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Ecological Restoration of Novel Lake Districts: New Approaches for New Landscapes

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Abstract Mine void pit lakes often contain water of poor quality with potential for environmental harm that may dwarf other mine closure environmental issues in terms of severity, scope, and longevity. This is particularly so when many pit lakes occur close together and thus form a new "lake district" landscape. Pit lakes that can be developed into healthy lake or wetland ecosystems as a beneficial end use provide opportunities for the mining industry to fulfil commitments to sustainability. Clearly articulated restoration goals and a strategic closure plan are necessary to ensure pit lake restoration toward a new, yet regionally-relevant, aquatic ecosystem, which can achieve sustainability as an out-of-kind environmental offset. Such an approach must also consider obstacles to development of a self-sustaining aquatic ecosystem, such as water quality and ecological requirements. We recommend integration of pit lakes into their catchments as a landscape restoration planning exercise with clearly-identified roles and objectives for each new lake habitat and its surrounds.

Keywords Australia · Germany · Mining · Pit lake · Rehabilitation · Restoration

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Introduction

With increased frequency and growing scale, open-cut/cast mining has left a legacy of many thousands of mine pit voids worldwide (Castendyk and Eary 2009; Klapper and Geller 2002). Where backfilled pits is not an economic or feasible option and the pit extends into the water table, then pit lakes ranging from very deep (e.g. hard rock mining pits >250 m deep) to shallow (e.g. dredge ponds <10 m) may form (Castro and Moore 2000).

At the same time, there is a growing demand on natural water resources. Many regions have seen reduced regional recharge and decreases in water quality through pollution, leading to damage or complete loss of aquatic habitats (Pyke 2004). This demand has been simultaneous with increased mining and may sometimes be a direct result of this activity. These pressures continue to contribute to an international loss of aquatic habitat types ranging from seasonal wetlands to entire lake systems.

Rehabilitation of post-mining terrestrial landforms to provide restored ecosystems has now become a well-researched (and generally successful) practice that borrows from both disciplines of ecology and engineering. Indeed, post-mining rehabilitated ecosystems are a significant landscape feature in many regions with mining history. However, this landscape restoration typically ceases at the edge of open-cut/cast pits, except where backfill and/or landscaping directly incorporate the pit back into the surrounding terrestrial ecosystem. Generally, pit lakes are left unconsidered in this process, as 'elephants in the mine closure room'. Geochemical weathering processes, such as acid and metalliferous drainage (AMD), may then lead to poor water quality, resulting in lake waters toxic to aquatic life (McCullough 2008). Such quality impaired pit lakes typically have few environmental values and may even detrimentally affect regional water bodies through contamination of surface and groundwater sources (McCullough and Lund 2006). Such pit lakes are often a social and environmental liability to the surrounding region (Doupé and Lymbery 2005), yet they are frequently underestimated in terms of their scope and the magnitude of their environmental impacts. Indeed, of all mine closure legacies, pit lakes frequently have the most severe environmental impacts, given that these impacts can continue even after the mine is closed and the greater catchment is rehabilitated (Younger 2002).

Notwithstanding the significant environment and community problems that can be caused by pit lake landscape features, a number of pit 'lake districts' have formed over the past few decades, or are currently being formed for closure and return to state governments over the next few decades (Table 1). Through improvements in scale of mineral extraction technology, these more recent pit lakes are generally deeper and of greater volume than older lakes. Although it is often assumed that pit lakes will follow an evolution from young to mature lakes, resulting in lakes with a well-developed ecosystem (Kalin and Geller 1998), there are many examples of pit lakes formed soon after open cut mining became commonplace that have not improved in environmental quality or in biological measures (such as biodiversity and ecological function) many decades after forming (McCullough et al. 2009b). Instead, many pit lakes present continued risks to surrounding natural ecosystems, and it is likely that many of these new habitats will continue to display degraded ecosystems for many hundreds of years (Castendyk 2011).

However, pit lakes also represent significant opportunities. There are many potential benefits, most of which are untapped during mine closure planning by mining companies and regulators concentrating on terrestrial restoration outcomes. If appropriate restoration can be achieved, these large pit lake water bodies represent potentially valuable environmental and social resources (McCullough and Lund 2006; McCullough et al. 2009a), particularly in the face of global aquatic ecosystem losses (Sklenička and Kašparová 2008). Such post-mining use of an industry legacy would help advance expectations of best-practice mining environmental sustainability when pit lakes are final landforms.

This paper explores options for ecologically restoration that are rarely applied to pit lakes. We identify both opportunities and constraints within a contemporary mine closure and restoration context, and recommend regional planning strategies to best realise a restored pit lake ecosystem that will have significant environmental value and that will be successfully integrated into its broader ecological landscape.

Historical and Current Practice

Traditionally, pit lakes and even the pit void structure itself have rarely been considered in mine rehabilitation and closure plans, aside from geotechnical health and safety aspects. The latter have generally been achieved through simple structures such as earthen bunds and fences, e.g. DMP/EPA (2011). Some engineering technologies even take advantage of this isolationist perception to use pit voids as reservoirs for tailings storage or as sacrificial sumps for AMD or erosion products from over-burden and other disturbed landforms (Puhalovich and Coghill 2011; McCullough and Lund 2006).

Some good examples of pit lake rehabilitation have occurred in Germany and Central Europe where community pressure and interest in beneficial end uses have encouraged development of pit lakes (Schultze et al. 2011; Żurek in press). However, there are very few examples of restored pit lakes where pit lakes and their immediate surrounds have been rehabilitated to specifically restore *ecosystem* values (regional or otherwise). Where restoration has been achieved, it has sometimes been incidental (Charles 1998) and/or some ecosystem properties and processes developing naturally after many decades or even following filling. As a result, there are no demonstrative examples of pit lake restoration success for most regions and mining types. This has been because rehabilitation of pit lakes, let alone restoration of a sustainable ecosystem therein, has not often been a focus for mine closure planning. Indeed, the closest examples to restoration of an

Table 1 International examples of pit lake districts

Lake district	Country	No. of lakes in district	References
Athabascan oil sands region	Canada	0 current (26 proposed)	Westcott and Watson (2007)
Borská Nížina lowlands	Slovakia	11 current	Otahel'ová and Otahel' (2006)
Central German and Lusatian Districts; Rhenish District	Germany	370 current; 205 current	Schultze et al. (2011)
Collie Lake District	Australia	13 current (more proposed)	Kumar et al. (in press)
Iberian	Spain	22 current	Sánchez-Espanã et al. (2008)
Łęknica	Poland	>100	Żurek (in press)

ecosystem of regional value typically appear when aesthetics for recreation are foremost goals for rehabilitation. For example, woodland or forest may then be created to develop this recreational end use, which indirectly benefits the regional environment, e.g. Żurek (in press).

The use of water quality as the most common, and often sole, criteria chosen by regulators may be because most countries have well developed water quality guidelines that lend themselves to this application (Jones and McCullough 2011). Consequently, in some instances, pit lakes have been relinquished to the state with restoration requirements, or at least consideration, to state or national water quality guidelines. For example, stock water drinking guidelines tend to be applied by regulators and as rehabilitation goals if the regional economy is predominantly agricultural, and environmental guidelines used if this is an explicit state or federal requirement (e.g. Axler et al. 1998) or if there is risk of discharge to other regional water bodies. Given that environmental water quality guidelines typically surpass guidelines for other water body uses (e.g. industrial, agricultural use), relinquishing a pit lake with environmental water quality standards may allow for many other end uses as well. However, other, equally-important, ecological variables are generally not considered (Lund and McCullough 2011; McCullough et al. 2009a).

Pit Lakes As Out-of-Kind Environmental Offsets

Rehabilitation practices mitigating environmental impact during operations and then rehabilitating remaining disturbed or reformed terrestrial habitat will undoubtedly reduce overall environmental impact and biodiversity losses from the post-mining landscape. However, it is difficult to see how the goal of achieving no net biodiversity loss in their operations, or even a “net positive impact” (NPI) on biodiversity, often proposed by many ‘blue chip’ mining companies, e.g. Rio Tinto (2008), can be achieved when a significant proportion of the mine footprint becomes inundated at completion of mining and consequent cessation of dewatering. Instead, developing aquatic ecosystems in and around a pit lake may help to achieve this biodiversity through a form of out-of-kind offset (Fig. 1). Such offsets are now well-established in regulatory policy in many countries, including USA, Australia and South Africa (McKenney and Kiesecker 2010) where concerns about mining and, in particular, mine water issues such as pit lakes, are growing (Newmont Golden Ridge Ltd. 2009). In this closure planning model, all mining activities ranging from the direct impacts of mining through to access corridors and other peripheral disturbances away from the mine footprint result in net loss of terrestrial ecosystems. Many contemporary restoration strategies may redress this

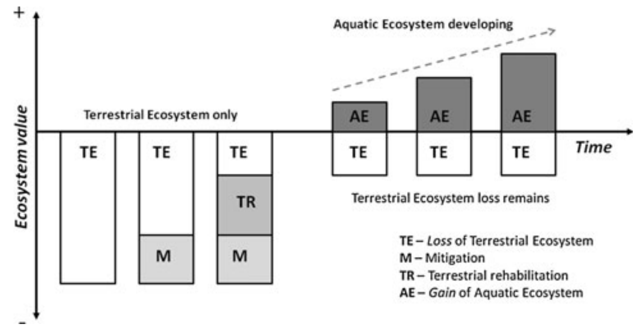

Fig. 1 Hierarchy of increasing biodiversity achievements through standard-practice terrestrial rehabilitation and then inclusion of pit lake aquatic ecosystem in post mining landscape restoration efforts (after NSW EPA 2002)

loss through mitigation of potential impacts and rehabilitation of impacted sites. Still, excavation of a vast open pit that floods to form a lake will result in irreversible net loss of terrestrial ecosystems. Recognition of the value of a developing aquatic ecosystem in the developing pit lake, and deliberate and targeted restoration of this ecosystem toward a regionally relevant aquatic ecosystem of value may be a suitable offset which redresses a net terrestrial ecosystem loss. Overall, there may even be a net ecosystem value (e.g. biodiversity) or gain following mine closure when the pit lake ecosystem is included in mine site rehabilitation accounting. As with terrestrial ecosystems, this gain is likely to significantly develop further ecological value over time as the lake fills and a burgeoning aquatic ecosystem develops.

Restoration theory and practice guidelines are generally well developed for terrestrial ecosystems and typically seek to restore the disturbed landscape towards a regional ‘analogue system’. This analogue system may represent either the pre-mining ecosystem type that was lost or alternatively a local reference ecosystem. For example, in the case of a forest lost due to mining, a reasonable analogue ecosystem in the first instance would be the exact pre-mined forest type, but if this was not possible, then a regionally-appropriate forest could be selected. However, there is often a gross dichotomy between mine closure criteria for terrestrial and aquatic communities on rehabilitated mining leases. This difference of expectations for ecological goals at mine closure extends even to the edge of the pit lake, where riparian vegetation is seldom either representative of the region or self-sustaining (e.g. Fig. 2). Some of this difference may be because the former habitat was not a lake and the former terrestrial habitat has been covered by significant volumes of lake water.

However, wherever the degree of environmental modification is severe, such as typically follows mining, it is common that post-mining landscapes are modified to such an extent that restoration to a pre-mining landscape is

Fig. 2 A typical 'bathtub' ring effect showing failure of a functional riparian vegetation community to develop, WO3 lake (50 years old), Collie Lake District, Australia

virtually impossible. Similarly, terrestrial goals for the areas now occupied by the lakes need to be abandoned and alternative restoration goals must then be sought. Pit lakes and their terrestrial surrounds are often seen as classic examples of novel ecosystems, with combinations of species and environmental conditions not previously found (Hobbs et al. 2009). However, this need not lead to a complete abandonment of restoring ecological values; as a first goal, areas above water that will form lake riparian and catchment could, and should be, clearly identified and restored to integrate pit lakes into the broader regional landscape. Obtaining at least some properties and/or values of regional reference aquatic ecosystems may even be a preferred goal, especially where amphibious ecosystems are regionally rare (Brewer and Menzel 2009). The process of determining and defining appropriate goals and end point criteria for completion, as well as monitoring to ensure restoration is on the right trajectory to meet these goals (Society for Ecological Restoration International 2004), are therefore integral components of ecological restoration relevant to developing pit lake ecosystems.

Environmental Restoration Goals for Pit Lakes

Ecological sustainability is paramount to the regional value of these new lakes and their collective lake district. As with all restoration goals, although significant management intervention may be required during periods of physical and ecological development, the objective of management should be to restore an independently self-sustaining ecosystem for both terrestrial and aquatic habitats that is integrated into the new landscape. The first step in development of a pit lake ecosystem of environmental value is to identify an "identifiable desired state" (c.f. Grant 2006) as a restoration goal. Desired environmental values may come from a number of different, and often complementary, end points. They may, for example, include the pit lake and its catchment providing habitat for charismatic (typically waterfowl and mammalian) species (Santoul et al. 2004). Simultaneously, the pit lakes may provide seasonal habitat for migratory bird species. Although it is unlikely that the inherently artificial nature of the pit lake landscape will provide the often specific and narrow habitat and food requirements that many rare species require (Kumar et al. in press), some endangered species may still be able to use pit lake districts as a long-term refuge if the catchment-scale landscape approximates that of a natural lake district (sensu Brewer and Menzel 2009). Importantly, for the pit lake and its catchment to contribute value to the regional environment, there should be a restoration target for aquatic, amphibious, littoral, riparian (lake edge shallows and immediate terrestrial margin), and terrestrial ecosystems, that will have ecological value and are regionally representative (Van Etten 2011). It should be noted that, in order to contribute to regional biodiversity, species that are found in the lake should not be those that are already common elsewhere. A similar caveat may hold for the genetic diversity within species that occupy the new lake ecosystems and their catchments through artificial translocation or natural migrations. Lake district ecosystems dominated by limited gene pool or demes will likely be less genetically diverse and resilient than natural lake districts that have developed over many thousands of years (Shwartz and May 2008).

Compromised Ecosystems

Some pit lakes and their catchments may be so disturbed, such as through extensive and inappropriate (e.g. steep and eroding) terrestrial catchment and lake morphologies, or through ongoing chemical processes such as AMD, that they present long-term legacies of compromised ecosystems.

Such lakes will present no environmental value, even with pro-active restoration strategies in place. Other pit lakes may be deemed 'unmanageable 'or 'un-fixable' due, not to limited treatment or remediation knowledge, but rather a lack of financial or community will. Such lakes should then be regarded as impaired ecosystems. An outcome for these lakes has been proposed as 'novel' ecosystems that may contribute to scientific understanding through 'natural experiments', c.f. Hobbs et al. (2006). Indeed, there have even been proposals to maintain especially acidic lakes such as these as valuable extreme and unique ecosystems warranting protection under legislation (Nixdorf et al. 2005). It is unclear, however, how a regional ecology could ever benefit from the presence of such potential risk in the landscape. A more preferable stance may be that restoration endeavours for pit lakes and their districts need to look past traditional measures of restoration success such as approximation of regional physico-chemical quality and biotic diversity and assemblages and instead focus on fundamental ecological processes that potentially could be restored (Hobbs et al. 2009). Such basic processes include development of nutrient cycling, functional feeding groups, and/or trophic structures that might satisfactorily compare to those of regional reference aquatic systems.

Similarly, measuring pit lake values in terms of recovery or development of ecosystem structure (sensu Bell 2001) and services, such as habitat complexity, forms of carbon storage (e.g. through net respiration: production ratios) and other measures, may help identify contributions of significant ecological values to a region's natural landscape, even for highly impaired pit lake ecosystems. Whether the lake district is natural or anthropogenic in origin may be entirely academic to the provision of these ecosystem services. Indeed, such new constructs containing common or even alien species may present greater opportunity for ecosystem services than their natural counterparts in the landscape (Ewel and Putz 2004; Lugo 1992).

Restoring Ecosystem Values to Impaired Pit Lakes

Some impaired pit lake systems may naturally develop ecosystems of environmental value over time though natural, albeit slow, remediative processes such as succession driven along a restorative trajectory, e.g. water quality remediation by primary production and sulphate reduction (King et al. 1974). However, these processes may occur at too slow a rate or may be inhibited by negative feedback loops that preserve degraded states, c.f. Suding and Hobbs (2009), (Fig. 3). The ecological successions of pit lakes in these instances will need to be mediated by management interventions. Due to lack of long-term studies, it is largely unknown to what degree pit lakes, often described as examples of primary succession (Kalin et al. 2001), follow classic succession models, which generally presume gradual, predictable recoveries.

Prior to mining, a landscape dominated by terrestrial ecosystems has ecological values that are definable by measures such as biodiversity, presence of rare species, productivity, and other ecosystem services (Fig. 3). During mining, the ecosystems may face a substantial decrease in their terrestrial ecosystem value due to vegetation clearance and topsoil removal, excavation of overburden, and actual ore extraction, forming an open mining pit. In addition, road building, vehicular disturbance (dust and noise), and loss of habitat connectivity around the pit void will extend this phase of decreased ecosystem value.

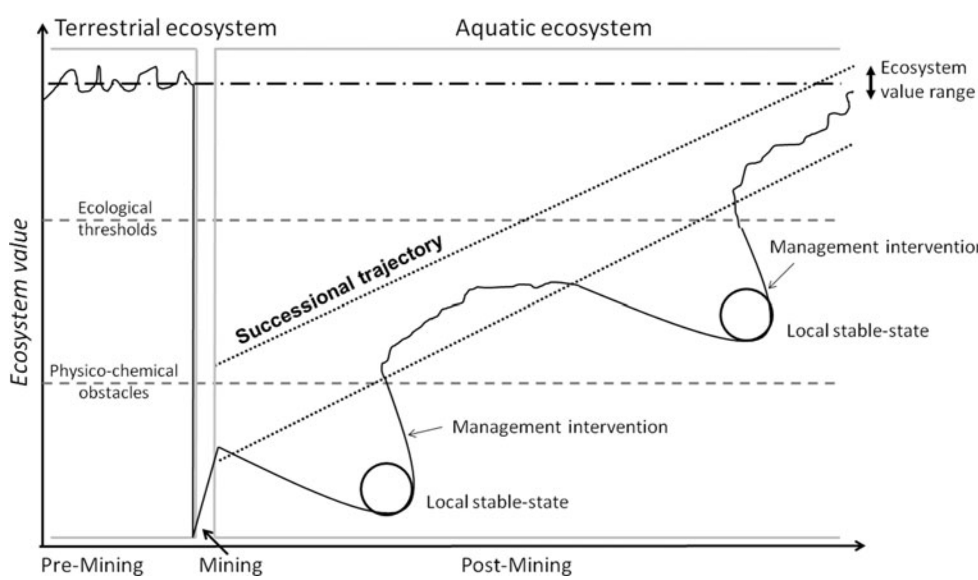

Fig. 3 Successional development of a pit lake ecosystem from low ecological value immediately following mining to attainment of prior ecological value, albeit now dominated by aquatic ecosystems. Local-stables states demonstrate fundamental ecological thresholds management restoration activities must overcome to realise a self-sustaining aquatic ecosystem of value (after Grant 2006)

Formation of the pit void and then flooding when dewatering ceases will mean significant loss of terrestrial habitat. Following rehabilitation of remaining terrestrial habitats, some terrestrial ecosystem of ecological value will be regained. However, the pit area will have been submerged and converted to an aquatic ecosystem habitat; terrestrial habitat thus lost cannot be rehabilitated and realised as terrestrial habitat ever again.

Through natural ecological succession processes, this evolving lake system may develop increased ecosystem values over time as some primary production begins both within and on lake banks and as fauna and flora colonise (Fig. 3). However, fundamental physico-chemical conditions may limit ecological development of the lake below a successional threshold, even at this early stage, such as through AMD toxicity or other water quality issues. The ecological consequences of AMD often include low species' diversity caused by pH stress and exposure to high concentrations of contaminants (Lee and Kim 2007; Nixdorf et al. 2001), low trophic states, low nutrient concentrations and low rates of primary production. Water quality is a master threshold factor for almost all pit lake ecological processes and especially for lower level species.

For example, pit lakes frequently display chemically-driven alternative stable states of poor water quality (sensu Sim et al. 2009). Abiotic processes may be the dominant determinant for that particular lake, e.g. ongoing and irreversible increases of salinity in regions of low net precipitation. Local stable states of poor water quality may also be due to biotic remediation processes that are present but weaker than their opposite and concurrent abiotic processes, for example catchment and internal formation of acidity occurring at greater rates than external and internal microbial driven-alkalinity generation processes. This state of aquatic ecosystem development may be very stable. For example, development of a basic self-sustaining food chain with phytoplankton algae in the lake is initially challenged by water toxicity and nutrient concentrations. In this example, management intervention to improve water quality, such as by active or passive remediation of AMD or similar issues, may be required before ecosystem development can continue to a high level of ecological complexity (Fig. 3). Thus, management intervention would be necessary to elevate the ecological succession path above a water quality threshold so that the pit lake ecosystem may continue to develop and achieve greater ecological value (Klapper and Geller 2002).

A pit lake ecosystem with high rates of primary production may contribute to the ecological value of a pit lake in many ways. Algal primary producers play an important role in natural lakes, providing the dominant allochthonous energy sources that are the basis of lake-ecosystem food webs (Bott 1996). Primary producers such as algae can facilitate sulphate production by providing a carbon source for sulphate reducing bacteria (SRB), which increase alkalinity and pH in AMD-impaired lakes (Lund and McCullough 2009). Algae can chelate metals directly, reducing toxicity and may absorb phosphorus and fix inorganic carbon into organic forms, reducing microbial carbon limitation and accelerating development of a natural food chain (Nixdorf and Kapfer 1998).

Conversely, AMD may lead to low pH and high acidity, increased metal and/or other contaminant concentrations, and a paucity of the macro-nutrients carbon and phosphorus, thereby limiting primary production rates and primary producer biomass. These limitations may then cascade as bottom-up controls on higher trophic levels and reduced abundance of taxa (McCullough et al. 2009b). Pit lake restoration efforts in this instance might target the biotic processes needing assistance or the water quality issues that limit ecological succession, such as low nutrient levels (e.g. phosphorus, carbon) (Tittel and Kamjunke 2004).

Adequate and appropriate revegetation within catchments is also important in developing functional lake riparian vegetation which, in turn, may play a key role in many pit lake ecological processes. Even with good pit lake water quality, many pit lakes fail to attain bank vegetation of any description, even after many years (Fig. 2). Riparian vegetation is important to integrate pit lakes into their greater catchments and to form connected and functioning landscapes. There may also be interactions between terrestrial and aquatic ecosystem components remediating physico-chemical water quality issues, in addition to providing ecological habitat. Individual ecological components must be clearly identified and considered in the context of the overall ecosystem as well as the pit lake ecosystem development. The contribution of organic carbon from riparian and catchment vegetation was recognised many years ago as a primary causative factor in water quality improvements in AMD pit lakes (Campbell and Lind 1969). Riparian vegetation may also contribute to bank stabilisation, facilitating further littoral and riparian establishment. The development of sustainable pit lake communities for finfish and large crustacea require an environmental suite that is more holistic than just water quality, including habitat such as fallen logs and bank overhangs, as well as food resources (McCullough et al. 2009b; Van Etten 2011).

Conclusions and Recommendations

Aquatic habitats are increasingly diminished in their frequency and quality through both local and global anthropogenic activities. Concurrently, the growing activities of open-cut mining are contributing potential lake aquatic habitats to post-mining landscapes. These pit lakes environments often display impoverished ecologies of little value to a regional environment and may even present an environmental risk to nearby natural water bodies due to poor water quality and/or other ecological factors. There is often little or no planning for a functioning pit lake of targeted ecological value. Pit lakes are often overlooked in rehabilitation efforts because aquatic habitats were not present previously in many of these disturbed mining locales. Nonetheless, pit lakes represent significant landscape restoration opportunities for replacement (or offset) of lost terrestrial habitat values with the alternative habitat values of an aquatic landscape or entire lake districts.

Fundamental restoration theory directs mine closure planners of post-mining landscapes that will contain pit lakes to first identify end use values. These may be environmentally specific endpoint values or endpoints that still allow alternative uses, such as recreation or aquaculture/agriculture.

How do we 'restore' pit lakes as ecosystems then? Achieving a desirable pit lake ecosystem involves more than just attaining good water quality. Water quality guidelines are only the beginning. Recognition of limiting factors to development of a self-sustaining ecology of regional values is essential. It must also be recognised that there the scope for management manipulation of the lake will be much more limited after filling; therefore, any obstacles to ecosystem development should be identified and remedied as much as possible prior to filling, starting with water quality. Establishing environmental values at higher levels than simply improved water quality must incorporate ecological approaches, a goal which is frequently ignored by restoration managers and regulators (Lund and McCullough 2011; McCullough et al. 2009b). Such an approach may assist in clearly articulating targets for the long term sustainability of pit lake districts. Such ecological versus physical/chemical-driven approaches should also recognise that mine water-affected landscapes, such as pit lakes, are more than just a geochemical environment, with consequent (though often simple) requirements for fundamental limnological and ecological processes that also need to be addressed if restoration to a representative functional ecosystem is to be successful.

Although it is likely that the broad environmental requirements for food and habitat will be very similar to those in natural systems, pit lake biota and their ecological requirements remain rarely studied and poorly understood. As such, there remains a pressing need for catchment-scale rehabilitation attempts of pit lakes to move towards development of aquatic ecosystems as a best practice. These restoration attempts are likely to initially fall short of attaining satisfactory ecosystem values due to a lack of knowledge of general pit lake ecological processes and intrinsic site-specific considerations. However, monitoring and ad hoc investigation studies of combined physico-chemical and ecological characteristics of these early attempts will provide fertile insight for future restoration attempts.

In conclusion, we hope that this paper serves to develop the field of mining closure planning by considering pit lake ecosystems as desirable and valid restoration goals. Considering mine water legacies in the context of their catchments, and vice versa, will also lead to realisation of more holistic environmental benefits to post-mining landscapes. We trust that the transdisciplinary perspective offered will translate into improved community and regulatory involvement in mine closure planning, and will encourage the mining industry to seek out additional opportunities to effectively achieve environmental sustainability targets when presented with new landscape challenges.

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