Are We Approaching Pit Lake Closure from the Wrong Perspective?

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Abstract Pit lakes are similar to natural lakes formed by faulting, glacial action, volcanic action and asteroid collisions. These natural lakes have, after thousands of years, developed into environmentally significant ecosystems. As artificial constructs, pit lakes can be modified prior to filling to enhance lake attributes, such as modification of catchment size, creation of littoral zones and addition of organic matter. Significant advances could be made in successful closure and relinquishment of pit lakes, by 1) choosing appropriate model lakes, 2) understanding successional processes, 3) designing pit lakes to enhance ecological values, and 4) recognizing that it will take time to develop desired characteristics.

Keywords water quality, ecology, closure, sustainability

Introduction

Pit lakes are often the greatest legaciesof open cut mining operations (Younger and Wolkersdorfer 2004), with closure planning being driven by local and international regulation. It is our contention that current approaches to pit lake closure do not best serve mining companies or the community because theyare driven by misperceptions about the goals (and realities) of mine closure, and do not consider the ecological potential of pit lakes.

Current closure planning considers pit lakes as short-term risks to be managed,with risks mitigatedby meeting water quality targets (often using 'in perpetuity' treatment systems) and ensuring the site is considered structurally safe (either through fencing, bunding or angle of repose slopes). Modelling of the pit lake then'confirms' that targets will be met over the next few hundred years, and the lake isthen accepted by regulators for closure(e.g. Vandenberg et al. 2011). The use of water quality targets are the most common (often sole) criteria chosen by regulators to ascertain environmental condition of pit lakes, likely because most countries have well developed water quality guidelines that lend themselves to this application (Williams 2009). Although the use of water quality guidelines forenvironmental protection may represent a 'gold standard' of rehabilitation (McCullough and Etten 2011), other important variables such as biodiversity and ecosystem processesare generally not considered.The current approach is inherently flawed because models exclude manybiological processes, which ultimately become the main drivers of water quality, as in natural lakes. Further, a gold standard of water quality does not guarantee a gold standard of biodiversity or ecosystem processes which may be limited by other factors such as poor sediment development or lack of habitats. A risk minimisation approach also does not extend the full potential benefits of these systems to the community(seeMcCullough and Lund 2006), and effectively excludes anyecosystem gainsthroughconnection to catchment processes (such as nutrient enhancement from input of terrestrial leaf litter).

In principle, the goal of ecological restoration is a "return to exact predisturbance conditions" (Mitsch and Jorgensen 1989); a circumstance which may be possible for the vegetation surrounding the pit lake, but not for the lake itself. A better term in reference to improving ecological conditions for pit lakes is'rehabilitation' when defined as "making the land useful again but with different land use and different species" (Mitsch and Jorgensen 1989).However, both terms (restoration and rehabilitation),though widely used,contribute to

the misperceptions around pit lakes and the goals of mine closure. Therefore, we suggest that a change in focus towards one of creating new lakes,rather than 'restoring' or 'rehabilitating' the landscape. The use of the term 'new lake' is not only more appropriate, but also reduces community expectations of quick fixes.

Pit lakes will become increasingly important in the future as sources of water and wildlife refugia (Chester and Robson 2013), particularly as natural wetlandsand lakes suffer from the effects of climate change. If we approach pit lakes from a new lake perspective, then we need to understand the ecological processes that drive lake development in order to establish realistic targets along a particulartemporal trajectory. Within the framework of closure goals, we can then seek to enhance these processes to speed up lake development and achieve key closure milestones by 1) choosing appropriate model lakes, 2) understanding successional processes, 3) designing pit lakes to enhance ecological values, and 4) recognition that it will take time to develop desired characteristics.

Choosing appropriate model lakes

The method of lake formation varies, with new lakes created by landslide blockages, faulting, damming of lotic systems, or *de novo*on new ground (i.e., land devoid of previous life). These latter '*de novo*' lakes can be formed by volcanic action (crater lakes), asteroid impacts, or glaciation. *De novo* lakes, like pit lakes, are characterized by deep waters, small catchments, oftenpoor water quality, and are unique in their complete lack of sediment/soil at formation.Despite their often dramatic beginnings, many of these lakes develop outstanding ecological valuesover many thousands of years (e.g. Crater Lake – Oregon, USA). In contrast to the current focus on ensuring pit lakes are representative of other regional lakes; these lakes are probably wholly unlike pit lakes in method of formation, trophic status and morphology. We suggest that *de novo* lakes may be more useful model systems for pit lakes, particularly when identifying biodiversity targets in closure planning.

Understanding successional processes

The success of pit lake rehabilitation is currently measured according to how similar the pit lakes are to local natural water bodies. If we are to accept the premise that pit lakes are more like crater or asteroid lakes, then the question of how locally representative a pit lake is starts to have less relevance. For example, in Western Australia, natural lakes are mainly <5 m deep and highly seasonal, which is wholly unlike pit lakes, making it difficult to accurately predict which species would colonise and persist in pit lakes. If we consider pit lakes as new lakes and accept that a full species complement will take many years to develop, a focus on demonstrating that a pit lake is making progress along a desired trajectory (see below) is probably an easier closure planning target for regulators and miners.

Pit lakes are sites of primary succession, an ecological process whichoccurs on new substrate lacking soil or vegetation. Primary successionoccurs along a temporal trajectory, and is characterised by initial establishment of pioneer species that, over time, subtlyalter environmental conditions (e.g., through the creation of soils/sediments),resulting in their eventual replacement by taxa more typical of the local area. The initial establishment process (from sterile substrate to pioneer community) is generally predictable,unless diverted by an external force (such as introduction of an exotic pest).

As an ecological concept, succession has been the subject of much debate, particularly around the stages that follow the pioneer communities. Grant (2006)identified the 'state and transition' model of succession as offering the greatest potential for use by mining companies for terrestrial rehabilitation. The state and transition model has potential for aquatic

systems(Scheffer et al. 1993). This model identifies a series of states (i.e. stable communities) that characterise the ecosystem, then transitions (natural events or management actions) that quickly move the ecosystem between states. Stateshave clearly identifiable characteristics (species), and a range of ecosystem processes (such as nutrient cycling, predation) that maintain those characteristics through feedback loops. States can also be undesirable, for example where for example, a community is dominated by exotic species. Therefore, catalogues of states (desired and undesired), transitions (and thresholds) for pit lakes can be created to develop a model showing progress along a trajectory towards the desired restoration goal (McCullough and Etten 2011). Basing mine closure on a primary succession approach, rather than potentially unattainable water quality targets, offers miners and regulators an opportunity to agree on progress towards relinquishment. Similar to the terrestrial rehabilitation case study in south-west Western Australia (Grant 2006), the use of a clearly defined catalogue of desirable and undesirable ecological states, driven bywell-researched management actions, provides a useful (and attainable) template for lease relinquishment. However, our current knowledge of pit lake succession is poor, and further research is needed.

Designing pit lakes to enhance ecological values

Among wetland types, mine pit lakes are physically unique, generally having small catchments, deep waters, little organic matter, and lack of fringing vegetation –characteristics that can limit biodiversity and ecological processes.Functioning sediment processes, such as nutrient cycling supported by organic material, are vital to the normal functioning of lakes. The sediment of pit lakes is dominated by bedrock and talus and has a very low organic content (Blodau et al. 2000), limiting the ability of the lake to develop and sustain ecological productivity (perhaps even more so than poor water quality). Maximising nutrient content of these (generally) ultra-oligotrophic lakes through careful void design and management is the first step to enhancing ecological values, despite poor water quality.

Littoral areas (shallow, gently sloping habitats at the lake edge) are poorly developed in most pit lakes, particularly hard rock mines, which are difficult (and expensive) to contour.In natural lakes, littoral areas generally contain high levels of biodiversity due to their spatial complexity, increased levels of dissolved oxygen, high amounts of organic matter, and location at the interface between the terrestrial and aquatic environments. One strategy for enhancing the littoral zones of pit lakes (in both spatial complexity and nutrient content) is to plant vegetation below the eventual pit lake water height, which will add organic matter to the littoral area when it is eventually flooded. A more 'active' management strategy would be the addition of organic materials to the littoral area, potentially obtained from mine site clearing, to foster sediment development and provide habitat and nutrients for biota. Promotion and enhancement of littoral zones in pit lakes through physical contouring to increase both the area of shallow water and diversity of depths and habitatsis a practical way to increase aquatic biodiversity and support ecological processes.

Aquatic ecosystems are fundamentally influenced by catchment properties(Blanchette and Pearson 2012，Blanchette et al. 2014), particularly through the provision of nutrients in the form of terrestrial leaf litter. Modern terrestrial rehabilitation programs generally approximate normal catchment biomass production (Lund et al. 2013). However, the size of catchments relative to lake area is usually very small compared to most natural lakes (n.b. exceptions being crater and asteroid lakes, emphasizing their potential as models). Where possible, increasing the catchment sizeof pit lakes would increase natural flow of nutrients into the lakes and stimulate succession. Catchment size is normally minimised prior to filling to reduce erosion and associated potential for contamination of the pit lake(Lund and

McCullough 2011). Engineering drainage lines into the catchment could allow catchments to be larger without increasing the risk of erosion. Connecting pit lakes to natural watercourses, while potentially risky for downstream ecosystems, provides the pit lake with a significantly larger catchment area as well as much-needed propagules, nutrients, and aquatic life,which more rapidly progresses succession (Mitsch et al. 2012). In addition to catchment size, catchment quality influences aquatic ecosystems, with addition of appropriate riparian (bankside) and fringing vegetation essential for normal lake processes (van Etten 2012) and erosion minimization.

Recognizing that it will take time to develop desired characteristics

Our model '*de novo*' lakes with significant ecological values have generally been in existence for tens of thousands of years.It is therefore unrealistic to expect pit lakes to develop rapidly without human intervention. We argue that designing pit lakes with the goal of enhancing ecological values can substantially speed up the process of succession. A focus on successional trajectory, rather than modelled water quality end points, means that early relinquishment should be more acceptable to regulators.

Acknowledgements

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