TECHNICAL COMMUNICATION

The future direction of pit lakes: part 1, Research needs

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Abstract

Pit lakes are common features of open pit mining and can present significant risks, and yet can also provide beneficial end use opportunities. Many processes that influence the magnitude of these risks and opportunities remains poorly understood, which presents a challenge to pit lake closure and management. In this two-part manuscript, four pit lake subject matter experts from Germany, Canada, Australia, and the USA recommend focus areas for researchers (Part 1) and strategies to structurally improve the practice of pit lake closure for mining industry regulators and corporate sustainability officers (Part 2). In this Part 1, we recommend nine research areas, organized by order of physico-chemical and ecological complexity, where greater understanding of fundamental pit lake processes would lead to improved pit lake management and reuse. Our intent is to guide the direction of emerging and future pit lake research by academic and industry research teams, with funding and oversight from industry and government.

Keywords Sustainability · Expert commentary · Hydrology · Geochemistry · Ecology · Socio-economy

Introduction

Pit lakes remain as final landforms of the post-mining landscape in many instances of open pit mining, also called cut mining and surface mining. Depending on the country and local vernacular, these legacies may also be known as mine pit lakes, mine lakes, void lakes, or end pit lakes.

Poorly planned pit lakes often present risks to the environment and human health and safety (Doupé and Lymbery 2005; Hinwood et al. 2012), such as slope instability, drowning, entrapment, falls hazards, and poor water quality (McCullough and Lund 2006). Poor water quality may result from: (i) the action of acidic and metalliferous drainage (AMD) with low pH and/or elevated contaminant concentrations associated with sulfide mineral oxidation, (ii) the addition of neutral or basic mine drainage with elevated concentrations of contaminants (e.g. Se, As), which are mobile at neutral to basic pH, (iii) saline conditions resulting from evapoconcentration, and/or, (iv) elevated nitrogenous concentrations as toxicants and nutrients from dissolution of blasting agents. Conversely, pit lakes that are well-planned and managed have the potential to become beneficial end use resources. Such end uses include ecological reserves, recreation areas, water supplies for irrigation or stock water, reservoirs for cooling water and energy production, and treatment facilities for contaminated mine water (McCullough et al. 2020).

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Over the past four decades, pit lake research has evolved from isolated single-discipline studies (e.g. Campbell and Lind 1969; King et al. 1974; Parsons 1964; Stundl 1937) to a more integrated and multidisciplinary field. To mitigate or prevent risks and proactively plan for beneficial end uses, an interdisciplinary understanding of many aspects of pit lakes including geology, hydrogeology, hydrology, hydrodynamics, inorganic geochemistry, microbial ecology, biogeochemistry, ecology (avian, aquatic and terrestrial), mining engineering, socioeconomic aspects, and the many dynamic relationships among these disciplines is required. Several recent research compilations outline the state of knowledge and best practices for pit lake monitoring, numerical modelling, and management. However, data gaps exist in fundamental aspects of pit lakes to advance the ecologically and socially sustainable closure practices mandated by companies and their stakeholders (Castendyk and Eary 2009; Gammons et al. 2009; Geller et al. 2013; McCullough 2011; Oldham 2014; Vandenberg and McCullough 2017).

In this Part 1 of a two-part series, we highlight key knowledge gaps and future research needs associated with the long-term closure of metal and coal mine pits. Although mining associated with other resources (e.g. oil sands, aggregate) may also generate pit lakes, metal and coal mine deposit types comprise most of the pit lakes that require substantial rehabilitation efforts due to acidification by relatively high sulfide mineral concentrations associated with their geologies (Eary and Castendyk 2013; Friese et al. 2013). In contrast, sand, gravel and other aggregate pit lakes typically have low sulfide content and are more benign in terms of water chemistry (Matern et al. 2019; Søndergaard et al. 2018), and are not considered herein. Oil sands pit lakes comprise unique organic chemical compositions relative to other pit lakes (Dompierre et al. 2016; Morandi et al. 2020) and are therefore also not explicitly considered herein. That said, many of the data gaps and study needs identified here are relevant to the aggregate and oil sands industries.

The authors of this paper represent a cross-section of experienced pit lake researchers, managers, and mine closure planners from around the world (Germany, Canada, Australia, and USA) who have worked in and across academia, government, and private industry. Based on our collective experiences of ≈ 100 years of practice and relevant literature, we discuss nine topics of pit lakes that we believe constitute key data gaps. For each area, we then identify potential paths forward to address research needs or open research questions. The intent of this paper is to provide a catalyst for researchers and funding agencies by identifying the research topics that would be most useful for advancing pit lake understanding and generating successful end uses. Our hope is to transform pit lakes into post-mining assets with acceptable risks, which become beneficial to our global cultures and environments, and which promote industry's social license to mine.

Key Research Needs

Understanding Interactions between Pit Lakes and Groundwater

The typically high connectivity between pit lakes and groundwater is a particular property that distinguishes pit lakes from other lake types (Brown and Trott 2014). Pit lakes are too young and often too oligotrophic to have accumulated thick, sealing layers of organic sediment along the pit floor (although as discussed in Part 2 (Vandenberg et al. 2022), disposed tailings can serve this purpose), and pit walls often cut deeply into alluvial aquifers and fractured bedrock. Metalliferous ore bodies are often located along geologic structures that form preferential flow paths for regional groundwater. In addition, blasting used in the mining process often generates fractures that may penetrate several meters into the pit wall, resulting in a "damaged rock zone" with a notably higher hydraulic conductivity relative to the interior host rock. Pit lakes in former lignite mines in Europe (e.g. Schultze et al. 2013b; Widera 2016) and Australia (Varma 2002) often intersect multiple stratigraphic units containing alternating layers of aquifers and aquitards, such that the pits form vertical connections between one or more aquifers. In contrast to the thick layers of sediment or impermeable bedrock that often form aquitards at the benthic floor of natural lakes, pit lakes generally lack such a benthic layer and are well connected to adjacent aquifers. Even artificial water bodies such as reservoirs are often sealed with engineered materials to minimize seepage losses or are located in low groundwater transmittivity sediments. The broad catchment area of many natural lakes and constructed reservoirs also supplies fine grained sediments to a reservoir, the deposition of which will slowly decrease the hydraulic conductivity of the benthic layer over time. Pit lakes typically have relatively smaller catchment areas and may show little change in benthic-layer thickness or flow properties over time. How these factors and processes affect short and long-term pit lake-groundwater interactions remains unclear.

The long-term pit lake water balance is critical to understanding many risks that a pit lake can pose to downgradient streams, lakes, and aquifers. The steady-state water level defines the final watershed area, the amount of aerially-exposed, sulfidic wall rock, and the area of the riparian and littoral zones. These factors directly affect mine closure planning (Sánchez-España et al. 2014; Werner et al. 2001).

Despite its importance, little research has been undertaken on the fundamental interactions between pit lakes and groundwater (Neumann et al. 2013; Seebach et al. 2010), and several issues related to these interactions remain poorly understood (Oldham et al. 2019), such as:

- How long will it take to form a low-hydraulic-conductivity, benthic layer that reduces hydraulic connectivity to adjacent aquifers? How will any materials placed into the pit void alter groundwater interaction locations and flow rates? This question is particularly pertinent to pit lakes that will contain mine waste or will be used as a treatment site for contaminated water or tailings.
- Where does groundwater enter and leave the pit lake–in the upper layers (e.g. the epilimnion), or in the deeper layers (e.g. the hypolimnion or monimolimnion)? What is the density (e.g. temperature and salinity) and chemical load of groundwater entering the lake with respect to receiving water layers within the lake? Both topics directly influence the physical (e.g. well mixed vs. perennially stratified) and chemical (e.g. redox conditions) state of the lake.
- How do groundwater inflow and outflow rates change over time in response to the rising cone-of-depression plus climate-driven variations in the regional water table? Are there seasonal changes in discharge intensity and/or the position (vertical and spatial) of groundwater exchange?
- What are the flow paths of the groundwater (into and out of the pit) and what are the residence times in different aquifers present along these flow paths? The flow path is particularly important where there are karst systems (Lee 1996), sulfide-rich, acid-generating aquifers upgradient of the filling pit (Schafer et al. 2020), or fractured bedrock or other aquifers with high hydraulic heterogeneity and anisotropy.

These questions are very relevant for developing sustainable planning and long-term management of pit lakes for both hydrogeological and water quality aspects (McCullough et al. 2011). As an example, the use of pit lakes for sub-aqueous mine waste disposal (discussed in Part 2; Vandenberg et al. 2022) may present risks to downgradient aquifers without a better understanding of the interaction between disposed waste, its pore water, and groundwater discharge as a function of pit lake elevation. In some cases, study methods are already available (Lewandowski et al. 2015; Rosenberry et al. 2015; Vandenberg et al. 2016). Detailed field investigations need to be conducted, and hydrogeological and limnological studies should be coupled to better estimate the effect of hydrogeology on lake physics, mixing and water quality.

Defining the Role of Pit Lakes Within the Hydrology and Geochemistry of Watersheds

Pit lakes are fundamental components of the post-mining landscape. Hydrologic and hydrogeologic processes (e.g. surface and groundwater flows and evaporation) (Younger 2002), biogeochemical processes (e.g. mobilization, transport, precipitation, or decay of chemicals) and ecological processes (e.g. wildlife feeding and breeding habitat) (Lund et al. 2013) can all continue past the pit void perimeter into the broader catchment and post-mining landscape. Where pit lakes infrequently intercept regional surface waters, they can contribute or diminish flows in these natural waterways (McCullough 2021). Similarly, where pit lakes more commonly intercept groundwaters, these resources may also be depleted as either through-flow or as terminal sinks (McCullough et al. 2013). Such terminal sinks may be used beneficially to intercept contaminated groundwater, but at the expense of regional aquifer recharge.

Currently, pit lake research still presents gaps as to which physico-chemical processes are essential to broader landscape connections, in particular, how can pit lake closure planning mitigate risks associated with these processes? For instance, how do catchment water inflows influence long-term pit lake quality (McCullough et al. 2012; McCullough and Schultze 2018), both in terms of long-term geochemical evolution and more poignantly in terms of remediation of poor water quality?

As a corollary, the influence of pit lake discharges on regional surface and ground water quality remains complex due to the interaction of AMD-derived elements (e.g. Fe, Al, trace metals/metalloids) with organic compounds. Additional complexity may result from eutrophication mediated by microbial processes (Kumar et al. 2016; Junge and Schultze 2016; Schultze et al. 2013b).

Quantification of these bio-geochemical processes is challenging but often still necessary for informed decision making. Similarly, the biogeochemical interactions along flow paths in the post-mining landscape and downstream mainly requires improved modelling instruments.

Evaluating the Role of Microorganisms in Contaminant Removal

The important role of microorganisms in biogeochemical processes like pyrite oxidation and sulfate reduction, and the relevance of these processes for water quality in mining-influenced water bodies has been well known for many decades. However, many details of specific reactions performed by specific microorganisms are still not yet well understood, e.g.:

- Why do benthic phototrophs precipitate hydrozincite well in one location but not in another, although all basic conditions are the same? Are the formed minerals stable over time, or will they be dissolved again by later microbial activity, such as decay of organic matter, including the remaining biomass of the above-mentioned autotrophs?
- What are the typical (net) rates of sulfate reduction in aquifers and pit lake sediments that can be used to predict self-neutralization (Opitz et al. 2020; Sienkiewicz and Gąsiorowski 2017), and how can we estimate them reliably for mine closure planning?
- What general characteristics of organic compounds lend themselves to pit lake sulfate reduction amendments (Neculita et al. 2007)?
- How does temperature influence microbially-mediated remediation processes? Are processes faster in warmer and slower in colder temperatures to such a degree that cold-climate pit lakes may not be remediated by microbial processes (Luek et al. 2017)?
- Are intermediate sulfide compounds, thiosulfates, a product of incomplete oxidation or incomplete reduction, and what is the role of microbes in these reactions?
- When adding a labile carbon source to a pit lake for the purpose of stimulating sulfate reduction, what is the best strategy to anticipate and minimize hydrogen sulfide gas production?
- Do inoculants accelerate remediation initiation rates or provide a more optimal microbial community?

Fundamental mechanistic understanding is needed to apply microbial contaminant removal at large scales. While an engineering approach may argue for an "if you build it, they will come" approach to microbes, detailed understanding of how to produce the right physicochemical conditions to generate a microbial ecosystem that targets specific contaminants would surely yield more predictable and reliable treatment.

In studies of in-situ treatment options, the question of longevity typically remains unanswered. If the constituents of concern are precipitated or adsorbed onto mineral surfaces, will they remain stably bound, or will they be released from sediment when conditions are no longer artificially manipulated? After treatments conclude, can sustained catchment loading maintain the necessary redox conditions?

In many experimental systems, nutrients are added to pit lakes to promote algae growth and uptake of metals. In these cases, is there a danger of irreversibly eutrophying a lake (Axler et al. 1998; Kumar et al. 2016)?

Assessing Ecotoxicology and Biomagnification

The effect of microbiota on pit lake water quality, particularly under eutrophic conditions, has been reasonably well studied across a variety of scales in recent years (Wen et al. 2015). However, risks of pit lake water quality to both microbiological communities and higher organisms is much less well understood, including the effects of biomagnification within and beyond the pit lakes, e.g. by piscivorous birds or mammals (McCullough and Vandenberg 2020). Such risk studies are largely limited to screening-level assessments of pit lake water ecotoxicology (McCullough and Sturgess 2020; Nicholson et al. 2013). There remains little information on how contaminant mixtures might interact to increase or decrease toxicity, including the role of pH, e.g. through metal speciation (Neil et al. 2009). In particular, there is little information on the effects of mining-derived mixtures of hardness, salinity, and sulfate toxicity (Mooney et al. 2020; van Dam et al. 2014).

Assessing the Value of Littoral and Riparian Zones

Although catchment vegetation is known to be important to the ecological functioning of pit lakes, substantial gaps remain regarding benefits to native and other representative biotic measures of regional diversity and ecosystem function, such as riparian vegetation (van Etten 2011). This is especially true for pit lake catchments receiving contributions from significant lotic systems (Lund et al. 2013). The relative importance of riparian and littoral communities to broader catchment vegetation is, nevertheless, not well understood (Lund and McCullough 2011; Lund et al. 2013). How riparian and littoral vegetation adapt to pit lake water quality issues such as low pH, elevated contaminant concentrations, or salinity is also a complication for many pit lake ecosystems compared to natural systems where communities have evolved alongside ambient conditions (Bylak et al. 2019; Luek and Rasmussen 2017).

The littoral zone of lakes is an essential habitat for many species and for the entire lake ecosystem. It is the lake compartment with the highest biodiversity (Vadeboncoeur et al. 2011). Together with the riparian zone, it forms an ecotonal bridge between aquatic and terrestrial ecosystems (Lund et al. 2013). Furthermore, the littoral zone is the location of important biogeochemical processes (Kleeberg et al. 2006). However, many pit lakes have high relative depth (Schultze et al. 2013a) and only a small littoral zone. There is very little research on the role and importance of the littoral and the riparian zone of pit lakes, leaving many open questions like:

- What are the essential processes occurring in the littoral and riparian zone for both the pit lake ecosystem and the

ecosystem of the post-mining landscape, and do these processes require essential species to be present?

- What are the typical time scales for establishing these keystone species? Do these essential species need to be supported within the remediation process, and what is the potential for natural succession to create a fully functioning community?
- Do riparian zones of pit lakes have similar potential of buffering inputs of contaminants from neighboring contaminated sites (e.g. leaking tailings ponds) as known for the transport of nutrients from agricultural areas into streams (Cole et al. 2020)?
- If unmined land is to be converted to littoral zone to support a pit lake, is it worth the cost, effort and loss of terrestrial resources?
- Is there a general principal for optimal size (or percentage of lake surface area) of the littoral and riparian zones for fulfilling their ecological role and/or accelerating lake closure? Do other general principles for natural lake morphology and hypsography, e.g. pertaining to euphotic depth, hold for pit lakes?

While various 'rules of thumb' proportions have been proposed for the littoral zone, there is little fundamental science underpinning these proportions. Emulating a natural analog lake environment is an ideal objective, but is rarely feasible within the post-mining landscape.

Understanding the functioning and roles of the littoral and riparian zones is essential for proper design of the final shape of the pit lake basin and its vicinity. Inclusion of littoral and riparian zones also has implications for safety, e.g. landslide prevention. Due to the engineering practicality and cost limitations imposed by material handling for pit void rehabilitation, such changes should be considered early in the mine planning process.

Determining the Influence of Pit Lakes on Post-mining Ecosystems

Ecologically, the values of pit lakes to regional biodiversity and ecological sustainability are not well understood, and quantitative knowledge on the interaction of terrestrial and aquatic organisms within pit lakes is virtually absent, except for some toxicological studies. This topic still requires more fundamental research.

Nutrient cycling in pit lakes is often different from natural lake analogues in terms of the many differences of: pit lake shape; percentage of vegetated area and role of vegetation within the broader watershed; the aforementioned hydrologic/hydrogeologic connections; residual mine chemistry; and ecological especially microbial (e.g. planktonic ecology) colonization (Yokom et al. 1997). Pits may initially have excess dissolved reactive nitrogen due to blasting residuals, but little dissolved organic carbon or dissolved reactive phosphorous due to relatively small catchments and geochemical precipitation processes. How nutrients are imported, transformed, stored, or exported from pit lakes is poorly understood. In particular, the individual and combined roles of iron and sulfur may dictate carbon cycling more so than phosphorus and nitrogen, even under eutrophic conditions (McCullough and Lund 2011; Wendt-Potthoff et al. 2012).

Will the sediments of a pit lake act as a sink or as a source and will this reservoir be stable over time? Poorly known details of the flow paths can often be decisive, and can be strongly influenced by hydrological processes and limnophysical conditions (i.e. meromixis vs. holomixis).

There are exceptional opportunities for research on ecological succession processes and for providing controlled sanctuary environments for conservation of endangered aquatic species within pit lakes that are barely realized (D'Souza et al. 2004; Galeotti et al. 2010; Lewin et al. 2015). These ecosystems may approximate natural analogs, or may be substantially different and novel ecosystems (McCullough and van Etten 2011; van Etten et al. 2014). In either case, they may meet equally valid end uses, e.g. an engineered upper trophic level as aquaculture with top-down repercussions to the rest of the pit lake food web. Although initial ecological successions in pit lakes may be quite fast, several years of research is still required, including multi-year field studies, because of seasonality and inter-annual variability of weather, hydrological, and other conditions, and since many species have generation times of several years.

The role of ecological corridors (continuous vegetation or waterways as connections) in facilitating colonization is not well understood, particularly in terms of how founder communities might accelerate pit lake ecosystem development. Deliberate introductions of fish as top-down predators may also be important for low-productivity pit lakes, especially under different nutrient regimes (Peterka and Kubečka 2011; Peterka et al. 2011).

Furthermore, substantial gaps remain regarding benefits to native and other representative biotic measures of regional diversity and ecosystem function (Younger et al. 2004). "Pit lake districts" (more than 10 pit lakes within a limited area) are known from Australia, Canada, Czech Republic, Germany, Poland, and the USA (Brenner et al. 1987; McCullough and van Etten 2011; Twaroski and Segroves 2011). However, what percentage of the lakes has to have good water quality to support a desired ecosystem in the surrounding landscape, and which percentage can remain as poor water quality without adversely affecting the broader landscape ecosystem? Some pit lakes show trends

of passively self-remediating over long time-scales (Opitz et al. 2020; Sienkiewicz and Gąsiorowski 2017), but are we as society prepared to wait that long? As such, this basic ecological question is also a socio-economic one (see further below).

Predicting the Effects of Climate Change on Pit Lakes

Climate change can influence pit lakes in three predominant ways: (i) alteration of pit lake water balance with changes in precipitation, evaporation, and inflow rates; (ii) altered biogeochemical reaction rates; and (iii) change in how pit lakes interact with surrounding terrestrial ecosystems. Climate change may alter median events but also their variability, including their greatest magnitude, e.g. annual exceedance probability. The first two contribute importantly as source terms to the management issue of water balance and water quality prediction. However, pit lake predictions often do not consider how these source terms will be influenced by climate change. Nonetheless, rather than simply amending empirical model input parameters, an understanding is also required of how and why sensitive hydrological processes and biogeochemical reaction rates are influenced by broader climate change. This understanding should exist not only with researchers, but also with mine planners and industry consultants. As discussed further in Part 2 (Vandenberg et al. 2022), achieving this may require that regulators impose expectations that mining permits and/or closure certifications must consider the effects of climate change in long-term pit lake predictions.

Advancing Pit Lake Models

In addition to climate change, many variables that are important to mine closure can only be predicted using numerical models. Mine closure planning typically requires the use of several interconnected models to forecast future water quality conditions (Castendyk et al. 2015; Vandenberg et al. 2011). The general approach begins with a projection of meteorology, hydrogeological conditions, and pit geometry at the end of operations. A groundwater and hydrologic model are generated, and ideally a solute transport model is coupled with these where there is significant risk of contaminant transport away from the pit lake. Geochemical models are applied to the lake itself, but are typically not coupled with advective groundwater flow models. Such coupling needs to become the standard but still requires research and development (Vieira Soares and do Carmo Calijuri 2021).

Many pit lake predictions assume fully-mixed conditions throughout the water column. This assumption is virtually always invalid, as most waterbodies deeper than ≈5 m stratify, even if only seasonally, due to external climatic conditions. Pit lakes are especially prone to meromixis (i.e. perennial stratification) owing to their depth, wind sheltering provided by pit walls, and their likelihood of containing elevated solutes that can produce vertical differences in water density (Schultze et al. 2017; Vandenberg and McCullough 2017). Stratification often causes deeper layers to become anoxic (Boland and Padovan 2002). As such, the water chemistry and colonization by organisms will be profoundly affected by vertical changes in redox conditions as well as differential hydrogeologic flow paths interacting with different vertical layers.

Modern limnological pit lake predictions incorporate hydrodynamic models prior to geochemical modelling to explore the depth of mixing and stratification on a seasonal basis (Oldham et al. 2009; Vandenberg et al. 2016). Such models consider the density of inflowing fluids, the geometry of the pit, and daily wind speeds and temperatures, which can all lead to stratification or mixing (Salmon et al. 2017).

Hydrogeochemists use laboratory results from static and kinetic tests to define the representative water quality input for each source (e.g. pit wall runoff, talus, groundwater, and drainage from other mine features) (Castendyk et al. 2015). These inputs are normally assumed to release a constant concentration or constant load to the pit lake over time. Alternatively, kinetic reaction rates may be used to change inflow concentrations over time, such as a concentration decrease caused by the leaching of soluble minerals, or a concentration increase as sulfide minerals begin to oxidize. Using geochemical equilibrium software (Parkhurst and Appelo 2013), inflow waters from a given time step are mixed at representative proportions. The final solution is brought into geochemical equilibrium with selected oversaturated minerals allowed to precipitate, and select undersaturated minerals allowed to dissolve. In some models, trace elements may be allowed to adsorb to or desorb onto the surface of fresh ferrous hydrous oxide minerals, such as ferrihydrite. The water quality and pH at the end of these reactions are considered to be the water quality of the pit lake at the end of a given time step.

One of the largest gaps in the practice of pit lake prediction is the lack of a user-friendly, transparent, and unified hydrodynamic-geochemical software capable of simultaneously predicting lake physics (stratification) and chemistry (water quality). Although some coupled models exist (Dunbar 2013; Hipsey et al. 2019; Mueller 2021; Prakash et al. 2015; Salmon et al. 2017), they are either: (1) difficult to apply and require extensive datasets and budget, or (2) proprietary with source codes and assumptions that cannot be third-party evaluated. Freely available, easy-to-use software, such as PHREEQC (geochemistry) and

CE-QUAL-W2 (physics) have allowed these tools to be widely applied to pit lakes, so modelers and reviewers alike are familiar with their functionality and limitations. However, a knowledge barrier remains that practically restricts many practitioners to using one or the other of these types of models. The development of a free, unified physical-chemical model would also ensure that fundamental processes are not ignored or omitted during empirical modelling.

Conducting Socio-economic Studies on End-use Opportunities

In recent years, pit lakes and artificial water bodies have been increasingly described as ecologically, socially, and economically valuable (Brinker et al. 2011; Koschorreck et al. 2020; McCullough et al. 2009a; McCullough et al. 2020; Seelen et al. 2021). For example, like other artificial water bodies, pit lakes can sometimes provide an ecological habitat that is relatively rare in densely populated countries or in arid regions. Such water bodies are often valuable even for common aquatic species (McCullough et al. 2009b; Seelen et al. 2021). Pit lakes may also provide sites for diverse recreational activities (McCullough and Lund 2006; Stephensen and Castendyk 2019; Williams et al. 2020) and may even provide a hub for new tourist destinations, as in the eastern part of Germany (Deshaies 2020; Kühn 2014; Wirth and Lintz 2006). With existing connectivity to electrical networks and an industrial area, another possible use for pit lakes is electrical power generation and/or the use of the pit water for cooling. This potential should stimulate interest in research questions surrounding end-use opportunities.

Pit lakes that develop in arid or water-stressed regions may have higher value for uses such as ecological reserves and recreational areas (McCullough and van Etten 2011). At the opposite extreme, the value of unimpacted groundwater may be many times higher than the value of the impacted water, such that pits may be perpetually pumped to supply fresh water for agriculture or domestic water supplies rather than allowing this water to evaporate and/or evapo-concentrate. Several data gaps exist in the evaluation of proposed mines in arid regions, and we anticipate that future mine permitting processes will evaluate multiple alternative water uses, such as the value of lake water lost to evaporation against the value of groundwater stored in an undisturbed aquifer and usable by future populations.

Of course, there are also risks related to the use of pit lakes. The effect of mine legacies on human health has been poorly understood (Noronha 2004). The influence of poor water quality on users of pit lakes remains a little understood concept, particularly because water quality differs so markedly from that considered by contact guidelines (constituents, mixtures, and concentration ranges) (Hinwood et al. 2012). In addition, the pit walls present significant physical risks from instability, such as shoreline/highwall erosion (McCullough et al. 2019), frequent rockfalls, seismic waves (McCullough and Diaz 2020), and occasional landslides. The probability of these hazards tends to increase as the water table rebounds and hydrostatic pressures within pit walls increase. These physical hazards alone can limit opportunities for post-mining human access and use. Nonetheless, there are some outstanding examples of pit reclamation and reuse that provide incentive for future study (Stephensen and Castendyk 2019).

Therefore, many aspects of pit lake evaluation are still under debate, and there is a lack of data, understanding, and instruments to quantify "objectively" the value of a certain pit lake. Studies on the socio-economic aspects of pit lake formation and use are just beginning (D'Souza et al. 2004; Hähnel 2016). As for lakes in general, quantifying the economic value of pit lakes is still challenging (Börger et al. 2021; O'Sullivan 2005). Data to quantify the intensity of pit lake use, such as numbers of visitors, frequency and length of overnight stays, or fishing success are rarely collected and hard to find if existent. Equally, studies on the value or pit lakes as commercial resources is also only in its infancy (D'Souza et al. 2004). Comprehensive monitoring and research are needed to develop instruments into an interdisciplinary approach including engineers, limnologists, terrestrial ecologists, architects, sociologists, and economists.

Conclusions

All of these topics merit promotion of pit lake research, but requires action and investment by the mining industry and regulatory authorities. Funding of the research is needed, and data should be made available for research. Accumulated knowledge and experiences from private research need to be published as well. Part 2 (Vandenberg et al. 2022) of this series provides some options on how to implement these requirements.

While we have generated many important and actionable insights over the past 4 decades, but many gaps exist in our knowledge of pit lake development and long-term outcomes. These gaps provide opportunities for a high degree of both breadth and depth in pit lake research. We hope that this article stimulates interest in additional pit lake research and helps identify key topics that must be resolved to achieve these outcomes.

Similarly, there are gaps in management practices that can be remedied at a corporate level, by practitioners and by regulators, as we will address in Part 2 (Vandenberg et al. 2022) of this series.

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