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Mark A. Lund
Edith Cowan University

Melanie L. Blanchette
Edith Cowan University

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Closing pit lakes as aquatic ecosystems: Risk, reality, and future uses

Mark A. Lund | **Melanie L. Blanchette**

Mine Water and Environment Research Centre (MiWER), Edith Cowan University, Joondalup, Western Australia, Australia

Correspondence
Melanie L. Blanchette, Mine Water and Environment Research Centre (MiWER), Edith Cowan University, 270 Joondalup Dr, Joondalup, WA 6027, Australia.
Email: m.blanchette@ecu.edu.au

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Abstract

Mine pit lakes are formed when open-cut pits flood with water, and these lakes occur by the thousands on every inhabited continent. The remediation and closure of pit lakes is a pressing issue for sustainable development and provision of freshwater ecosystem services. While pit lakes can be spectacular examples of recreation and renewal, pit lakes may be better known for their poor water qualities and risks to communities and the environment. Often the public wants to simply "fill the pits in" to restore a terrestrial landscape, but this is not always possible. Therefore, planning for remediation and future uses is likely to provide the best outcome. Poor water quality is not necessarily a barrier to future use, although it may limit the number of uses. Short-term future uses tend to require commercial viability, active infrastructure investment, and maintenance, and should transition to complementary long-term uses that promote biodiversity. Long-term future uses require relatively less ongoing maintenance beyond the initial investment and adhere to the principles that pit lakes should be safe, sustainable, and non-polluting in perpetuity. Pit lakes will eventually develop "ecosystem values," and the time to do so depends on the nature of the intervention and the values ascribed by the community. Where possible, closing pit lakes as sustainable ecosystems is the most realistic goal that permits a variety of future uses that is likely to see pit lakes valued by future generations.

This article is categorized under:
Engineering Water > Planning Water
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Human Water > Water as Imagined and Represented

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anthropocene, ecological restoration, mine closure, novel ecosystem, post-industrial society

1 | INTRODUCTION TO PIT LAKES: NEW INLAND SEAS

Water is integral to every aspect of the modern mining process. Humanity depends upon mining, and the technical and social importance of "mine water" to civilization cannot be overemphasized (Younger et al., 2002). Surface mining creates open cut voids; in the mid-1800's, shallow coal-strip mines were created in the United States using horse-drawn scrapers (Gibb & Evans, 1978). As mining technology has advanced, these voids have become larger and deeper such as the Bingham Canyon Mine in Utah (USA) (3.3 km width, 1.3 km depth [Bakken et al., 2020]).

All mines eventually close, whether for economic, legal, social, political, or catastrophic reasons. Mine pit lakes (hereafter referred to as "pit lakes") are by-products of open cut mining operations and form when the mining stops. Pit lakes are created after active removal of pit water (dewatering) ceases and the open void is filled with rainfall, catchment runoff, and groundwater. While not all mine voids are destined to become pit lakes, all pit lakes are formed by mining. In this article, we focus on large mineral and coal mining pits (rather than gravel pits or quarries) which tend to have high depth-to-surface area ratios, steep sides, and flat benthic surfaces. The natural analogues of pit lakes are volcanic or impact crater lakes (Blanchette & Lund, 2016), with their often deep waters, reduced catchment size and steep, rocky banks (Figure 1). Pit lakes can occur in arid regions where natural lakes are unlikely to exist, and when filled, create new inland seas.

Thousands of pit lakes are present on every inhabited continent, although the exact number is unknown and difficult to determine (Castendyk & Eary, 2009). One of the greatest negative legacies of pit lakes is their potential to contaminate ground and surface waters due to poor water quality (Younger & Wolkersdorfer, 2004). When pit lakes occur near communities, environmental issues can exacerbate the tensions of economic downturn at the end of local mining operations (Pérez-Sindín & Blanchette, 2020). Pit lakes have been sensationally described as "giant cups of poison" (Woodbury, 1998), containing a "foul brew" (Robbins, 2016). Fear of pit lakes (Kean, 2009) is heightened during incidents involving charismatic animals, such as the thousands of snow geese that died on the acidic and metalliferous Berkeley Pit in Montana (Robbins, 2016).

The United Nations (UN) has identified water—it's quality, access, assessment, and conservation—as priorities for sustainable development (United Nations Environment Program, 2016; United Nations General Assembly, 2018). While the impacts of mining on natural waterways were considered by the UN's global water assessment program (United Nations Environment Program, 2016), it is unclear how pit lakes factor into this overall plan. Global loss of wetlands due to direct human activity was estimated to be from 30% (Hu et al., 2017) to 50% (Davidson, 2014), which may be compounded by the threats to wetland ecosystem services by climate change (Green & Alcorlo et al., 2017; Janse et al., 2019). Efforts to recognize the anthropogenic creation of surface waters are increasing (Saulnier-Talbot & Lavoie, 2018), and pit lakes with neutral water quality may have a place in mitigating the loss of natural wetlands. Despite their substantial environmental and cultural impact, pit lakes are often ignored by the wider scientific community (Bernasconi et al., 2022; Blanchette & Lund, 2020; Talento et al., 2020).

Mine closure planning is the process of addressing the impacts of mining before it ends and is a deliberate strategy to provide long-term solutions for ecosystems and communities. Many pit lakes have been abandoned due to company collapse and legal dispute and responsibility falls to the state. These lakes will never have a closure plan, existing in various states from "dangerous" to "benign" but may provide ancillary social and ecological benefits. The remediation and closure of pit lakes is a pressing issue for sustainable development and the provision of freshwater ecosystem services. Pit lakes are waterbodies subject to the same chemical and ecological processes as natural lakes, although a shift in thinking is required when considering pit lake remediation. For example, excess nutrients are universally considered a threat to lakes (United Nations Environment Program, 2016), but appropriate nutrient inputs may be required or desirable if pit lakes are to be closed as aquatic ecosystems (King et al., 1974; Luek et al., 2017; Lund et al., 2020; Martin et al., 2003).

Ultimately, pit lake closure is underpinned by risk: who pays for the remediation, the initial state of the lake and surrounds, the regulatory framework, and the political and community will for achieving a particular "end use." Many ideal visions of pit lake use have been proposed, and spectacular examples of pit lake use have been achieved, yet many proposals are impractical, expensive, and most importantly, inappropriate for the location. Pit lakes with "neutral" water qualities, whether naturally or by remediation (Benthaus et al., 2020), are important sites of culture and recreation. In Germany, pit lakes have become the centerpieces of family holidays and environmental renewal (Weber, 2020). Companies and states are unlikely to accept liability for risky, aspirational, or limited end uses, and regulators are more likely to approve closure plans with multiple uses (Dept. of Mines and Petroleum and Environmental Protection Agency, 2015).

In this article, we assess pit lake closure and future uses from a practical standpoint, focusing on the risks and options available. We use the term "future uses" rather than the more established term "beneficial end use"

FIGURE 1 Mine pit lakes are morphologically like natural crater lakes with steep banks 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) abandoned gold pit lake (near Granny Smith Mine), 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). Figure first appeared in Blanchette and Lund (2016) and is republished under Elsevier Open Access.

(e.g., Doupé & Lymbery, 2005; McCullough et al., 2020) because a desired end use is by nature "beneficial." We do not review the socio-political aspects of pit lake closure, but recognize they are critical to closure success (Pérez-Sindín & Blanchette, 2020; Rogers et al., 2013; Rosa et al., 2020; Svobodova et al., 2021). We suggest that in most cases, closing pit lakes as aquatic ecosystems is the most realistic goal that permits a variety of future uses in the short- and long-terms. Focusing on the practical issues around pit lake creation and closure allows a realistic assessment of repurposing pit lakes for delivering ecosystem services and benefits to communities.

2 | CANNOT WE JUST FILL IN ALL THE PITS?

The public is often confused as to why open-cut pits are simply not "filled in with dirt" after the mining stops (see Campbell, 2016) to rehabilitate the land. Mountains of waste rock (overburden) are created during open-cut mining next to the growing pit (Figure 2). The United States Surface Mining Control and Reclamation Act (1977) has been used as an argument both within and outside the US to mandate backfilling of voids and prevent the formation of pit lakes (Walters, 2016). However, the reality of open-cut mining is that many voids, both old and new, will not be backfilled because the process is impractical, expensive, causes stakeholder financial conflict (Castrilli, 2010; Macey & Salovaara, 2019), prevents further mining and does not guarantee an improved environmental outcome.

Open-cut mining permanently changes aquifers and natural watercourses because active pumping and river diversions are normally required to access ore (Doley & Audet, 2013; Flatley & Markham, 2021). Therefore, backfilling is not simply "putting the dirt back in" but a complex and potentially dangerous activity requiring careful attention to water bodies that may be contaminated by acid mine drainage (AMD) or salinity (Fanning et al., 2017; Geldenhuis & Bell, 1998; Nordstrom et al., 2015). Backfill can be highly porous and transmit water as subsurface flow or act as an "anthropogenic aquifer," discharging water offsite into existing natural aquifers or emerging as springs (Cánovas et al., 2018; Younger et al., 2002). Europe backfilled pits with municipal waste, although in 1999 the European Union Landfill Directive largely ended the practice due to fears around contamination of groundwater (Younger & Mayes, 2015).

Given the scale of new mines, backfilling is economically expensive (nearly a billion US dollars to fill one open-cut pit; Walters, 2016) and uses heavy machinery for a prolonged time that creates dust, noise, emissions, and in turn consumes resources. Overburden may have naturally rehabilitated into native forest ecosystems after many decades (Figure 3) to become valued by communities (Campbell, 2016; van der Plank et al., 2016). Further, re-establishing a pre-mining environment will never be truly possible due to irreversible changes in physico-chemical conditions (Cooke & Johnson, 2002; Gwenzi, 2021; Hobbs et al., 2009; Ross et al., 2021).

Therefore, the answer to the question of "can't we just fill in all the pits?" is a resounding "no." While careful planning and available funds may facilitate the partial or complete backfill of many potential pit lakes, thousands of voids (and therefore, pit lakes) will continue to occur on every inhabited continent in greater numbers.

FIGURE 2 The open-cut mining process creates mountains of overburden (background). Re-filling the pit requires extensive dewatering and earthmoving. Photo by M. Lund, 2004, Western Australia.

FIGURE 3 Natural forest growth on overburden after the end of lignite mining in the 1940s, Western Australia (WA). (L) forested overburden behind pit lake, (R) overburden slope showing leaf litter, understory and canopy vegetation commensurate with native Jarrah forest. Photos by M. Lund, 2003.

3 | RISKS OF PIT LAKES

Pit lakes pose a variety of risks to communities and catchments due to water quality, void morphology, and location. Toxicity to aquatic and terrestrial animals, groundwater and surface water contamination, salinization, groundwater drawdown, outflow groundwater mixing, drowning risks, and disease reservoirs were initially identified as the main risks of pit lakes (McCullough & Lund, 2006). More recent studies have identified risks such as radioactivity (Manjón et al., 2013; Manjón et al., 2019; Mantero et al., 2020), watercourse “flow-throughs” (Lund et al., 2018), build-up of gasses (Boehrer et al., 2016; Sánchez-España, Yusta, & Boehrer, 2020), and cyanobacterial blooms (Blanchette & Lund, 2021; Goździejewska et al., 2021). Each pit lake is unique, and depending on future use, requires a tailored approach for delivering ecosystem services and community benefits.

Water toxicity is one of the most well-known risks of pit lakes, particularly due to the potential for discharges to downstream environments (Commander et al., 1994; Newman, Poulson, & McCrea, 2020; Punia et al., 2021). Extremely low pH levels due to AMD is a widespread and well-studied water quality issue in many pit lakes (Blanchette et al., 2019; Gammons & Icopini, 2020; Geller & Schultze, 2013; Sánchez-España, Yusta, Ilin, et al., 2020) and therefore will not be examined further in this article. Toxic waters within the pit lake limit initial aquatic biodiversity (Bylak et al., 2019) and can impact wildlife and stock (Sampson et al., 1996). Bioaccumulation of metals and metalloids in fish can limit opportunities for recreation or aquaculture (Casey & Siwik, 2000; Miller et al., 2013). Elevated levels of uranium radioactivity are a concern in some pit lakes, particularly in Sweden where they are used for recreational activities (Mantero et al., 2020) or where radioactive mine water has been discharged downstream such as in Morocco (Manjón et al., 2019) and Spain (Manjón et al., 2013). When water quality does not support reproduction and biodiversity increase, pit lakes may become “ecological traps,” appearing attractive for biota for egg laying but wasting overall reproductive effort (sensu Sievers et al., 2018).

Saline (predominantly sodium chloride) pit lakes occur in regions with salt-bearing geologies and saline groundwaters (Commander et al., 1994; Hancock et al., 2005) and are exacerbated by evapo-concentration (Eary, 1998; Lund & Blanchette, 2021; Newman, Poulson, & Hanna, 2020). However, natural hyper-saline lakes and wetlands are common in arid regions of the world (e.g., South Africa, Australia, and the southwest USA) and therefore saline pit lakes with neutral pH and low metal concentrations may have unique biological value (Timms, 2018; Williams et al., 1990).

Biological activity, though desirable, can also create water quality issues in pit lakes. As observed in natural lakes, cyanobacteria blooms can create toxicity and amenity problems in pit lakes with circumneutral pH levels (Goździejewska et al., 2021; Lund & Blanchette, 2021). While biological activity is often considered a positive occurrence in acidic lakes for generating alkalinity (Davison, 1987; Geller & Schultze, 2013), undesirable outcomes may occur such as the production of hydrogen sulfide or methane (Boehrer et al., 2016). As in natural lakes, acidic pit lakes have the potential to accumulate gases such as H_2S, CH_4, and NH_3 from microbial activities in the sediments or from the dissolution of carbonates (producing CO_2), leading to dangerous accumulations (Boehrer et al., 2016), and uncontrolled releases (Sánchez-España, Yusta, & Boehrer, 2020).

In addition to water quality, water quantity is a risk associated with pit lakes, particularly in relation to climate change. In a drying climate, filling and maintaining pit lake water levels (see below) can divert water from the rest of the catchment (Lund et al., 2018; Schoenheinz et al., 2011). Further, creating a new lake in a landscape that may otherwise have no surface water (such as an arid lanscape) can cause long-term declines in groundwater, perhaps at an even greater rate than naturally formed lakes (Newman, Poulson, & Hanna, 2020). However, too much water can also be an issue. Pit lakes generally have small catchment sizes; therefore, surface runoff and direct rainfall are unlikely to quickly fill large pits under "normal" rainfall conditions (Lund et al., 2020). However, in regions subject to typhoons and seasonal flooding, large volumes of water entering pit lakes may cause unplanned discharges resulting in infrastructure damage, economic loss, social stress, and downstream water quality changes (Sharma & Franks, 2013).

In the Hunter Valley on Australia's east coast, there are mine pits that will take a thousand years to fill (Australasian Groundwater & Environmental Consultants Pty Ltd, 2012). Connecting pit lakes to the wider catchment using river "flow-throughs" have neutralized extreme pH levels in acidic pit lakes, added beneficial terrestrial nutrients, and more rapidly filled pits (see Grünewald & Uhlmann, 2004; Lund & Blanchette, 2018; McCullough & Schultze, 2018). The main risks of this approach are on the river downstream. In Australia, an intermittently flowing river was connected to an acidic pit lake (Lake Kepwari) formed from open-cut coal mining (Lund et al., 2018, 2019, 2020; Figure 4). Connecting the river to the lake improved lake water quality from pH ≈ 4–7 but impacted the hydrology and water chemistry in the river downstream (Lund & Blanchette, 2018). Lake Kepwari is in a drying Mediterranean climate, and consecutive years of drought could delay or reduce river input and increase the acidity of the lake as well as decrease flow downstream (Lund et al., 2018). While flow-through strategies benefit the lake, connecting intermittent rivers to pit lakes is a potentially risky scenario in a drying climate.

The high walls and steep banks of pits can cause falls and landslides. Steep pit walls are not well-stabilized by water pressure until the lake is full (Schultze et al., 2010), a process that may take hundreds of years. A landslide at Lake Concordia in Nachterstedt, Germany resulted in the loss of several houses and the deaths of three people when a 350 m-long swathe of land suddenly slumped into the pit lake (Graupner, 2009). Landslides in pit lakes can also create hazardous "tsunami" waves such as in the Berkeley Pit, USA in 2013 (Duaime et al., 2014), retroactively calculated to be 3–6 m tall traveling 6–61 $m\ s^{-1}$ (McHugh, 2019). Earth contouring and geotechnical works can ameliorate or reduce the risk above the final water level, however, the cost generally precludes preventative contouring or works below the final level.

Artificial lentic habitats such as reservoirs, wastewater treatment ponds, irrigation channels, and rice paddies may spread water borne diseases (Norris, 2004). Pit lakes may also act as reservoirs for mosquito-borne diseases as well as schistosomiasis and intestinal helminths (Doupé & Lymbery, 2005; McCullough & Lund, 2006). Although mosquitoes are generally absent from waters >10 m deep (Norris, 2004), they may be found in the sheltered backwaters and highly

FIGURE 4 An intermittently flowing river connected to an acidic pit lake (Lake Kepwari) formed from open-cut coal mining in Western Australia (Lund & Blanchette, 2018). Photos by M. L. Blanchette, 2013.

vegetated areas of lakes (Minakawa et al., 2012). In experimental additions of organic material to acidic (pH 3) and metalliferous (Al 27.2, Co 0.30, Mn 1.8, Ni 0.36 all in mg L^{-1}) pit lake waters in outdoor mesocosms, habitats were initially colonized by mosquito larvae until the assemblage was invaded and eventually dominated by predatory invertebrates (Lund & McCullough, 2015).

Each pit lake is unique in the risks it poses to communities and the environment. Pit lake remediation can reduce the risks caused by poor water qualities.

4 | PIT LAKE REMEDIATION

Water quality is not necessarily limiting for future uses. "Acceptable" water quality is defined by intended purpose, ranging from drinking water quality as the "highest" standard to aquatic ecosystems, recreation, irrigation, and agricultural or industrial uses (e.g., ANZECC/ARMCANZ, 2018). The higher the standards met the more versatile the water body for future use, whereas lower standards limit pit lakes to specific uses. Maximum flexibility for future uses around water quality standards might require some form of remediation of the water prior to or as part of the rehabilitation. However, "in perpetuity" active treatments such as liming, "pump-and-treat" or in situ bioreactors (Benthaus et al., 2020; Blanchette & Lund, 2016; Fisher & Lawrence, 2006) only reduce risk until technological advances or nature provide a permanent solution and may be out of reach for remote or developing communities. Where investment is possible (e.g., Anchor Hill Pit Lake, South Dakota, USA, and Island Copper Mine, British Columbia, Canada), lakes may be turned into bioreactors, controlling water quality problems in the short-term (Fisher & Lawrence, 2006; Park et al., 2006).

Some lakes (e.g., Nifty Copper and Tallering Peak Mines, Western Australia) can be converted into terminal sinks, where all inflows are contained within the lake due to high evaporation (McCullough et al., 2013). Terminal sinks theoretically have a very low likelihood of overflow and can be used to collect AMD from the mine site and thereby prevent contaminated flows offsite (McCullough et al., 2013). The terminal sink pit lake, however, remains a potential hazard for future generations.

Rapid fill of a pit lake using pumped river water or river flow-through (as above) can lessen acidification by reducing oxidation of the pit walls that can occur through prolonged natural filling (Salmon et al., 2008). At sites where groundwater is also low in pH, rapid fill with neutral river water can restrict the inflow of acidic groundwater into the pit lake further reducing the acidification of the water column (Grünewald & Uhlmann, 2004).

In situ remediation approaches using organic matter (OM) to reduce acidity have been trialed with mixed results (Brugam & Stahl, 2000; Fisher & Lawrence, 2006; Green & Mather et al., 2017; King et al., 1974; Kumar et al., 2011; Lu & Öhlander, 2005; McCullough et al., 2008; Opitz et al., 2020; Park et al., 2006; Preuss et al., 2007). In the coal pit lake district of Western Australia, a lake with poor water quality (yet the most OM) had higher macroinvertebrate species richness and abundance than lakes with better water qualities and lower levels of OM (Blanchette et al., 2019; Lund et al., 2014). Over the past 50 years, OM studies on pit lakes globally have demonstrated that pit lakes are subject to the same ecological and biophysical processes present in natural lakes (Coe & Schmelz, 1972; King et al., 1974; Opitz et al., 2020; Sienkiewicz & Gąsiorowski, 2016), and even gravel pit lakes with poor water quality have the potential to develop ecosystem services and benefits to communities (Seelen et al., 2021).

Pit lakes will develop "ecosystem values," and the time required to do so depends on the level of intervention (Blanchette & Lund, 2016) and what is considered "valuable" by the community. The method of remediation is guided by level of investment, and political and community will for a future use within the bounds of acceptable risk. We recognize that some pit lakes have water quality and geomorphological profiles where the challenges for improvement are simply too great due to cost or available technologies. The most problematic pit lakes are often historical legacies, as improved handling of potentially acid-forming materials reduce the chances of AMD and associated metals and metalloids (e.g., Abfertiawan & Gautama, 2011). In some instances, the option to continue dewatering and keep the pit dry may be a temporary but useful approach until the problems can be resolved (Parry & Stefanoff, 2020). More widespread adoption of modern techniques such as rapid filling of pits can reduce final acidification (McCullough & Schultze, 2018; Salmon et al., 2008).

5 | FUTURE USES OF PIT LAKES

Closure plans that are risky, expensive, and complicated are likely to fail, and the local community often shoulders the burden of these failures. While examples of closed pit lakes with extensive public infrastructure exist (e.g., Weber, 2020), open-cut mining in remote locations or developing countries will not receive the same investment. Consideration as to the location of the pit lake, who is likely to use the facilities and return on infrastructure investment are key considerations in assigning future uses. Current major uses of pit lakes include permanent storage of reactive mine waste, water supply for industry or agriculture, aquaculture, as ecosystems ("functional habitat for aquatic life"), recreation and tourism, metal recovery, and scientific study (Doupé & Lymbery, 2005; Gammons et al., 2009; McCullough et al., 2020; McCullough & Lund, 2006).

Future uses of pit lakes can be divided into two broad categories based on technological lifecycle and the activity level of the investment: active "short-term" and more passive "long-term." Many uses could be considered active "short term" (see McCullough et al., 2020), calling into question the fate of the lake, catchment, and community when the current use has completed its lifecycle. Examples of short-term uses include energy production and storage, aquaculture, irrigation, recreation, and water storage. Passive long-term uses include aquatic ecosystems, waste storage and treatment, flood mitigation, as well as recreation. Recreation such as swimming or fishing can be deliberate or accidental depending on the local community and final water quality. Ideally, closure planning would include both short- and long-term future uses depending on community needs. However, where pit lakes occur in remote areas, closing pit lakes as aquatic ecosystems is likely to be the safest and most cost-effective strategy.

5.1 | Short-term future uses

Many short-term future uses rely heavily on commercial viability and active infrastructure investment and maintenance. Renewable energy production in the form of floating photovoltaic (PV) panels (Exley et al., 2021; Song & Choi, 2016) and pumped hydro energy storage (PHES; Kougias & Szabó, 2017; Pujades et al., 2017) is gathering international attention. Pit lakes could also be used as water storages for industrial or municipal use (Annandale et al., 2019; Rybnikova & Rybnikov, 2020; Verger et al., 2018), recreation or aquaculture. The economic viability of these future uses depends on proximity of the lakes to communities, existing grid infrastructure, electricity market price, site ownership, management status, and competition with other technologies (Kougias & Szabó, 2017).

The use of floating PV panels on mine lakes has been proposed in regions where land-use conflicts or existing power grid infrastructure makes the investments socially and economically attractive (Exley et al., 2021). Large arrays of PV panels may impact light attenuation, temperature, and water movement in the lake (Exley et al., 2021; Song & Choi, 2016), although if panels are located away from the lake's edges to avoid breaking waves, littoral areas could be developed to attract aquatic life. In terms of economic feasibility, modeling of a simulated PV array on an "ideally situated" pit lake in South Korea indicated that return on investment would take approximately 12.3 years (Song & Choi, 2016). Overall, given the cost of retrofitting panels for buoyancy, combating erosion and the effect of shading by high walls, using pit lakes for PV panels is unlikely to offer value over terrestrial placement or alternative sources of local energy.

Lake stratification offers temperature and salinity gradients that may heat and cool buildings (Menéndez et al., 2020), store seasonal thermal energy (Novo et al., 2010), or harvest energy from nearby underground mine workings (see Gzyl et al., 2016). PHES is a variation on traditional hydropower technology using water height differences to operate both turbine and pump (Kougias & Szabó, 2017; Rehman et al., 2015). PHES using pit lakes is being constructed in north-eastern Australia on an abandoned gold mine (Australian Renewable Energy Agency, 2021; McConnell-Dowell, 2021) co-located with an existing 50 MW solar farm and is a 250 MW/2000 MWh storage facility (Australian Renewable Energy Agency, 2021). A variation on PHES using pit lakes is "underground pumped storage hydropower" (UPSH) where the upper reservoir is located at the surface or shallow depth, and the lower reservoir is under the surface in a groundwater lens (Pujades et al., 2017). The technical viability of PHES/UPSH using pit lakes depends heavily on pit location and morphology to store and deliver energy. Poor water quality can corrode infrastructure and must be factored into the design. Stability of pit walls is also critical as the frequent changes in water depth could result in catastrophic collapses. Human-induced rapid water level changes in natural deep lakes may rapidly degrade lake ecosystems, particularly in littoral areas, increasing eutrophication-like symptoms such as cyanobacterial blooms via internal nutrient loading processes (Zohary & Ostrovsky, 2011). Therefore, the use of a pit lake in PHES likely precludes aquatic ecosystem development and would therefore share characteristics of an unrehabilitated pit lake while active.

Pit lakes can be used as water storages for a variety of purposes. Pit lakes can provide storage for power station cooling waters as occurs in Collie, Western Australia (pers. obs.) or as off-river water storages for municipal drinking water, especially where river flows are intermittent and the risks of contamination from the pit is low (Verger et al., 2018). Pit lake water is currently the primary source of drinking water for the town of Rezh in the Ural Mountains, Russia (Rybnikova & Rybnikov, 2020). In some regions, pit lakes may provide a valuable source of water for irrigating crops (Annandale et al., 2019). As above, if pit lakes are to be used as water storage, large fluctuations in water level may not support ecosystem development and algal blooms may occur.

Pit lakes can be used for recreational and tourism activities where water quality and bank stability are appropriate (see McCullough et al., 2020; Stephenson & Castendyk, 2019; Weber, 2020). Depending on the level of infrastructure investment and maintenance, short-term recreation and tourism can co-exist with long-term future uses (below). Because of their deep, sheltered waters, and location well away from the coast, pit lakes can become attractive inland SCUBA dive sites (Buzzacott & Paine, 2012), such as Ojamo mine in Finland, Mexico's Cenote "El Pit" or the iron ore pit mines of Minnesota containing intentionally sunk attractions for divers.

Aquaculture is increasingly limited by water availability and the risks associated with discharging effluent high in organic matter and nutrients into natural waterbodies (Ahmad et al., 2021; Ahmed & Thompson, 2019). Pit lakes provide a large quantity of water that could be used to support inland aquaculture and as potential disposal sites for aquaculture wastes (D'Souza et al., 2004; Mallo et al., 2010; Otchere et al., 2004). However, nutrient loading can lead to algal blooms (Axler et al., 1996), or fish may bioaccumulate metals and metalloids from the water to dangerous levels, as occurred in Burkina Faso (Compaore et al., 2020). Treating acidic pit lake water with limestone using a fluidized bed reactor enabled it to be used to grow fish and the freshwater crustacean Marron in Western Australia (Evans et al., 2003). Aquaponics using floating islands for food crops on a mine water dam were tested to control molybdenum and phosphorus concentrations responsible for the growth of toxic cyanobacteria (Fabbro et al., 2008), and might be a potential commercial opportunity for local communities.

By their very nature, the above future uses are relatively expensive and short-lived. Short-term future uses, such as energy production and water storage also may be best served by minimizing biodiversity development. Investing in short-term future uses should be viewed as a transition to complementary long-term uses and performing activities such as sculpting a littoral zone before the lake fills should be a priority (Blanchette & Lund, 2016).

5.2 | Long-term future uses

Long-term future uses should be safe, self-sustaining and, therefore, more passive, requiring little ongoing maintenance beyond initial investment. Examples of long-term future uses would be flood mitigation (McCullough & Schultze, 2018; Schultze et al., 2019), storage of waste materials (Schultze et al., 2011), carbon sequestration (Younger & Mayes, 2015), development of aquatic ecosystems, and recreation. Depending on the morphological and water quality safety profile, aquatic ecosystems and recreation can co-occur with other future uses.

Pit lakes in Germany have been successfully used for flood mitigation, forming a bypass for flooding rivers with control structures for river offtake and lake outflows (McCullough & Schultze, 2018; Schultze et al., 2019). Flood waters are stored and then slowly released minimizing the peak of the flood downstream. In times when river water levels are low, the water stored in the pit can be released to meet environmental flows or water rights (M. Schultze, pers. comm.). Pit lakes connected to rivers can also improve river water quality by removing sediments, nutrients, and some metals (McCullough & Schultze, 2018) although removal of solutes is selective and may not be a net positive for the river (Lund & Blanchette, 2018; Mpetle & Johnstone, 2018).

Mine waste materials and organic matter can be disposed of at the bottom of pit lakes (Schultze et al., 2011; Younger & Mayes, 2015). Organic matter may remediate acidic lake water by supporting sulfate-reducing bacteria (Green & Mather et al., 2017; McCullough et al., 2008; Schultze et al., 2011). Depth adds little additional aquatic habitat, especially if the lake stratifies and the bottom layer becomes anoxic or hypoxic. Therefore, reducing the depth of the lake to store waste materials is a sensible option, especially if it avoids storing waste materials in spoil piles. Submerged waste covered with an inert layer (organic or otherwise) may prevent contamination during mixing events, and in lakes with a monimolimnion (salinity stratified bottom layer), the unlikelihood of mixing allows the waste to be stored uncovered. Anoxia within the monimolimnion or waste pile will prevent acidification through sulfide oxidation and lining the bottom could prevent groundwater contamination. Base Mine Lake, a former oil sand pit lake, has been used to test the storage of fluid fine tailings (FFTs) under a 10 m-deep freshwater cap (Tedford et al., 2019). The FFT has settled despite dimixis, and the development of sediment biofilms may reduce turbidity caused by lake mixing (Cossey et al., 2021). Toxicity of the FFT is expected to decline to safe levels allowing these lakes to be permanently closed (but see Brown & Ulrich, 2015). Gradually infilling pits with organic materials can act as a long-term net sink for CO_2, as in peat formation in natural lakes, with anoxia and sulfate reduction limiting methanogenesis aiding carbon storage (Younger & Mayes, 2015). While infilling the pit lake requires ongoing investment, only minimal maintenance would be needed which is in-line with long-term future uses.

Pit lakes can increase the diversity of post-mining landscapes by adding aquatic ecosystems where formerly there were only terrestrial ecosystems (McCullough & van Etten, 2011; Figure 5). Development as aquatic ecosystems is an inevitability for most pit lakes, although the timeframe for this to occur could be great and the ecosystem endpoint is often undefined (Blanchette et al., 2019; Blanchette & Lund, 2021). Small and shallow pit lakes have been successfully closed and rehabilitated or have naturally evolved (Campbell & Lind, 1969; King et al., 1974; Opitz et al., 2020; Stephenson & Castendyk, 2019). Relatively few large pit lakes have been rehabilitated and closed (Mpetle & Johnstone, 2018; Pérez-Sindín & Blanchette, 2020), although the lignite pit lakes of Lusatia and the Central Mining District in Germany have been closed through active water quality management (Benthaus et al., 2020; Figure 6). However, it is unclear if the German lignite pit lakes demonstrate long-term ecological sustainability given that regular application of chemicals is required to stabilize pH in many of them.

FIGURE 5 Lake Kepwari, Western Australia, a former coal pit, is a place of recreation and a new aquatic ecosystem. Photo: M. L. Blanchette, 2013.

FIGURE 6 Pit lake aquatic recreation infrastructure in the former lignite-mining district of Lusatia, Germany. (L) SCUBA diving center (Zwenkauer See) and (R) water sports and dining (Lake Senftenberg). Photo: M. L. Blanchette, 2016.

The evolution of pit lake water quality and ecosystems is often modeled (Castendyk, 2009; Castendyk et al., 2015; Müller et al., 2011), rather than measured, so few long-term data sets exist (Shevenell, 2000; Zhao et al., 2009). Traditionally there has been a desire to find suitable analogues or reference lakes to set rehabilitation goals for pit lakes (McCullough & Lund, 2006), but this may not be possible at all locations (Blanchette & Lund, 2016). Pit lakes are located on a "sliding scale" of interacting factors that increases the complexity of rehabilitation (Blanchette & Lund, 2016). These factors include size, location, rock type, water quality, proximity to natural water bodies, and community expectations. Without active introduction, any pit lake can only contain a proportion of the locally available taxa as all species have different abilities to disperse (Lund & McCullough, 2011a). Pit lakes are ecological "islands," and the species richness of a pit lake will be governed by its surface area and proximity to other waterbodies (sensu MacArthur & Wilson, 1967). Pit lakes may occur in lake districts, and are ideal systems for testing temporal community dynamics, particularly primary succession (Miguel-Chinchilla et al., 2014).

A saline pit lake in Poland (Machów) was rehabilitated as an aquatic ecosystem using buried waste, sculpted littoral zones, and river connection (Bylak et al., 2019). However, the macroinvertebrate community was less rich and more invasive than expected and may have been limited by salinity. A lack of large lakes nearby meant that it was unclear whether the salinity was unusual for the area, illustrating the challenge of relying on natural analogues for pit lakes (Bylak et al., 2019). Invasion of introduced species at Machów could be a deviated state where management action is required. In unrehabilitated Australian saline pit lakes, biodiversity was lower than could be explained by water quality; lack of habitat, riparian, and littoral zones, and terrestrial carbon inputs constrained pit lake biodiversity (Blanchette & Lund, 2016; Lund & Blanchette, 2021; Lund & McCullough, 2011b; van Etten, 2011). The "state and transition approach"—a series of ecological "states" used to assess rehabilitation progress—has been used for terrestrial mines and could be adapted to pit lakes (Grant, 2006). "Deviated states" requiring corrective management actions could be identified (Grant, 2006). Regardless, closure of pit lakes as aquatic ecosystems requires stakeholder agreement as to what ecosystem development means, what ecological state is desirable, and what is achievable over a particular timeframe.

All pit lakes contain ecosystems, even if mainly microbial (Sánchez-España, Yusta, Ilin, et al., 2020; Stierle et al., 2006). Improving habitat, plant communities and littoral areas of pit lakes appears to improve biodiversity, at least to the point where only water quality becomes limiting as seen in Machów (Poland) (Bylak et al., 2019). Connecting pit lakes to a surface water network to facilitate input of terrestrial litter and nutrients is a passive design strategy that may improve aquatic biodiversity for long-term closure (Lund et al., 2020). When a pit lake has a diverse and self-sustaining ecosystem it is an asset to communities and catchments and is likely the lowest risk long-term closure strategy.

6 | CONCLUSIONS

If most mine voids cannot be re-filled, and pre-mining conditions can never be replicated (Ross et al., 2021), pit lakes will continue to be created. Pit lakes are a mining legacy in the landscape for thousands of years, and planning for their future uses can mitigate negative effects and improve outcomes. The success of pit lake closure is underpinned by risk which is a function of water quality, mine location, pit morphology, and community perception (Pérez-Sindín & Blanchette, 2020). Closing pit lakes challenges basic tenets of limnology such as eutrophication (Smith et al., 1999), given that, if desired, increasing nutrients in the appropriate balance improves biodiversity and water quality in these new aquatic ecosystems (King et al., 1974). Unfortunately, some issues with pit lake closure are currently intractable and may require significant technological advances and investment to resolve. In this case, it is up to planners to ensure the community avoids bearing the burden of failed closure.

Short-term future uses that rely on commercial viability and substantial infrastructure investment such as floating PV panels, aquaculture, or pumped hydro may be politically attractive, but are unlikely to be sustainable given the ongoing costs. In remote, developing, or disenfranchised communities these schemes may become "white elephants" (e.g., Sharma, 2020). However, pit lakes have the potential to become valuable assets for generations, such as the more than 50 unique pit lakes that compose the lignite mining district of the former German Democratic Republic (Weber, 2020). The higher the standard of water quality, the more versatile the water body in terms of future uses. Passive treatments such as terrestrial leaf litter input can improve aquatic biodiversity in gravel pit lakes even if water quality does not improve substantially (Seelen et al., 2021). Mitigating the risks inherent in pit lake closure requires a tailored approach and closing pit lakes as aquatic ecosystems may be the most flexible and realistic long-term solution.

AUTHOR CONTRIBUTIONS

Mark A. Lund: Conceptualization (lead); writing – original draft (lead); writing – review and editing (supporting). **Melanie L. Blanchette:** Conceptualization (supporting); writing – review and editing (lead).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Mark A. Lund https://orcid.org/0000-0002-2047-3476
Melanie L. Blanchette https://orcid.org/0000-0003-2138-2864

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