Key issues in Mine Closure Planning Related to Pit Lakes

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ABSTRACT

Pit lakes form when surface mines close and open pits fill with water, either through groundwater recharge, surface water diversion or active pumping. Historically, the success in closing mines with pit lakes has varied tremendously: there are well known examples of legacy sites requiring perpetual treatment, whereas some other pit lakes have achieved various beneficial end uses. Although access to case studies is often limited, mining companies contemplating new open pit mines have a number of examples in both success and failure from which to draw "lessons learned" that can be used in future mine closure planning.

This paper discusses key issues that should be addressed in the mine planning process to increase the likelihood of successful mine closure. Examples of issues and potential management strategies to address them are given. The key issues examined in this paper include: determining potential risks and beneficial end use opportunities, developing closure objectives and criteria, which may include various water quality, riparian and littoral targets; anticipating and meeting stakeholder and regulator expectations; subaqueous disposal of liquid and solid mine waste; predicting and managing water balances; identifying contaminants of concern; historical reliability of model predictions; mitigating acid mine drainage; the importance of understanding long-term vertical mixing regimes; and health and safety issues.

Keywords: mine pit lakes; sustainability, AMD, closure, planning

INTRODUCTION

Pit lakes form when surface mines close and open pits fill with water, either through passive groundwater recharge, surface water diversion or active pumping. They often display poor water quality through Acid Mine Drainage/Acid and Metalliferous Drainage (AMD). Historically, the success in closing mines with pit lakes has varied tremendously: there are well known examples of legacy sites requiring perpetual treatment, whereas some other pit lakes have achieved various beneficial end uses. Although access to case studies is often limited, mining companies contemplating new open pit mines have a number of examples in both success and failure from which to draw "lessons learned" that can be used in future mine closure planning (Castendyk 2011).

This paper discusses key issues that should be addressed in the mine planning process to increase the likelihood of successful mine closure. Examples of issues and potential management strategies to address them are given with reference to previous experiences in North America, Australia and Asia.

KEY ISSUES

Determining Closure Objectives and Developing Closure Criteria

Discharge criteria applied to pit lakes are site-specific and dependent on the responsible regulatory agency. In most jurisdictions, there are no set guidelines for pit lake discharge. If pit lake water concentrations are below applicable generic water quality guidelines, then water quality would be deemed acceptable, but this will rarely be the case. More likely, site-specific objectives will need to be developed by the proponent of each pit lake. Site-specific objectives can be derived based on effects thresholds, technological limits, background concentrations, or combinations thereof.

Pit lakes are generally expected to be managed as closed-circuit waterbodies until they achieve water quality that will not cause adverse effects to aquatic life, at which time they can be reconnected to the receiving environment. If water quality in the pit lakes is not adequate by the time the lakes fill, active treatment may be required, as well as water diversions around the pit lake.

There are three nested "layers" that can be used to define and gauge success in pit lake closure:

1. **End use –** will the pit lake and associated watershed meet land use requirements for post-closure mine sites that are set regionally and nationally?
2. **Objectives –** will the pit lake meet functional targets that are achievable, desirable to stakeholders and acceptable to regulators?
3. **Criteria –** will the pit lake meet prescriptive criteria, such as site-specific water quality and toxicological thresholds?

There are several sources of information that can be used to define success, such as:

- Corporate sustainability goals and targets (MMSD 2002);
- Commitments made by the mining company in environmental impact assessments (EIAs) and other applications, which include commitments made by previous property owners;
- Numerical predictions that have been generated in EIAs and that have been used in ecological risk assessments;

- Stakeholder expectations;
- Regulatory requirements (Jones and McCullough 2011);
- Analogue lake studies (Van Etten et al. 2014);
- Observed water quality from existing pit lakes in similar geologic deposits (Johnson and Castendyk 2012)
- Leading, international mining-industry practice; and
- Prescriptive, site-specific objectives that are based on biological thresholds and ecological risk assessments.

The importance of developing closure criteria for pit lakes early in the planning process cannot be overstated, because all mine closure design and mitigation should be directed toward meeting these criteria.

Anticipating and Meeting Stakeholder and Regulator Expectations

As with the other components of mine operation and closure, all stakeholders should be identified early and consulted for their input on end of mine life quality and objectives, including objectives for pit lakes (Swanson 2011). Early engagement of stakeholders can lead to constructive input into the planning of pit lakes, reduced costs, fewer delays, and overall public/stakeholder/regulator acceptance.

Design for pit lakes is typically done by involving engineers and scientists, but not stakeholders (Swanson 2011). It is recommended to consult stakeholders on visions for pit lakes and potential beneficial end uses of pit lakes (McCullough and Lund 2006). Participation by communities in developing mine remediation targets leads to better decisions, and in some cases to lower overall costs for mine remediation (NOAMI 2003). This is because the major stakeholders were involved from the beginning in decisions that could affect their enjoyment/use of the landscape. Information presented to communities on pit lake predictions can be complex, and thus information should be presented in an easy-to-understand format in order to engage the stakeholders in constructive discussions (NOAMI 2003).

Predicting and Managing Water Balances

The time to refill pit lakes is site-specific and must be determined on a case-by-case basis. In cases with high rates of evaporation or highly permeable aquifers, the pit lakes can refill in a few years. In arid regions, some pit lakes will never refill passively, and are termed “terminal” pit lakes (McCullough et al. 2013) because they act as a groundwater sink. While not ideal, such lakes may be used as mitigation to prevent contaminated groundwater from migrating away from a mine site. In terminal lakes, evaporation is the only route through which water leaves a pit lake, so it can be expected (and readily predicted with mass balance models) that concentrations of solutes will increase over time (Castendyk and Eary 2009; Geller et al. 2013a). The ultimate concentrations may be controlled by solubility, which can be predicted using geochemical software.

In the sub-Arctic region of Canada, where net evaporation is low, it is expected that pit lakes will refill passively, but it is preferable to accelerate the filling process to reduce the closure management period. This option should be evaluated as part of the closure planning process, in consideration of regional surface hydrology and availability of water to be used for filling.

Connection of the pit lake to surrounding groundwater sources can play a large role in the water quality and hydrological cycle/budget of the pit lake; if a pit lake water surface is above the water table, water will flow out of the pit to the groundwater and thus provide a pathway to transport potential contaminants to a larger area (Castendyk and Eary 2009).

Understanding Long-term Vertical Mixing Regimes

Compared to natural lakes, pit lakes are more prone to become meromictic (lower layers non-mixing) because they generally have smaller surface areas, larger depths and higher salinities. Vertical mixing in lakes is primarily driven by wind currents across the lake surface, and the smaller fetch of pit lakes provides less opportunity to translate wind energy into water currents that are necessary for lake turn-over.

In pit lakes, as in natural lakes, the frequency and depth of vertical mixing will affect many other variables. These parameters must be defined in advance of developing geochemical predictions of water quality so that accurate volumes for epilimnion, hypolimnion, and monimolimnion layers can be accurately represented and mixed at appropriate intervals. Vertical mixing transports oxygen to the lower portion of the lake, which in turn affects biological and chemical reactions. For example, oxidation state influences the mobilization of metals and cycling of nutrients. Of particular importance is the potential effect of oxidation state on sulfide minerals; under oxidizing conditions, sulfide minerals will react to form sulfuric acid and dissolved metals, whereas under reducing conditions, sulfide minerals will precipitate – a process that has been used to mitigate AMD in meromictic pit lakes (Pelletier et al. 2009). Given the influence of vertical mixing on these processes, the anticipated mixing behavior of a pit lake should be evaluated and understood as early as possible in the mine planning process.

There are a variety of guidelines that describe lake geometries that will affect lake mixing. The most common is the relative depth, defined as the maximum depth as a percentage of mean diameter. Natural lakes usually have relative depths of less than 2%, whereas pit lakes typically have relative depths of 10 to 40% (Doyle and Runnels 1997). While measures such as relative depth provide useful descriptors of pit geometries, they are not predictive measures because they do not account for other important variables, such as water density and wind speed. The most reliable method for predicting lake mixing is through the use of numerical models (such as CE-QUAL-W2 or DYRESM) that mechanistically account for these variables.

Identifying Contaminants of Concern

There are a wide range of contaminants of concern (COCs) in pit lakes. The most common COCs in hardrock pit lakes are low pH and elevated element concentrations caused by acidic mine drainage (AMD). AMD is a phenomenon that occurs when sulfur-bearing waste rock, tailings or other materials are weathered during mining and mine closure practices. Weathering of sulfide minerals can lead to release of acid and elevated concentrations of contaminants in runoff, groundwater or pit lake water. These acidic waters often carry a high load of elements that are more soluble at low pH. AMD is commonly associated with coal and hard rock mines

The COCs at a given mine are often, but not always, related to an obvious source such as the ore body or extraction chemicals. For example, the Berkeley Pit Lake in Montana, which is perhaps the most famous "worst-case" example of a pit lake, is a former copper mine pit that now contains levels of copper, zinc, and iron that exceed water quality guidelines by orders of magnitude (Gammons and Duaime 2006). Similar contamination has been observed at copper mines in California (Levy et al. 1997) and Sweden (Ramstedt et al. 2003).

Long-term water quality in a pit lake can be influenced by hydrochemical processes such as geoenvironmental characteristics, water balance, mineral solubility, and sediment biogeochemical processes (Geller et al. 2013a). Constituents that most often exceed guidelines are copper, cadmium, lead, mercury, nickel and zinc, followed by arsenic, sulfate, and cyanide (Kuipers et al. 2006). Blasting residues such as ammonia and nitrate are also often elevated in mine waters, and may persist into closure (Banks et al. 1997). In sub-Arctic Canadian mines, salinity and major ions are typical COCs (Environment Canada 2012) because of saline groundwater that must be dewatered for mining. The saline groundwater may be disposed of in pit lakes, or saline groundwater may flow passively into pit lakes at closure when dewatering ceases. In oil sands pit lakes, the COCs are primarily organic constituents such as naphthenic acids, phenolics and polycyclic aromatic hydrocarbons originating from process waters and tailings (CEMA 2012).

Less obvious COCs may be present as well. For example, at the proposed Gahcho Kué Diamond Mine (De Beers 2012), geochemical testing of pilot plant tailings identified phosphorus as a COC, which led to changes in the closure plan to mitigate runoff from mine wastes and to avoid eutrophication of closure waterbodies. Total suspended solids can be expected to be elevated during the early years of lake development, before vegetation becomes established in the littoral zone, but this should be a temporary phenomenon in a properly designed pit lake.

In summary, while there may be obvious COCs at a given mine, a full suite of metals, major ions, nutrients and organics should be evaluated to determine site-specific COCs prior to mine development.

Mitigating Acid and Metalliferous Drainage (AMD)

Poor water quality degraded by AMD is the single biggest environmental risk and cause of beneficial end use loss for pit lakes (McCullough 2008). Mine drainage may be acidic, neutral or even alkaline as constituents such as metals and metalloids may be in elevated concentrations in all. Once begun, the process of AMD is very difficult to stop. Hence, the emphasis on AMD management should always be first on preventing weathering of potentially acid generating (PAG) materials by exposure to water and oxygen (Castendyk and Webster-Brown 2007). This process begins by long-term geochemical characterization of all materials that may contact pit lake water or water sources including above ground sources, such as waste rock dumps and tailings impoundments, and below ground sources, such as backfill and fractured geologies.

Disposal of PAG materials above the water table is usually best suited to arid climates where AMD production will be limited by water availability. However, a strategy often considered to reduce pit lake AMD issues is subaqueous disposal of PAG occurring in tailings, waste risk and pit shell exposures (Dowling et al. 2004). However, subaqueous disposal of waste should not be thought of as a singular solution to PAG management. Rather it is merely one consideration of a broader closure strategy that, when used appropriately and in certain circumstances, may reduce AMD production and long-term environmental and social liability.

Where AMD has not been prevented, a number of active and passive treatments are available, although all of these treatments should be considered requiring ongoing attention and maintenance (Gammons et al. 2009; Geller et al. 2013b; Younger and Wolkersdorfer 2004). Active treatments may be simple limestone or lime putty additions to treat acidity, although the ongoing cost, particularly in remote areas once mine infrastructure is closed should not be under-estimated. The economic liability to the remaining responsible jurisdiction is likely to exceed the economic benefit from mining with a few generations of treatment, which is why active treatment is only typically sought when there is a risk of off-site contamination exposure to social or environmental receptors.

Passive treatments may range from strategic catchment-scale diversions of inflows to attenuate and dilute pit lake waters (McCullough and Schultze 2015) to initial or ongoing treatment with biologically active materials such as nutrients and organic matter (Kumar et al. 2011).

Subaqueous Disposal of Liquid and Solid Mine Waste

The option to dispose of mine waste in pit lakes is often attractive to mining companies because it is more cost effective than other treatment or disposal technologies. Disposal of mine waste in pit lakes is an accepted practice in some industries and regions (Davé 2009; Dowling et al. 2004; Schultze et al. 2011). However, it is controversial and considered unproven until demonstrated at the field scale in the oil sands industry (OSTC 2012). If successful, several other companies in the region will likely apply water-capped tailings technology with a potential savings of billions of dollars for the industry as a whole compared to other disposal technologies. Deep pit disposal of fine tailings has also been approved for the diamond mining industry in Northern Canada (De Beers 2012).

If subaqueous disposal of tailings are contemplated, the following issues should be evaluated to reduce risks to closure water quality:

- **Tailings resuspension** – a hydrodynamic analysis should be completed to understand the potential for resuspension of fine particles, and the formation of buoyant plumes;
- **Metal leaching and AMD** – geochemical testing should be completed to predict the potential for acid generation and metal leaching, and to understand which oxidation state would minimize these effects on water quality; and
- **Sediment toxicity** – standard bioassays should be conducted to predict the toxicity to benthic organisms.

Health and Safety Issues

The most significant acute health and safety risks for persons in and around pit lakes relate to falls and drowning. Pit lake highwalls may often be unstable, particularly following rebounding groundwater pore pressures and decades of wave action. Unstable walls frequently result in slips that may endanger nearby structures and persons near the highwall (McCullough and Lund 2006). Where communities reside nearby, pit lakes may present risks for recreational swimmers where there is a risk of drowning with the steep lake margin typically of pit lake edges or by falls from high walls into water or submerged obstacles that have not been regraded (Ross and McCullough 2011).

Chronic health risks are not well understood, but there is potential for health issues for recreational users in AMD contaminated pit lake water; even in remote areas where pit lakes may be used as recreational opportunities. Low pH and elevated contaminant concentrations may lead to skin and eye damage and irritation, particularly for regular exposures in vulnerable groups such as children and the elderly (Hinwood et al. 2012).

There are also human health risks where end uses include fisheries; either planned or unplanned. Aquatic ecosystem foodchains have been found to accumulate contaminants such as selenium, mercury and cadmium. These metals bioconcentrate in keystone predator sportsfish and crustacea (McCullough et al. 2009b; Miller et al. 2013).

Historical Reliability of Model Predictions

The reliability and accuracy of mine water predictions was examined by Kuipers et al. (2006) in a comparison of water quality predictions made in environmental impact statements to operational water quality observed at hardrock mines. The mines that were examined included major mines across the Western USA, but the issues they identified are applicable to mines worldwide. They found that in the majority of cases, water quality predictions did not perform well, and impacts were often underestimated. They identified three main causes for the discrepancies:

- **Inadequate hydrologic characterization** – inaccuracies arose from overestimating dilution potential, poor characterization of the hydrologic regime and poor flood forecasting.
- **Inadequate geochemical characterization –** inaccuracies arose from inadequate sampling of geologic materials, lack of proper geochemical testing of materials such as metal leaching and AMD potential and improper application of test results to models.
- **Mitigation failure –** in many cases, mitigation was assumed to reduce concentrations, but the mitigation was either not effective or not implemented.

Although poor water quality prediction performance has been found at hardrock mines, present and future pit lake modelling efforts should be able to improve upon this record. Success in predicting water quality will be reliant on following leading modelling practices that were not adhered to in many of the case studies in Kuipers et al. (2006). Guidance for predicting pit lake water quality is provided in a companion document by Maest et al. (2005) as well as by Vandenberg et al. (2011).

In particular, a post-audit of water quality predictions is essential (Dunbar 2013) for identifying excursions from predictions early in the mine life and applying adaptive management strategies as soon as possible. Post-audits of modelling predictions should be available to stakeholders, reviewed by regulators, and ideally, disseminated to the wider modelling community so that they can learn from the strengths and weaknesses of past experiences and continually improve their methods.

CONCLUSIONS

Pit lakes are highly variable systems with a wide range of outcomes observed worldwide in terms of chemical characteristics and suitability for aquatic habitat. While there are examples of very unsuccessful pit lakes, these serve as "lessons learned" that can be followed to increase the likelihood of success in constructing future pit lakes (Castendyk 2011). The most important lessons learned are to develop a conceptual model of the pit lake and understand its processes as early as possible; engage stakeholders early in the process; begin environmental monitoring at the exploration stage and conduct a post-audit of predictions to guide adaptive management (Castendyk 2011; Gammons et al. 2009).

The key issues described above should be considered in each of the planning, designing, commissioning, and abandonment stages of a pit lake. The outcome of a decision made or an assessment completed during a previous stage of development may be found to be incorrect or no longer valid as environmental data or stakeholder or regulator requirements evolve. Or, the pit lake and its inflows may be altered by changing mine plans or mine closure plans in response to fluctuating commodity prices. Consequently, mining companies should anticipate an iterative process whereby assumptions and decisions are refined to reduce uncertainty related to the issues above. This may involve reconsidering options and revisiting strategies discounted earlier under different circumstances such as understanding of the physico-chemical context and of regulatory and other social constraints and expectations. This iterative process of pit lake closure planning refinement should form an explicit part of mine closure planning for the broader site (McCullough et al. 2009a).

Guidance manuals (e.g., CEMA 2012; McCullough 2011) and compilations of pit lake experiences and research (Castendyk and Eary 2009; Gammons et al. 2009; Geller et al. 2013a) have been developed in the past five years, and these should be consulted throughout the planning, design, and construction process for additional details.

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