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Pit lakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities

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Pit lakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities

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The impact of large-scale mining on the landscape is a permanent legacy of industrialisation and unique to the Anthropocene. Thousands of lakes created from the flooding of abandoned open-cut mines occur across every inhabited continent and many of these lakes are toxic, posing risks to adjacent communities and ecosystems. Sustainable plans to improve water quality and biodiversity in 'pit lakes' do not exist due to: (1) confusion as to the ultimate use of these lakes, (2) involvement of ecologists only after the lake is filled and (3) pit lake ecology struggling to reach the primary literature. An integrated approach to pit lake management engages ecologists in pit lake design, prioritising ecological progress and passive treatment in mine closure planning, ultimately empowering communities with post-mining options.

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Introduction

At approximately pH 2.6, Berkeley Pit Lake in the US state of Montana is one of the largest accumulations of toxic mine water in the world [1]. Currently over 244 m deep and still filling, the lake contains such 'extreme' concentrations of heavy metals (e.g., 0.15 g L^{-1} copper, 0.6 g L^{-1} zinc, 1 g L^{-1} iron) [2] that from 2003 to 2012, copper was mined from the lake waters itself [1]. When the lake fills to a 'critical' water level, it will contaminate aquifers and streams adjacent to the residential areas of the town of Butte. The US Environmental Protection Agency has mandated that lake water must never reach critical level, and as no *in situ* treatments are currently proposed, the water must be actively pumped out and treated in perpetuity (i.e., 'active treatment'). Pit lakes, such as Berkeley and other similar examples (e.g., Rum Jungle in Australia and the Alberta oil sands in Canada), generate fear in local communities [3], leading these water bodies to be aptly described as 'giant cups of poison' [4].

Pit lakes form when open-cut mining operations cease and the remaining pit fills with ground, surface and rain water. Mine pits, and therefore pit lakes, tend to have high depth-to-surface-area ratios with relatively flat bottoms and steep sides in order to minimise resource extraction costs (n.b., for the purposes of this review we are focussing on large mineral/coal mining pits as in Figure 1, rather than gravel pits formed in fluvial settings). Fuelled by increasing demands for resources, pit sizes have increased over time as resource extraction technologies become more sophisticated and able to operate at larger scales (e.g., the modern Bingham Canyon Copper Mine, Utah is approximately 970 m deep, whereas early 20th century coal strip mines in the USA were only 1–5 m deep [see 5]). The morphologies of most modern mine pit lakes resemble those of asteroid [6] or crater lakes (e.g., Crater Lake in Oregon, Figure 1), rather than co-occurring lakes which tend to be shallower and more nutrient-rich. Water quality varies among pit lakes as a function of surrounding geology and catchment interaction (e.g., connection to groundwater and rivers, riparian vegetation, mine discharge) and so covers the full spectrum from alkaline to acidic, fresh to saline, and toxic to non-toxic [7]. Many ore-bearing landscapes are rich in sulfides (particularly FeS_2); when mining exposes these materials to water and air, oxidation is accelerated to produce acidity, which in turn leaches metals from surrounding rocks, creating acid mine drainage (AMD, as in the Berkeley Pit, above). By virtue of their size and potential interaction with the wider catchment through ground-water and surface-water outflows, pit lakes can have substantial environmental impact [8,9].

Mine closure planning (MCP) has been progressively introduced worldwide in an attempt to reduce the likelihood of environmental disasters (such as Berkeley Pit) occurring at the end of mining [10]. Mine 'closure' is the process of transferring responsibility for mined lands from the mining company back to the state. In order for the state to accept the land, it imposes environmental and

Figure 1

Mine pit lakes are similar to natural crater lakes with steep, mobile banks, little vegetation, and small catchments. **(a)** Pingualuit meteorite impact crater in Nunavik, Quebec, Canada (*Photo: PD/NASA*), **(b)** Crater Lake, Oregon (*Photo: GFDL/Zainub Razvi/2006*), **(c)** Highland Valley Copper pit lake (BC, Canada), **(d)** gold mine-pit lake in Laverton, Western Australia, **(e)** maar district, Daun, Germany *(Photo: CC BY-SA 3.0/Martin Schildgen)*, **(f)** lignite pit lake district, Lusatia, Germany *(Photo: PD/Peter Radke/2008).*

safety criteria on the company that must be met in accordance with state and/or national legislation, which varies world-wide [see 11]. Where pit lakes occur near populated areas, communities can serve a vital role in the MCP process by helping to define the ultimate use of the pit lake and surrounds. Pit lakes, while posing risks to a catchment, can also have significant benefits if remediated, providing space for recreation and environmental amenity, as well as alternative industries (e.g., tourism, aquaculture, irrigation) that allow small towns to survive economically after the mining ends [12].

However, changes in the economy can result in mines being abandoned without rehabilitation [13], and the increasing size of pit lakes coupled with the cost means that the filling in of pit lakes is unlikely to occur (n.b., the Surface Mining Control and Reclamation Act virtually stopped coal pit lake formation in the United States [14]. However, these were shallow strip mines (as described above) — cheaper to fill than modern mines). Pit lakes may occur alone in the landscape or in 'districts' (Figure 1), resulting in large-scale challenges for planners (i.e., Collie, Australia [15], West Bengal, India [16] and Lusatia, Germany [17]). Although MCP can reduce the likelihood of pit lakes forming, the extant lakes are a current legacy and new pit lakes will inevitably be created across all inhabited continents.

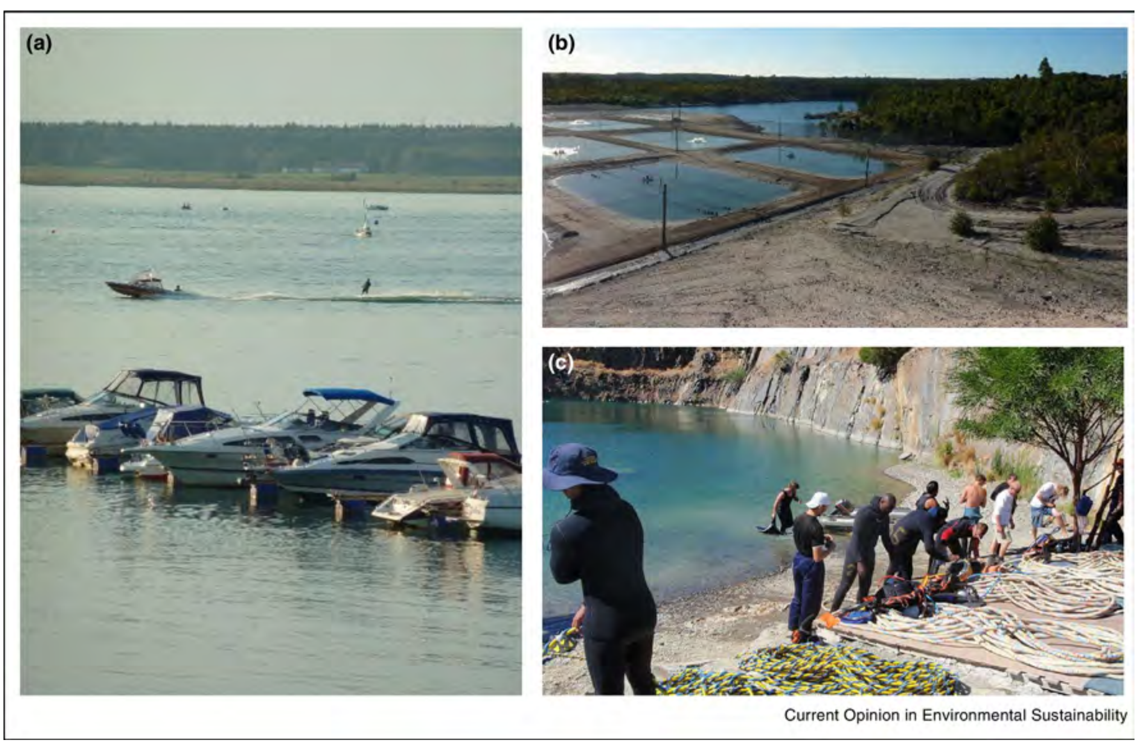
We contend that pit lakes pose unique environmental sustainability challenges because (1) there is often no clear vision as to the ultimate use of these lakes, (2) pit lake planning and design typically excludes ecologists, increasing the complexity of rehabilitation and restricting provision of ecosystem services and (3) pit lake ecology (theory and application) has struggled to find a foothold in mainstream literature, limiting scientific exposure to the issue of pit lakes and holding back advancement of the development of remediation and closure approaches. The current barrier to achieving sustainable pit lake ecosystems lies with our limited application of ecological successional approaches to enhance passive remediation of water quality and provide ecosystem services. Currently, MCP is dominated by geological, hydrological and limnological modelling which prioritises physico-chemical conditions. Unfortunately the emphasis on the physical and chemical design of the pit lake leads to highly engineered environments that run counter to ecologists' understanding of the need for diverse microhabitats and landscape connectivity necessary for ecosystem development. We contend that a truly integrated approach to sustainable MCP would involve ecologists at the pit lake design stage to negotiate necessary trade-offs between the physical, chemical and ecological aspects of closure, leading to positive outcomes for the community.

Closing pit lakes

Historically, the rehabilitation of pit lakes has frequently remained in the 'too hard' basket, with lakes locked away, either mandated for 'perpetual' treatment (i.e., active treatment) or expected to meet unrealistic legislative requirements (e.g., that pit lakes exist in 'similar condition' to naturally co-occurring lakes). However, there are a range of options for 'beneficial' uses of pit lakes, such as conservation, aquaculture, irrigation, recreation, storage of harmful substances (e.g., tailings) and water supply [12] (Figure 2). The pit lake district of Lusatia (Germany) is currently being developed for public recreation, and is projected to contribute an estimated €10–16 M annually to the local economy [18]. Each end use for pit lakes carries its own risk to environment and human health, and in South-western Australia, wildlife conservation was considered to be lowest risk and irrigation the highest [19]. Essentially, stakeholders will have to decide if more favourable outcomes can be achieved by prioritising some ecosystem services over others; all of these services are unlikely to be simultaneously maximised. Trade-offs will occur (potentially in a dynamic fashion) as lakes respond to changing biophysical conditions [see 20].

Once the end use is agreed upon by stakeholders, it is necessary to set closure criteria and the steps required to achieve it. Water quality closure targets are usually viewed through the lens of possible risk to the wider catchment through lake decant (discharge), attempting to address community concerns about threats to drinking water, agricultural land, and environmental amenity. Therefore, legislation relies heavily on pit lakes meeting local riverine water quality guidelines, regardless of whether adjacent natural waterways achieve similar standards. We suggest that the use of water quality targets

Figure 2



Examples of beneficial end uses for pit lakes **(a)** active recreation in Lusatia, Germany, **(b)** aquaculture of Marron (large crustacean) in Collie, Australia, **(c)** Commercial diver training at Blue Rock Quarry, Gordon's Bay, South Africa (*Photo: CC BY-SA 3.0/Peter Southwood/2009*).

alone for successful closure of pit lakes tend to favour 'in perpetuity' active treatment solutions, where technology is relied upon to remove contaminants from waste water discharges. Current *in situ* treatment options are expensive and unsustainable, being broadly limited to active interventions (e.g., liming of acid waters [7], pumping and treatment (as in Berkeley Pit, above), or *in situ* bioreactors [as in Island Copper Mine, Canada; [21]. It is naïve to expect private companies or governments to maintain these expensive and risky treatments indefinitely.

Another current approach is to compare the pit lakes to a desired 'reference' water body, although the challenge with this method is determining what should be a reasonable reference for a pit lake (a crater lake?) and then how similar the pit lake has to be to the reference to be acceptable for closure [see 22•]. Even where water quality is very similar, the morphological differences among pit lakes and co-occurring lakes create significant differences in biological communities despite rehabilitation [23,24•]. Further, expecting a large pit lake to approximate the qualities of co-occurring natural lakes (a common closure requirement) often makes no sense, particularly in light of the variability found among co-occurring natural lakes [see 25], especially when many pit lakes occur in arid environments. Essentially, the physical parameters for closure success are entirely arbitrary.

The broader conundrum for miners and regulators is how to close large toxic pit lakes in a way that matches community expectations. Until recently (e.g.), simply fencing off an area has been used as a closure technique in inland Australia. This 'lock-and-leave' approach not only does not address the underlying water quality issues in large, toxic lakes, it also creates community safety issues [see 12]. There are examples of pit lakes improving over time using the lock-and-leave approach, eventually becoming publically-valued recreation spaces [particularly in the coal-strip lakes of the US mid-west — e.g., [26]]. Essentially, these were 'natural passive treatment systems.' However, in contrast to the aforementioned large, toxic pit lakes, these improved coal-strip lakes were shallow (1–2 m), less toxic, and had larger catchments, resulting in significant inputs of terrestrial organic matter and propagules from naturally co-occurring wetlands (important for lake development — see below). Tellingly, this development towards improved water quality and ecosystem services indicates that pit lakes are subject to the same ecological and biophysical processes present in natural lakes. Therefore, we venture that a new pit lake (even a large, potentially toxic lake) is simply a lake that has the potential to evolve into a self-sustaining ecosystem and fulfil community expectations of an attractive, useful, bio-diverse water body [sensu 27].

Pit lakes are also difficult to 'classify,' (and therefore, legislate to particular closure standards) with each lake presenting a unique suite of biophysical characteristics. Rather than grouping pit lakes based on defined characteristics, potentially a more useful way to view any one pit lake is as inhabiting a point along a sliding scale of interacting factors that increases the complexity of rehabilitation, and where ecosystem services become increasingly limited. These factors could be (e.g.): water quality, catchment interaction (as described above), size, location (climate, geology), morphology, hydrology, or water depth affecting limnological processes [see 28]. For example, a very large, highly toxic lake, prone to frequent cyclones with acidic groundwater incursion may be at the 'difficult/lower ecosystem service' end of the scale, whereas a small, pH-neutral lake in an area with high community investment for recreation in a forested area (i.e., high catchment interaction via leaf litter input) may be considered 'easier/higher ecosystem service.' Ecologists integrated into the MCP design phase would consider these bio-physical variables as the template for ecosystem development in passive treatment (see below).

Using ecology to bring sustainability to pit lakes

Research into the ecology of pit lakes has been mostly limited to cataloguing aquatic taxa and measuring rates of primary production in response to simple nutrient additions, particularly in meso-cosm and microcosm studies [see 7,29•]. Published studies on pit lake ecology (and pit lakes in general) tend to appear in the 'grey' literature (such as conference proceedings or technical reports) or peer-reviewed mining industry journals, as seen in this review. Essentially, the current body of pit lake research, while important for understanding these systems, has yet to fully engage ecological theory to improve long-term environmental outcomes. Established principles from the field of restoration ecology can potentially remove barriers to the evolution of pit lakes, and potentially give communities, miners and regulators new, more meaningful criteria to demonstrate when a pit lake can be considered a safe (and potentially useful) aspect of the landscape.

Tantalising glimpses into 'passive' processes that might enhance ecosystem development in pit lakes have been shown for artificial wetlands connected to a river supplying propagules, allochthonous carbon and other nutrients [30]. Pit lakes have demonstrated capacity for ecosystem development indicating that they can behave as artificial wetlands or natural water bodies [see 31,32••]. The steep, highly mobile banks and absence of fringing/riparian vegetation characteristic of many pit lakes (Figure 1) create an aquatic 'desert,' starving the lake of nutrients and habitat complexity. Similar to the sculpting of terrestrial spoil piles to approximate local landforms, we suggest that pits should be sculpted to match the critical components of natural lakes, namely the formation of littoral areas and integrated catchments. Littoral zones in natural wetlands are biodiverse, spatially complex, and contain increased levels of dissolved oxygen and organic matter relative to the rest of the water body [see 33]. Designing gently sloping banks with a variety of depths creates heterogeneous edges (the littoral zones) to receive inputs of terrestrial organic matter from the wider catchment. Landscape contouring can also extend beyond the lake shoreline to facilitate passive input of allochthonous carbon (e.g., leaf litter). The connection of pit lakes to natural watercourses such as rivers — while potentially risky for adjacent ecosystems — provides the lake with a larger catchment as well as much-needed propagules [34] and nutrients [35].

Adding organic material and promoting sustained aquatic biomass growth allows pit lakes to act as sinks for atmospheric CO_2. Pit lakes with high levels of sulfates (from AMD) inhibit bacterial methanogenesis, preventing them from emitting methane [36]. Low oxygen conditions common in deeper pit lake waters will enhance the carbon sink, essentially incorporating the activities of a major economic sector to mitigate the effects of CO_2 emissions [see 36,37].

In most water bodies, carbon availability generally increases over time, leading to more complex ecosystems [34], yet in pit lakes, this often does not occur due to acidic conditions with nutrients binding to pit substrata which limits primary productivity [38,39]. Large inputs of nutrients are often required to support primary production in pit lakes [40] (although eutrophication may be a risk in pH-neutral pit lakes), and sustaining these improved conditions using 'traditional' active nutrient treatment is problematic. For example, iron-ore pit lakes in the US state of Minnesota were converted to aquaculture facilities, resulting in eutrophication from increased levels of phosphorous, although within 18 months of aquaculture cessation (and elimination of the phosphorous source) the lakes had returned to pre-aquaculture conditions [41].

Regression after nutrient addition, limited responses to low levels of nutrient additions [42], and the importance of catchment and in-lake vegetation to the development of P cycles [43] suggest that sustained ecosystem development in pit lakes is a challenge yet to be solved by ecologists. If post-mining ecosystem services were as important as resource extraction, an integrated management program would see ecologists involved in the pit design process even before ground is broken on a new project. However, once the resource is extracted to maximise safety and profit, ecologists can still provide advice about landscape sculpting (as above) to maximise ecosystem development and sustainable provision of ecosystem services.

Conclusion: designing sustainable lakes through collaboration

A focus on ecosystem development in pit lakes could provide a consensus point among stakeholders, allowing mining companies to close land while satisfying community demand for stricter environmental standards. In practice, however, collaboration between ecologists and the mining industry may be challenging. When ecologists eschew the mining industry, the opportunity for beneficial, pioneering research is lost. However, in order for this relationship to be viable, mining companies must recognise shared intellectual property [sensu 44]. The main priority for companies with mine lakes is achieving closure requirements; ecologists can provide the expertise to influence ecosystems and mitigate environmental damage. For ecologists, extreme problems may require extreme solutions, with the collaboration allowing researchers to perform large-scale *in situ* manipulative experiments that would not be socially or environmentally acceptable in other systems [see 7,45].

Even if fossil fuels were to become obsolete, the materials for building solar panels, wind farms, sustainable homes and computers must still be obtained through mining. Therefore, the creation of new pit lakes is inevitable. Collaboration and greater expansion of pit lake science into the primary literature will clear the pathway for addressing a significant legacy of the Anthropocene — the manner in which we have fuelled our civilization through mining, and the resulting effects on our communities and landscapes.

We suggest that integrating ecologists into the pit lake design process will introduce ecological development and passive treatment into mine closure planning, providing the framework for improving the quality of pit lakes, and delivering beneficial community and environmental outcomes. Ultimately, the solution to how these lakes will be safely returned to the community as sustainable ecosystems will only be realised under an integrated approach.

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