that the pit lake will be fully mixed.

Integrate Climate Change into Pit Lake Predictions

Water balance models and their application have evolved over the past 40 years from being virtually unconsidered to being an often-mandatory component of planning and managing pit lakes. Model software is widely used today to generate both deterministic and probabilistic water balance predictions of future pit lakes. Modelling the water balance of future pit lakes requires making long-term predictions on the order of centuries. Such predictions rely heavily on local meteorological variables such as air temperature, precipitation rates, and wind speeds, which are uncertain in a variable and changing climate. Even where mine water balances are carefully modelled, many mine closure plans do not explicitly consider potential consequences of climate change. Climate change can affect the pit lake water balance by affecting both inflows (e.g. precipitation) and outflows (e.g. evaporation), and consequently, the long-term water level.

Additional effects may result from or accompany changes in water levels. Varying the water surface elevation affects groundwater discharge rates (i.e. by changing the local hydraulic gradient) as well as closure risk by changing mean and extreme pit lake water levels. The position of the water surface may also affect wall rock pore pressures and slope stability, the exposure of potentially acid forming material (PAF) in wall rock, and the areas of the riparian zone and littoral zone. Evapoconcentration may become more relevant to water chemistry where climate change reduces mean annual precipitation and increases net evaporation (Eary 1998). Higher ambient temperatures may also accelerate microbially-mediated processes (e.g. eutrophication) and change the composition of the phytoplankton to higher proportions of harmful cyanobacteria (Paerl and Huisman 2008).

Climate change is predicted to increase temperatures globally but will likely increase or decrease precipitation differently in different regions. With some local exceptions, precipitation is predicted to decrease over much of the equatorial belt and over most of Africa and Australia. In contrast, precipitation is predicted to increase over most of North America, Europe, and Asia over the next century. In many regions, the climate may be more variable, regardless of long-term trends (IPCC 2021). Forecasting which of these conditions is likely at a given mine site over its long-term closure is necessary for planning and building climate resilience.

Climate model predictions that extend beyond a decade should be accompanied by climate change scenarios that account for changes in both median conditions and extreme variability to meteorological parameters. Using generalized circulation models (GCMs) and regional downscaling tools, climate change scenarios can be translated into site-specific forcing data (specifically, temperature and precipitation) for a given pit lake. However, caution should be applied to the specific IPCC scenario chosen, as neither the representative concentration pathway (RCP) scenario 2.6 (which assumes pro-active, international policies to reduce greenhouse gases) nor the RCP scenario 8.5 (which assumes a rapid expansion of coal power) are now considered plausible based on current emissions trends and international commitments (Burgess et al. 2020; Hausfather and Peters 2020; Ritchie and Dowlatabadi 2017). As yet, GCMs do not reliably predict evaporation rates. Present meteorological models cannot accurately hindcast wind speed and wind direction at a given location over long-term past conditions, let alone confidently predict long-term future conditions. As such, caution should be applied in translating the results from GCMs into long-range pit lake models, as GCMs have been shown to consistently overpredict warming relative to observations over the decades since they were developed (Fyfe et al. 2013; Papalexiou et al. 2020). The upcoming IPCC AR6 model results, due in 2022, may provide more realistic scenarios upon which to base long-term forecasts for pit lake models. Until then, a prudent approach would be to simulate a range of future scenarios that consider different meteorological conditions with the understanding that these represent a range of possible outcomes, each with unknowable probabilities.

While the issue is complex and multifaceted, companies are encouraged to integrate climate change trends and variability into pit lake studies so that future changes can be better anticipated and managed. At the least, models can be used to assign reasonable bounds on key variables and required adaptations.

Improve the Quality of Technical Reporting

The full context of pit lake predictions, as presented in model reports, can be difficult to understand by stakeholders and regulators, and even often by expert reviewers. A given set of predictions may incorporate multiple complex models, each with sets of inputs, assumptions, and limitations that are seldom well articulated. Often, coupled models are developed and documented by multiple sets of consultants, each performing a different aspect of the modeling effort, with no one company responsible for the overall synthesis of concepts. Models are also increasingly complex. As noted by Drever (2011), “We have lost transparency – there is no realistic way an outsider can repeat the [pit lake] calculation as a check.”

Inputs, which include the values of meteorological variables, bathymetry, water balance over time, loading source term chemistry, and initial conditions, should be clearly described in terms of measurement technique and data sources (e.g. unpublished case studies or published data). Each input data type should be provided using summary statistics, time series graphs, or digital appendices.

Assumptions include all conceptualizations and simplifications that are necessary to replicate the pit lake and its relevant processes. Examples include dimensionality, excluded processes, synthetic inputs where they have not been measured, future climate scenarios, and other factors where the numerical model may differ from reality. Discussing all assumptions allows the modeler to transparently inform the reader about how the model works and allows the reader to understand the model’s uncertainty.

Similarly, model limitations involve simplifying assumptions that are made due to technological necessity or gaps in data, such as limitations in computing power, complexity of model algorithms, availability of input data, or other aspects of the model that limit our ability to reproduce the system. Model limitations do not necessarily invalidate a model because models are fit-for-purpose, simplified systems, but they should be transparently discussed so that readers are aware of what the models are incapable of, as well as conditions that would invalidate predictions (e.g. inability to simulate a pit wall failure).

Uncertainty is also usually poorly communicated, with modelers focusing on a single source of uncertainty, such as input data, climate, or geochemical reactions, to the exclusion of other important sources of uncertainty such as errors in conceptualization (Bredehoeft 2005). By articulating the inputs, assumptions, and limitations, both the modeler and the reader will gain a better understanding of overall model uncertainty.

Adopting a comprehensive list of best practices for reporting pit lake predictions will help standardize and streamline communication, eliminate redundant information, create more transparent documents, and ultimately, improve stakeholder trust. Thus, companies should demand improvements to the quality of written material by their consultants. In all likelihood, this will have the added benefit of better decision making by the managers that contracted the modelers.

Generate Industry Guidance on Pit Lake Rehabilitation

Many pit lakes either currently in existence, or in development, will pose water quality risks to environmental receptors (Gammons et al. 2009). Risks may develop immediately or gradually over time as a product of long-term evapoconcentration (Eary 1998) and/or following the consumption of acid-neutralizing minerals in exposed wall rock (Schafer et al. 2020). Of particular concern are lakes that might discharge contaminated water and impact the values of receiving environments such as regional surface water or groundwaters (Lee et al. 2008; McCullough and Evans 2021; Park et al. 2006).

Treating the water at the point of discharge is a conventional water treatment approach, and technologies exist to treat many forms of mine water (Johnson and Hallberg 2005; Geller and Schultze 2013; Skousen et al. 2017). To this end, pit lakes can perform a key role in the treatment process by capturing and storing mine impacted waters (McCullough et al. 2013). However, in situ (semi-passive) treatment can be used to reduce or eliminate the need for active treatment.

Experimental systems that rely on nutrient amendments to promote in situ biological treatment have been employed in pit lakes with various levels of success around the world (McCullough and Vandenberg 2020). Diverse treatment approaches have been proposed and applied, often using combinations of the following:

- Rapid inundation of reactive, sulfide-rich wall rock in order to limit oxygen supply and pyrite oxidation.
- Addition of limestone to raise pH and precipitate metals (Benthaus et al. 2020).
- Addition of nutrients to stimulate phytoplanktonic growth, leading to metal removal by adsorption (Kumar et al. 2016; Wen et al. 2015).
- Addition of labile carbon to stimulate sulfate reduction and stimulate alkalinity production (McCullough et al. 2008).
- Establishment of flow-through conditions using river channels to provide a continuous and long-term supply of both phosphorus and carbon to the lake microbial ecosystem and to provide buffering capacity to the lake water (McCullough and Schultze 2018b).

However, there is no systematic approach or even generalized guidance for remediating pit lake waters. With a few exceptions, the long-term remediation programs that exist remain poorly published with detailed methods and results largely inaccessible to the broader pit lake remediation community. Consequently, each remediation project starts from an abridged knowledge base, with a transfer of publicly available conceptual information, or from the practitioner's personal experience from a few case studies. As an added drawback, regulators and mine companies generally view biogeochemical approaches as unproven technologies, and prefer to assess mine closure bonds based on conventional treatment technologies alone.

Our hope for the next 40 years would be that in-situ treatment specialists coalesce as a specialized industry and develop generalized guidance on pit lake treatment approaches with reference to published case studies. The many developing pit lakes present a business case for such a specialized industry. In a best-case scenario, treatment may be paired with economic metal recovery, which in turn, pays part of the cost of long-term treatment. Providing critical reviews and performing research on new or untested approaches is a task for applied research (Part 1). As a first step, creating an industry-wide pit lake treatment guidance document, similar to recent guidance documents developed for tailings facilities (ICMM 2021; MAC 2019), would greatly improve the achievement of closure objectives while providing a foundation for the standardization of pit lake treatment.

Explore Opportunities for Subaqueous, In-pit Disposal of Waste

It has long been recognized that subaqueous disposal of mine waste, notably sulfidic tailings, in pit lakes presents several advantages (Gammons et al. 2009; Ramsey and Martin 2009; Schultze et al. 2011), such as:

- Avoiding the need for above-ground waste landforms like tailings dams and overburden dumps, and eliminating their risk of failure.
- Avoiding the need for trafficable tailings surfaces.
- Reusing previous mine features, thereby minimizing the mine footprint and reducing rehabilitation costs.
- Stabilizing sulfidic material in an anoxic environment.
- Reducing water demand during operations and the water volume required to fill a pit lake.
- Storing reactive waste in an environment that may be permanently isolated from the surface environment (i.e. the monimolimnion or bottom layer of a perennially stratified pit lake).
- Reducing groundwater discharge from a pit lake if tailings have a low hydraulic conductivity.
- Reducing facility closure costs compared to surface rehandling and reclamation of tailings and other mine wastes.

Given recent tailings dams failures (Franks et al. 2021; Santamarina et al. 2019), pit lakes are increasingly considered an alternative option for the long-term storage of tailings (Puhalovich and Coghill 2011; Williams 2009). Subaqueous disposal of potentially acid-generating materials is considered good practice and is a requirement in some jurisdictions (APEC 2018; Commonwealth of Australia 2016; Verburg et al. 2009). Conversely, the practice is considered too risky and outright prohibited in other jurisdictions (Alberta Energy Regulator 2018). Still in other cases, subaqueous waste storage has been an unintended result of operational cost reduction practices. For example, pit lakes that developed in former coal strip mines often had reactive overburden dumped inside the pits prior to flooding, which submerged PAF materials.

Obviously, we do not yet have a standardized approach or universal confidence in the long-term safety of subaqueous tailings disposal. Nevertheless, pit lakes show promise for this application, and we encourage mining companies to explore opportunities for sub-aqueous disposal in pit lakes as a waste storage option.

Create a Positive Legacy through Beneficial Uses of Pit Lakes

When taking a long-term perspective, mining companies and stakeholders should be interested in developing a post-mining landscape that permits beneficial end use(s), such as use by humans or recovery by nature. Pit lakes should be considered as potential opportunities to establish long-term beneficial uses for communities that will remain after mine closure. While risk assessment and liability limitation will always be necessary, the socioeconomic and environmental costs of mining can be offset to some degree with the benefits of a useful waterbody (McCullough and Lund 2006; McCullough and van Etten 2011). In particular, pit lakes with an appropriate water quality and engineered habitat can provide good wildlife habitat (Otchere et al. 2002).

Often, expectations of end uses are overly optimistic, unrealistic and unlikely to be achievable. For example, closure of Lake Kepwari (Western Australia) resulted in an acidic pit lake that failed to meet company-promoted community expectations of a recreational resource (Evans et al. 2003) until water quality was strategically remediated (McCullough and Evans 2021). To arrive at realistic expectations, early and ongoing engagement with stakeholders is critical in appropriately matching realistic end uses to the pit lake characteristics (Vandenberg and McCullough 2017).

Several beneficial uses of pit lakes have been documented (Keenan and Holcombe 2021). Beneficial end uses should be considered as closure options for all pit lakes, ideally at the initial stages of mine planning. While end uses will vary with geography, climate, and stakeholder expectations, the goal should generally be to create assets that return value to the post-mining community and ecosystem. Such an approach is likely to be consistent with a company's environmental, social, and governance (ESG) objectives.

Alternatively, second-generation industries, such as power (Song and Choi 2016), water supply, tourism (Caesarina and Hirsan 2020), or aquaculture (Mallo et al. 2010) may be created to sustain local communities when the mine no longer provides employment. In addition to providing benefits to local communities, transitioning to another industry may offset closure costs because the new company may be willing to take on some of the reclamation work to create an environment that supports their venture. We encourage mining companies and their stakeholders to reconsider the value of end uses for pit lakes throughout the mine life cycle.

Long-term water quality has been found to be the most important variable determining the success of end uses (McCullough et al. 2020), especially in terms of wildlife habitat. Accordingly, companies should ensure that:

- water quality determinants are understood through geochemical and water balance studies prior to and during mining;
- water quality prediction is undertaken in a comprehensive and conservative manner (Vandenberg et al. 2011);
- rehabilitation works to mitigate poor water quality (e.g. covering geochemical exposures) are planned and budgeted early in the life-of-mine.

Doing so will improve the likelihood of end use success and reduce long-term water quality related remediation costs.

Verify Predictions using Long-term Monitoring

With few exceptions, pit lake model results are highly theoretical predictions that are subject to numerous input factors that can vary by orders of magnitude with a nearly unquantifiable level of uncertainty. Hence, real-world validation using site-specific or analogous data sources should be required of any pit lake model. To this end, there should be renewed emphasis to test model predictions against observed data collected from pit lakes.

By far the greatest and most persistent challenge in pit lake prediction is the lack of publications that compare predicted water quality against observed water quality from the same lake and allow practitioners to learn from the revealed strengths and weaknesses of a given modelling approach (i.e. post-audits). The few studies that have been undertaken have revealed overly-optimistic water quality predictions at the time of modelling (Kuipers et al. 2006). The only true validations of model predictions are through side-by-side comparisons of predicted and observed data spanning multiple years. Unfortunately, most predictions are generated to gain regulatory approval for some specific activity (e.g. permitting, expansion, closure planning) or for financial assurance and bonding, and there is a lack of follow up to verify predictions after the approvals are granted.

There is also a critical need to review the fundamental geochemical inputs and assumptions used in models, and to identify which assumptions are realistic and which are overly conservative or optimistic. Where the necessary expertise does not reside within the corporate team, third-party reviewers should critically review predictions.

Moreover, there is a pressing need to develop a unified framework or platform to archive model predictions and to make it possible to later verify (or learn from) these predictions. Once more predictions and observations on pit lakes are available, a rigorous analysis of "what worked" and "what did not work" can begin (Schultze et al. 2022). Many models from different geological and hydrological settings should be reviewed as part of such an analysis. This effort could yield a comprehensive "best practice tool box" for pit lake prediction that defines the data needed and sub-models used in the generation of a pit lake prediction based on past learnings. Such an effort would require an industry-wide commitment or possibly a regulatory driver.

As a possible prototype for this concept, INAP has assembled the aforementioned database of observed water quality from over 100 mine pit lakes from different ore body types (Johnson and Castendyk 2012), which allows modelers to compare a water quality prediction for a specific ore body against the observed water quality of pit lakes within the same ore body. The theory behind this tool is that existing pit lakes of similar geology and climate provide the best means to validate a future prediction of water quality in the absence of direct observations (Eary and Castendyk 2009). Such efforts should be expanded.

Improved Regulatory Standards

While many of the necessary improvements to professional practice and management rest with industry, some of the required improvements are only likely to be adopted if regulations require the entire industry to comply, at least within a jurisdiction. Thus, regulatory standards have a role in shifting the future direction of pit lake sustainability.

Raise Expectations of Corporate Pit Lake Closure Planning and Execution

Pit lakes are artificial water bodies. As such, water quality protection to the same degree as natural water bodies is often inappropriate and regulations can be inconsistent (Bolen 2002; Nixdorf et al. 2005) with unrealistically high standards in some jurisdictions or entirely absent in others (Wolkersdorfer 2002). However, one universal approach to protection of any water body, and especially that of artificial water bodies such as pit lakes, is the clear identification of end uses for any water body and associated water quality values required to satisfy those *a priori* end uses (McCullough et al. 2020). Stakeholder engagement is key to this end use identification process (Lintz et al. 2012; Scholz 2010; Swanson 2011; Swanson et al. 2011).

The regulations of many mining jurisdictions are also often descriptive and refer to "not significantly different from natural baseline", "non-polluting", "no environmental harm", etc. (APEC 2018; Commonwealth of Australia 2016). This narrative is not a problem in itself, but it lacks sufficient detail to provide advice to both regulators and mining companies as to what long term pit lake condition might be acceptable and how these should be assessed. Moreover, setting expectation defined by risk alone provides little incentive for companies to develop end uses that go beyond no harm by adding local value during post-closure.

To determine what is acceptable under most regulations, one needs to appropriately assess potential environmental risks, which are often substantial for pit lakes (Kroll et al. 2002). A lack of published pit-lake-relinquishment criteria furthers this lack of regulatory clarity. To assist future planning, it would be beneficial to summarize and disseminate: (i) where pit lakes have been released from liabilities, (ii) what pit lake conditions have been deemed acceptable by regulators, and (iii) what precedents and assessment techniques have been used.

Regulatory questions include:

- Should a pit lake be expected to have the same water quality as natural baseline groundwater or surface water surrounding a mine, and is this possible given biogeochemical constraints of the pit shell and the physicality of a new, deep water body where none existed before (Yokom et al. 1997)?
- Should a pit lake be required to have a functional ecosystem; and if so, what level of ecosystem functionality and diversity is acceptable for regulatory compliance (McCullough and van Etten 2011)?
- Do plant and animal pest controls apply to pit lakes, or would any ecosystem (including one with non-native, invasive species) be favourable relative to a sterile, ultra-oligotrophic ecosystem (McCullough et al. 2009)?
- Is it desirable, or even possible, to avoid an ecosystem developing in a pit lake (McCullough and Sturgess 2020)?
- Should fishery or hunting opportunities be realised in pit lakes, thereby increasing the likelihood of human access to the water surface or exposure to other hazards during post closure, as well as the possible ingestion of fish by humans (Lawrence and Chapman 2007)?
- Should other upper-trophic-order grazers and predators such as waterfowl, large reptiles, and mammals be allowed to access the lake, and can this be avoided (Miller et al. 2013; Palace et al. 2004)?

All of these questions will be site-specific because they relate to regional environmental constraints, stakeholder expectations, and regulatory requirements. However, minimum global standard requirements for regulatory expectations regarding pit lake relinquishment would provide guidance and certainty for mining companies and would remove incentives to opt for cheaper options such as perpetual management of fenced-off pits.

Acknowledge Good Pit Lake Closure Examples

The regulator has an important role not only in enforcing standards and expectation but in raising industry standards through competition by acknowledging companies that exceed those standards. One approach to drive competition in pit lake sustainability is to highlight and reward examples where former open pit mines have been transformed into beneficial end uses with great value to society today. Such examples exist on every continent except Antarctica, and yet, only a few have been recognized as either examples of success or benchmarks for closure. Closure awards are valuable to mining companies because they support the social licence to continue to operate and expand. Such an award could be further promoted through social media and the press to gain wider knowledge among the public as well as shareholders looking for sustainable investments.

Balance the Need to Simulate Long Closure Periods with Expectations of Model Reliability

In addition to the global challenge of generating meaningful, long-term predictions, a challenge for regulators and mining companies is defining an appropriate model duration for a pit lake prediction that is short enough to be reasonably accurate, but long enough to be useful. Managers and planners are accustomed to quantifying the frequency and magnitude of a given risk using past observations and statistical methods, such as the risk of a tailings dam failure associated with a 100 year, 500 year or 1000 year rainfall event (APEC 2018). Applying similar expectations to pit lake predictions, regulators often require predictions of water quality that extend several hundred or even thousands of years after the end of operations. And yet, the current margin of error in fundamental variables (e.g. precipitation and temperature) derived from global climate change models beyond the year 2100 is extremely large (Collins et al. 2013). Given the influence of climate change on pit lake water quality and chemistry, some modelers implicitly assume an exponential relationship between model uncertainty and model duration beyond the period of measured input data. This limitation creates a paradox where the perceived duration required for decision making frequently exceeds the duration of reliable predictions by several centuries.

One simple approach involves lowering the required prediction period to decades or to one century, provided that additional modelling becomes required at the end of this duration. Another pragmatic approach for addressing this paradox is to simulate a range of scenarios for every pit lake to understand, to the best of our current ability, the sensitivities of the overall system to the likely range of variability in future precipitation and evaporation. Even using the multiple scenario approach, a more realistic model end date should be applied commensurate with the known error and limitations of the input data. A prediction is only as strong as its weakest input assumption. At any rate, the model predictions should not be taken as gospel but instead should be used to support an adaptive management or resilience plan for long-term mine closure.

Consider the Value of Pit Lakes as Future Water Resources during Permitting

While beneficial end uses may be achievable in many closure landscapes and regions, pit lakes may impose environmental costs that extend to regional aquifers. For instance, in the case of future mines proposed in arid regions, the combination of groundwater discharge and net evaporation could perpetually deplete or degrade regional groundwater resources.

Cost benefit analysis, in consideration of the overall mining and mine closure life cycle, may inform whether the value of mineral extraction outweighs the potential depletion of future water resources through the formation of pit lakes. To this end, regulators should understand (1) whether future pit lakes (individually and cumulatively) will become perpetual sinks on aquifers that are valuable resources to future generations; and (2) whether salinization is also a risk to maintenance of these values, within the pit lake and in affected aquifers. In doing so, future water resources beyond the pit lake itself can be factored into public-interest decisions.

Require Closure Costing and Bonding Commensurate to Closure Risks

The terminology used to return pit lake ownership to the government varies with country and jurisdiction, and may be called abandonment, bond return, certification, institutional control, relinquishment, or walk-away closure. In the process, the mining company is released of all financial and legal obligations related to the mine site, and any posted bonds or bond insurance policies are returned or cancelled following this designation by regulators. Any residual risk–known or unknown but not nil–is thereby transferred to the general public.

The liability associated with the safe closure of orphaned or abandoned mines has generally fallen back to the public through government ownership. The cost to appropriately close an individual mine site may run from tens of thousands to over a billion dollars in terms of social and environmental mitigation (APEC 2018). Poorly designed pit lakes can present a significant rehabilitation cost due to the substantial risks they present (Younger 2002). Closure assurances (i.e. bonds or insurance policies) are therefore often required to ensure that finances will be available to rehabilitate disturbed mining areas should they not be closed in the manner agreed with regulators (IGF 2013). The value set for these assurances are informed by closure cost estimates.

Although some jurisdictions require bonds as part of mine approvals, numerous audits of the bonding schemes and balances have found them to lack sufficient funds to undertake full reclamation if the mining company fails to fulfil its obligations. Many sites globally have been abandoned without remediation and left for the local government to manage in perpetuity. Filled or forming pit lakes feature heavily as liabilities amongst these sites (Johnson and Wright 2003). These bonds may be insufficient to address pit lake risks due to the complexity of addressing pit lake hazards (e.g. unstable high walls). Remediation might require extensive pit reshaping, covering, mitigating PAF wall rock, rapid filling, or even backfilling the open pit. Closure cost estimations must therefore explicitly consider and address (through operational and closure works) the long-term risks that would otherwise encounter financial liability if left untreated. These costs should include water remediation, high wall stabilization, etc. in perpetuity, should this be required.

Conclusions

Although we generally have a good understanding of many pit lake issues and their causes, mine closure planning and execution practices for pit lakes remains poor or unproven. Because pit lakes often pose less immediate risks than above-ground facilities such as waste dumps and tailings dams, they have received lower priority and have generally fallen below the standard of care relative to other mining legacy landforms when it comes to addressing long-term closure risks. However, these risks may increase over time and extend long after the designated "closure period" as pit lakes fill and water quality deteriorates. There is significant scope for improvements in planning, prediction, rehabilitation and remediation, and ongoing pit lake management within the global mining industry and for involving stakeholders in these processes. Besides closing knowledge gaps by research (see Part 1; Schultze et al. (2022)), mining industry and regulatory practices would benefit from the proposed improvements discussed above. Our hope is to transform pit lakes into more acceptable risks and, where practicable, into mining legacies that provide ongoing benefit to our global communities and environments.

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