Meeting environmental goals for pit lake restoration – factoring in the biology

M.A. Lund *Mine Water and Environment Research Centre (MiWER), Edith Cowan University, Australia*

C.D. McCullough *Mine Water and Environment Research Centre (MiWER), Edith Cowan University, Australia*

Abstract

Pit lakes may be the greatest legacies of open cut/cast mining operations, yet they are often the least considered at mine closure. Internationally, there are generally well established best practice approaches to the rehabilitation of terrestrial legacies from mining. In contrast, world-wide mine closure guidelines for pit lakes are often simplistic, with a strong focus on water quality. Water quality will generally dictate the functioning of newly created pit lakes, however ecological theory suggests pit lakes should evolve along a predictable trajectory from simple (predominantly) inorganic chemistry driven processes to eventually becoming dominated by biochemical processes. The transition towards significant biological processes developing in the pit lake can be extremely slow due to self-reinforcing chemical processes which buffer against change. Typically, the ecological community that develops will be a subset of that found in regional water bodies. The size and importance of the subset will be largely determined by the similarities in the physical and chemical environments that can be achieved in the pit lake to those of regional water bodies.

This chapter discusses important components of natural water bodies and how these are represented in pit lakes. Consideration needs to be given to which factors typically limit the development of key biotic processes within pit lake systems. These factors may include: 1) unnaturally small catchments of pit lakes which limit opportunities for organic matter and nutrients to accumulate in the lake; 2) lack of riparian zones, which are typically ignored in the terrestrial revegetation of the pit lake catchment, but play an important role in a range of processes associated with natural lakes; 3) limited littoral habitat for the establishment of complex biological communities, as shaping of the lake edge is predominantly confined to considerations of safety and stability (angle of repose); 4) lack of normal lake sediments as the pit lake bed lacks the organic matter content needed to support biological processes; and 5) water quality issues associated with extreme pH and toxicity may form positive feedback loops limiting establishment of biological communities. A brief overview of the natural development of pit lakes is presented, as are recommendations for specific considerations that may improve the rate of biotic development. Internationally, understanding of pit lake ecology is limited and mine closure planning may provide opportunities to investigate and trial restoration issues prior to relinquishment.

1 Introduction

Technological advances have allowed open cut mines to be larger in extent and depth, making them uneconomic to backfill. Therefore, more pits are likely to become pit lakes, making them an increasingly common feature of mined lands. Furthermore many mining regions or mines consist of multiple pits leading ultimately to multiple lakes creating a landscape of lakes – an engineered lake district (McCullough and van Etten, 2011). Lake districts of pit lakes can pose further problems for closure as the pit lakes might not be independently linked via surface or groundwater.

Natural aquatic habitats are also becoming increasingly diminished in their frequency, area and quality through both local and global anthropogenic activities. Concurrently, the growing activities of open cut mining are contributing pit lake aquatic habitats to post-mining landscapes. This offers opportunities during mine closure for mining companies to create a positive environmental legacy (McCullough and van Etten, 2011).

This chapter focusses on pit lakes that will ultimately form part of a region's ecosystem values. The development of biotic processes and an aquatic ecology within these lakes is considered, followed by a brief review of what is currently known and finally how better consideration of the biological fate of pit lakes during mine closure can enhance the development of these processes in a positive trajectory.

2 Key features of lakes that need to be considered in mine closure

2.1 Hydrology

Lake hydrology is essentially a balance between the volume of water in the lake, relative to the volume entering from surface runoff, groundwater and direct rainfall, and the volume leaving the lake via evaporation, transpiration, groundwater and surface discharge (Sawatsky et al., 2011). Pit lakes are no exception to this; although groundwater contributions are often the dominant component. It may take decades for the water table of deep pit lakes to rebound following cessation of dewatering and fill the pit lake. Although pit lakes may be located in, or near natural drainage lines restored upon closure, most pit lakes are deliberately isolated from these sources to reduce risk of environment impact. Nevertheless, the complicated nature of groundwater aquifers in many mined areas and the ongoing need to dewater during operations can make it difficult to accurately predict the final height of water rebound (Figure 1).

Figure 1 An extensively 'rehabilitated' 20 year old pit lake in southwest Western Australia showing the limited catchment of some pit lakes (bounded by the tree line) and the difficulty in predicting final rebound heights. Final water height is at least 2 m below that predicted, reducing the value of much of the bankside contouring for development of a littoral and riparian margin

2.2 Catchments

Any lake is a product of its catchment. Natural lakes connected to drainage lines often have large catchments relative to the lake surface area. However for many pit lakes, the catchment area to lake area ratio is relatively low at <4:1 (Figure 1). Surface inflows may bring high quality rainwater into the lake which can help maintain water quality against evapo-transpiration and solute inputs (Figure 2). However surface runoff, in pit lake catchments is often deliberately minimised to reduce the potential inflow of acid and metalliferous drainage (AMD) from the mine waste in the catchment. Oxidation of sulfidic minerals in exposed mining waste in the presence of water and bacteria can lead to AMD when there is limited neutralisation capacity in the catchment.

Prior to relinquishment, catchments are often shaped to geotechnically stable slopes and revegetated to the waterline. However, many pit lakes fail to attain riparian vegetation, even many years following closure (Figure 1). This is mainly due to a lack of riparian-species specific planting, unstable pit lake margins, low nutrient concentrations in the soils and rapidly changing pit lake water levels during filling (van Etten, 2011). The contribution of organic carbon (C) by terrestrial riparian and catchment vegetation was recognised many years ago as a primary causative factor in water quality improvements in AMD pit lakes (King et al., 1974). Riparian vegetation will also contribute physically to bank stabilisation, facilitating further littoral and bank vegetation establishment. One approach that has worked successfully in the southwest of Western Australia was planting of terrestrial vegetation in areas that were subsequently flooded as the pit lake filled; the dead vegetation then contributed to sediment organic C and habitat in the new lake's littoral zone.

A number of variables within physical, chemical and ecological subsets must therefore be considered when developing a pit lake for an ecological end use. These variables will begin with basic and site-specific physical considerations such as climate and void shell shape that will determine lake size, bathymetry and mixing regime, through to chemical variables such as catchment geology and other land uses that will largely determine water quality (Figure 2). Ecological variables such as the presence of catchment and riparian vegetation and diversity and abundance of primary producers (algae or aquatic plants) which form the base of food-chains for first and second order consumers such as zooplankton and fish will be dependent on the nature of these underlying and often largely pre-determined features.

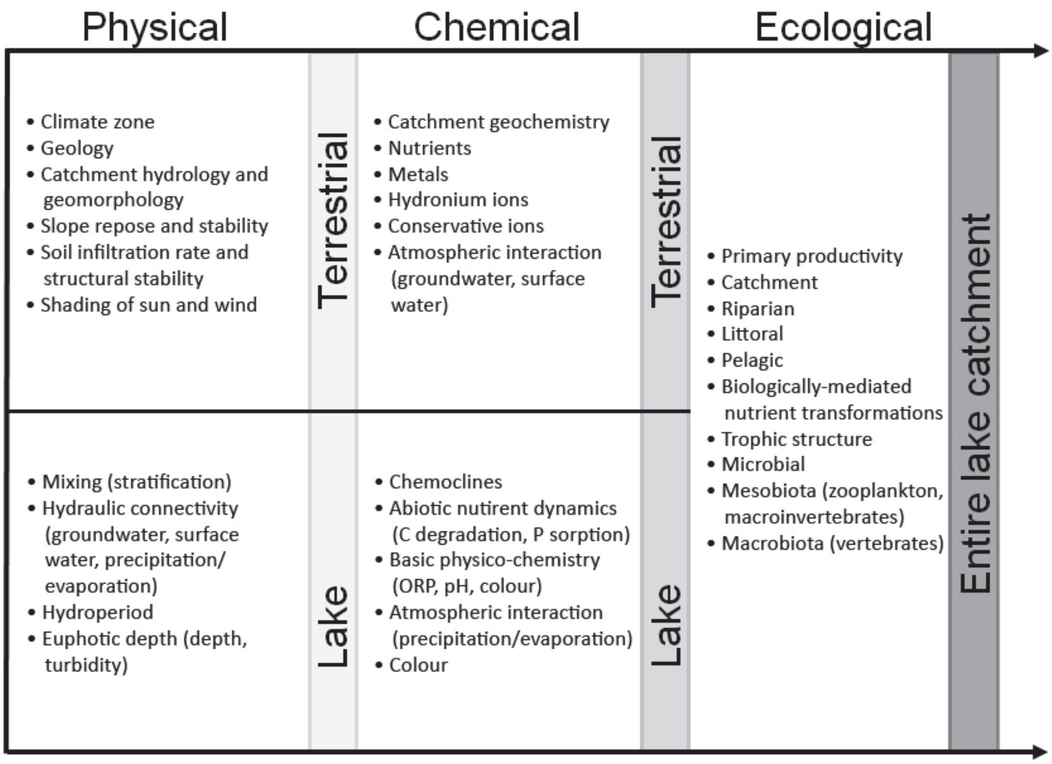

Figure 2 Catchment influences on lake development at different key stages of lake ecosystem development

2.3 Bathymetry

Mine planning attempts to minimise the removal of waste materials, such as overburden, while maximising ore recovery. As a consequence, pit voids are typically steep sided and deep relative to surface area. Pit lakes are often located high in the landscape or away from natural drainage lines. As a result, catchments are predominantly artificial and therefore often small. Where natural watercourses have been diverted to allow mining the pit lake can be reconnected to the catchment, although this creates risks of contaminated discharges. The extent of backfill is often limited due to cost and a desire to avoid burial of potential future resources, so tends to reduce the area of the pit rather than substantially altering its depth profile (Puhalovich and Coghill, 2011). The shape of pit lakes and their surrounds are often important in influencing the phytoplankton communities that occur in the lakes (Weithoff et al., 2010). Pit lakes are also often surrounded by mining waste such as overburden piles which can shelter the pit from normal wind patterns (Huber et al., 2008); reducing water column mixing within the lake. The bathymetry of pit lakes resembles that of many oligotrophic (low productivity) lakes, with steep sides and limited littoral areas relative to limnetic zones (Hakonson et al., 2009). The littoral margin is the shallow productive edge of lakes (Wetzel, 2001). It receives sufficient light for extensive plant and algae communities to grow and provide habitat and food for plankton, macroinvertebrates, fish, amphibians, waterfowl and mammals. The limnetic zone extends beyond this, where a lack of light prevents rooted plant surviving, but not necessarily all types of algae and cyanobacteria. The other important habitat area is the benthos which is the community of species living on, in or near the lake bed.

Habitat availability to biota is further complicated in pit lake ecosystems due to stratification. Stratification is encouraged by the steep sides, low surface area and low wind action, a process that can create a hypolimnion (bottom water layer) isolated from the surface. In many pit lakes, chemical oxygen demand (the low productivity of pit lakes often means that biological oxygen demand is not the principal reason) ensures that the hypolimnion is anoxic. Anoxic water bodies are unsuited to most desired lake organisms such as fin fish and crayfish. For example, in Collie, Western Australia, large freshwater crayfish (marron, *Cherax tenuimanus*) utilise the lake benthos when the lake is fully mixed but rise to depths above the hypolimnion during stratification; presumably due to anoxia. The population size of this desirable endemic fishery is therefore dependant on the size and resources (food and habitat) of the oxic littoral area of the pit lake, which is typically small in pit lakes.

2.4 Nutrient availability

Aside from any water quality issues associated with extreme pH and metal toxicity, most newly formed pit lakes are limited in available macronutrients; primarily C, nitrogen (N) and phosphorus (P), although micro-nutrients any also be limited. The Redfield ratio suggests that 106 moles of C, for every 16 of N and 1 of P are required for algal growth (Redfield and Ketchum, 1963). In natural lakes, C is typically readily available: through allochthonous (external) sources such as riparian vegetation input from the catchment, through natural dissolution of atmospheric CO_2 into the water (bicarbonate buffering), and from carbonates derived from the catchment and/or lake geology. Autochthonous (internal) production by algae and aquatic plants also fixes dissolved C into organic compounds in the lake. Nitrogen is also fixed from the atmosphere by some species of cyanobacteria and bacteria, and also washes in from the catchment from biological or geological sources (surface and groundwater). In natural lakes, sources of P are mainly limited to erosion of geological materials and the limited quantities in allochthonous sources of organic matter. As a result, it is typically P that limits primary productivity in natural lakes (Wetzel, 2001). In pit lake waters, the abundance of metals such as iron, manganese and aluminium ensure that P is often bound to sediment or precipitated out of the water column, further limiting its availability (Kleeberg and Grüneberg, 2005). Iron and manganese bound P is redox sensitive, released when these metals are reduced. This situation commonly occurs during stratification and development of an anoxic hypolimnion.

Nitrification is also limited or restricted under low pH (Nixdorf et al., 2001) which prevents the conversion of ammonia to nitrate/nitrite (NOx). As either NOx or ammonia are both available for algal uptake, this probably has little impact directly on algae, however is an area where pit lakes with relatively high ammonia concentrations differ from natural lakes with proportionally higher NOx. Significantly, denitrification of NOx is a source of alkalinity that is limited by NOx availability (Davison, 1987). Pit lakes have a typically low C concentration in sediments and the water column. The substrate is often almost completely mineral when the lake fills, with the only sources of C commonly being refractory coal and carbonate minerals in host geologies. Organic C accumulates very slowly in the substrates of pit lakes due to low input rates from allochthonous (poor riparian development, small lake catchment size) and autochthonous (in-lake plants and algae limited by nutrient availability) sources. Benthic algae and bacteria often occur across the lake sediment absorbing both nutrients from groundwater entering the lake and bound to sediment. Despite what appears on occasion to be relatively heavy benthic algal biomass, this growth may make little effective contribution to increasing substrate organic matter concentrations (Laskov et al., 2002). In strongly acidic pit lakes C is limited to dissolved CO_2 gas as the major C source. Heterotrophic photosynthetic bacteria also require dissolved organic C for growth (Tittel and Kamjunke, 2004). Low turbidity and dissolved organic carbon concentrations are typical in acidic waters, and results in extreme water clarity that creates ultra violet light (UV) exposure problems for a range of biota that could live in the lake. Furthermore, the UV and acidity accelerate dissolved organic C mineralisation to CO_2 which is then lost from the lake ecosystem (Schindler and Curtis, 1997), further limiting C availability. Low nutrient availability is often reflected in deep chlorophyll maxima, with algae occurring in peak abundances at depth to enable access to nutrients in the hypolimnion while protected from UV exposure.

2.5 Habitat

A major difference in the littoral area between natural oligotrophic lakes and pit lakes is that natural lakes tend to have diverse structural elements such as rocks, logs and plants (emergent and submerged) that provide habitat for organisms (Figure 3). Pit lakes have a typically poorly developed riparian zone, few plants and logs, and often sandy or muddy edges (McCullough et al., 2009). The substrate of pit lakes is also dominated by bedrock and talus and has a very low organic content (Blodau et al., 2000). Therefore the littoral regions of pit lakes are generally much poorer habitat than those found in natural lakes. In natural lakes, macroinvertebrates and decomposers (bacteria and fungi) breakdown organic matter into usable dissolved forms and a small quantity of small fragments form a denser layer in the sediment. Little is known of how these processes work in acidic pit lakes.

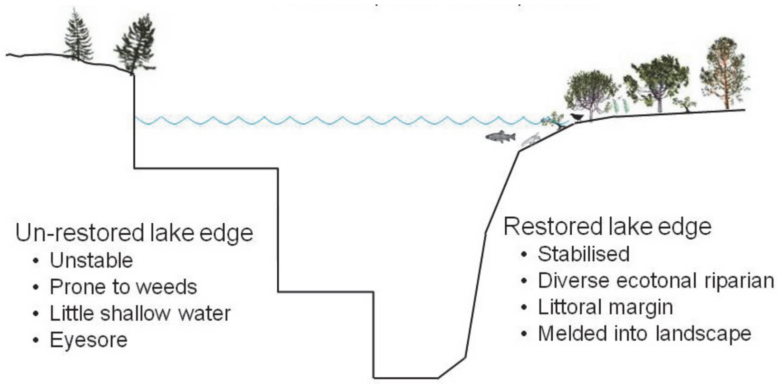

Figure 3 Development of riparian and littoral edges increases biodiversity and provides ecosystem processes to facilitate pit lake ecosystem development

2.6 Taxa

Primary production contributes to the ecological value of a pit lake in many ways. Algal primary production and allochthonous C form the basis of lake food chains providing the energy sources that are the basis of lake-ecosystem food webs (Wetzel, 2001). Primary producers can also facilitate sulfate reduction, increasing alkalinity and pH in acidic pit lakes (Nixdorf and Kapfer, 1998; Lund and McCullough, 2009), chelate metals directly causing toxicity or sorbing phosphorus (Kalin et al., 2001), and help mitigate carbon limitation (Nixdorf and Kapfer, 1998). There has been remarkably little research completed on the biota of pit lakes, with algae (benthic and planktonic) receiving the most attention (Beulker et al., 2004), with limited studies of zooplankton, macroinvertebrates (Proctor and Grigg, 2006) and very few for vertebrates.

Toxicity due to acidity and elevated metal/metalloid concentrations limits the richness of species found in pit lakes primarily to more cosmopolitan and tolerant taxa (Neil et al., 2009). Abundance is also typically low, however this appears to be primarily due to limited food resources rather than due to pH or metal toxicity (Wollmann et al., 2000). Pit lakes that are circum-neutral tend towards the diversity and abundance of macroinvertebrates in natural lakes (Proctor and Grigg, 2006; Lund and McCullough, in press), although still limited by the availability of food and habitat in pit lakes.

Terrestrial animals often use pit lakes as a source for watering, e.g. feral animals such as pigs and goats and native animals. Pit lakes can pose a significant risk to animals if the water quality is toxic or the sides of the lake have not been bunded and create a falling risk. Water birds will also use the pit lake for habitat as protection from predators, if water quality is suitable and there are sufficient food and habitat resources.

3 Natural analogues for pit lakes

What are the analogue systems for pit lakes? Firstly, pit lakes cannot be returned to pre-mining conditions, as formerly there was typically no lake/wetland. Pit lakes are characteristically large in area and deep and as such may not have any natural counterparts in the region. For example, where natural lakes are very shallow, they may still provide some value as analogues for the pit lake littoral area (McCullough et al., in press). However, there remains no reference for the limnetic or profunal zone of the pit lake. Despite the problems, it will possible to use regional aquatic systems as 'analogues' for at least specific habitats within a pit lake and use this to as a reference for what goals might be achievable (McCullough and van Etten, 2011).

4 What happens if you do nothing?

The 'do nothing' approach to pit lakes considered here, is following relinquishment and compliance with minimum regulatory requirements, such as stable slopes, fencing, etc. Geochemical weathering processes in the catchment of a pit lake can lead to poor water quality and toxicity to aquatic life (Neil et al., 2009). Affected lakes typically have limited ecological value and may affect regional water bodies through contamination of surface and groundwater sources (McCullough and Lund, 2006).

Given sufficient time many pit lakes will move from being dominated by chemical processes to biological processes. In this way, pit lakes are similar to any other area on the planet that has not had biological life on it previously, e.g. lava flows, landslides, etc., King et al (1974) describes natural restoration of pit lakes though natural, albeit slow, remediation processes such as water quality remediation by primary production and sulfate reduction. This finding has lead to an assumption that pit lakes will follow an evolution from young to mature lakes resulting in lakes with a well-developed ecosystem (Kalin and Geller, 1998). However, there are many examples of pit lakes formed soon after open cut mining technologies became commonplace that have not improved in environmental quality measures such as biodiversity and ecological function (McCullough et al., 2008, 2009). Therefore for many pit lakes, the 'do-nothing' restoration approach which assumes that primary succession will eventually lead to a mature lake is likely to take periods of time that are too long (hundreds to thousands of years) to be acceptable to regulators or the public (Schultze et al., 2009; Jones and McCullough, 2011).

5 Considerations for mine closure planning

The following are suggestions with regards to the future biology of pit lakes that can be considered during mine closure planning:

- Although it may be unfeasible to create a 'natural' bathymetry for a pit lake, biological development will be enhanced by first creating geotechnically stable slopes. The shallow littoral region of lakes is the most productive area. However, in pit lakes this area tends to be designed to meet slopes for human safety rather than the shallower slopes that would be more beneficial to biota.
- Pit lake catchments are generally minimised to reduce risks associated with offsite contamination. The ecology of pit lakes could be enhanced by maximising water flows across uncontaminated soils into the lake and thereby enhancing the potential for allochthonous C washing into the system.
- Dedicated planting of riparian vegetation to create a source of C and habitat to support biodiversity in the littoral areas. This is particularly important for attracting birds and amphibians. The use of cleared vegetation from operation areas, including tree trunks, stumps and branches in and around the littoral area may help stabilise lake banks and provide a source of slow release C and other nutrients during decomposition and also importantly animal habitat. Alternatively, amendments with complex organic materials could be made in some circumstances to accelerate this development process. Creation of a three-dimensional structure in the littoral area in

particular, through use of logs, organic matter, riparian and if necessary inert materials would enhance habitat available for larger species, e.g. birds, fish and amphibians.

- In pit lakes amendment with low concentrations of P and/or N may stimulate primary production. Amendments with nutrients and organic matter are also known to stimulate a range of biological alkalinity producing processes that will work to improve water quality.

6 Conclusions

As a pit lake fills, biological activity begins in the lake; it is initially limited by physical, chemical and pH constraints. In many instances biological development will overcome the physical and chemical constraints and start to develop a pit lake aquatic ecosystem. Although little is known about pit lake ecology, our understanding of natural lakes suggests that relatively inexpensive and practical treatments applied to the pit prior to filling and during its early life should be able to improve the rate of ecological development significantly. Recognition during mine closure planning that many relinquished pit lakes will eventually develop ecosystem values would allow trials of many of the ideas presented in this chapter. A by-product of this investment is that environmental end use goals for pit lakes are recognised almost universally as the 'gold standard' and will assist companies with their plans to successfully close leases pit lakes with minimum liabilities remaining with stakeholders.

Acknowledgements

Thanks to the Australian Coal Research Programme (ACARP), the Western Australian Department of Water, and the mining companies: Rio Tinto, Premier Coal, Xstrata, Griffin Coal and Kemerton Silica Sand that have all supported our research work restoring pit lakes that have then formed the basis for the ideas developed herein. Thanks also to Will Stock and Eddie van Etten of Edith Cowan University for fruitful discussion.

References

Beulker, C., Lessmann, D. and Nixdorf, B. (2004) Aspects of phytoplankton succession and spatial distribution in an acidic mining lake (Plessa 117, Germany), Acta Oecologica, Vol. 24, pp. S25–S31.

Blodau, C., Peine, A., Horffman, S. and Peiffer, S. (2000) Organic matter diagenesis in acidic mine lakes, Acta Hydrochimica et Hydrobiologica, Vol. 28, pp. 123–135.

Davison, W. (1987) Internal elemental cycles affecting the long-term alkalinity status of lakes: implications for lake restoration, Scweizischer Zeitschrift fur Hydrobiologie, Vol. 49, pp. 186–201.

Hakonson, T.E., Meyer, V.F. and Dean, A. (2009) Significance of biological productivity of pit lakes for interpreting ecological risks, in Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability, D.N. Castendyk and L.E. Eary (eds), Society for Mining, Metallurgy and Exploration, Colorado, pp. 179–186.

Huber, A., Ivey, G.N., Wake, G. and Oldham, C.E. (2008) Near-surface wind-induced mixing in a mine lake, Journal of Hydraulic Engineering-ASCE, Vol. 134, pp. 1464–1472.

Jones, H. and McCullough, C.D. (2011) Regulator guidance and legislation relevant to pit lakes, in Mine Pit Lakes: Closure and Management, C.D. McCullough (ed), Australian Centre for Geomechanics, Perth, Australia, pp. 137–152.

Kalin, M., Cao, Y., Smith, M. and Olaveson, M.M. (2001) Development of the phytoplankton community in a pit-lake in relation to water quality changes, Water Research, Vol. 35, pp. 3215–3225.

Kalin, M. and Geller, W. (1998) Limnological fundamentals of acid mining lakes, in Acidic Mining Lakes, W. Geller, H. Klapper and W. Salomons (eds), Springer, Berlin, pp. 423–425.

King, D.L., Simmler, J.J., Decker, C.S. and Ogg, C.W. (1974) Acid strip mine lake recovery, Journal of the Water Pollution Control Federation, Vol. 46, pp. 2301–2315.

Kleeberg, A. and Grüneberg, B. (2005) Phosphorus mobility in sediments of acid mining lakes, Lusatia, Germany, Ecological Engineering, Vol. 24, pp. 89–100.

Laskov, C., Amelung, W. and Peiffer, S. (2002) Organic matter preservation in the sediment of an acidic mining lake, Environmental Science and Technology, Vol. 36, pp. 4218–4223.

Lund, M.A. and McCullough, C.D. (2009) Biological remediation of low sulphate acidic pit lake waters with limestone pH neutralisation and amended nutrients in International Mine water Conference, Pretoria, South Africa, 19–23 October, International Mine Water Association, 8 p.

Lund, M.A. and McCullough, C.D. (in press) How representative are pit lakes of regional natural water bodies? A case study from silica sand mining, in Proceedings of the International Mine Water Association (IMWA) Congress, Aachen, Germany.

McCullough, C.D. and Lund, M.A. (2006) Opportunities for sustainable mining Pit lakes in Australia, Mine Water and the Environment, Vol. 25, pp. 220–226.

McCullough, C.D., Lund, M.A. and May, J.M. (2008) Field scale trials treating acidity in coal pit lakes using sewage and green waste, in Proceedings 10th International Mine Water Association (IMWA) Congress, Karlovy Vary, Czech Republic, pp. 599–602.

McCullough, C.D., Steenbergen, J., te Beest, C. and Lund, M.A. (2009) More than water quality: environmental limitations to a fishery in acid pit lakes of Collie, south-west Australia, in Proceedings of the International Mine Water Conference, Pretoria, South Africa, 19–23 October, International Mine Water Association, pp. 507–511.

McCullough, C.D. and van Etten, E.J.B. (2011) Ecological restoration of novel lake districts: new approaches for new landscapes Mine Water and the Environment, DOI (10.1007/s10230-011-0144-6).

McCullough, C.D., van Etten, E.J.B. and Lund, M.A. (in press) Setting restoration goals for restoring pit lakes as aquatic ecosystems: a case study from south west Australia, in Proceedings of the Heavy Minerals 2011 Conference, Perth, Australia, 4–5 October.

Neil, L.L., McCullough, C.D., Lund, M.A., Tsvetnenko, Y. and Evans, L. (2009) Toxicity of acid mine pit lake water remediated with limestone and phosphorus, Ecotoxicology and Environmental Safety, Vol. 72, pp. 2046–2057.

Nixdorf, B., Fyson, A. and Krumbeck, H. (2001) Review: plant life in extremely acidic waters, Environmental and Experimental Botany, Vol. 46, pp. 203–211.

Nixdorf, B. and Kapfer, M. (1998) Stimulation of phototrophic pelagic and benthic metabolism close to sediments in acidic mining lakes, Water, Air and Soil Pollution, Vol. 108, pp. 317–330.

Proctor, H. and Grigg, A. (2006) Aquatic macroinvertebrates in final void water bodies at an open cut coal mine in Central Queensland, Australian Journal of Entomology, Vol. 45, pp. 107–112.

Puhalovich, A.A. and Coghill, M. (2011) Management of mine wastes using pit void backfilling methods – current issues and approaches, in Mine Pit Lakes: Closure and Management, C.D. McCullough (ed), Australian Centre for Geomechanics, Perth, Australia, pp. 3–14.

Redfield, A.C. and Ketchum, B.H. (1963) The influence of organisms on the composition of seawater, in The Sea, M.N. Hill (ed), Wiley Interscience, New York, USA, pp. 26–79.

Sawatsky, L.F., Fitch, M.A., Beersing, A.K. and Vandenberg, V.A. (2011) Hydrologic and geomorphic design of pit lakes for long-term sustainability, in Mine Pit Lakes: Closure and Management, C.D. McCullough (ed), Australian Centre for Geomechanics, Perth, Australia, pp. 53–62.

Schindler, D.W. and Curtis, P.J. (1997) The role of DOC in protecting freshwaters subjected to climatic warming and acidification from UV exposure, Biogeochemistry, Vol. 36, pp. 1–8.

Schultze, M., Geller, W., Wendt-Potthoff, K. and Benthaus, F. (2009) Management of water quality in German pit lakes, Securing the Future and 8th ICARD, Skelleftea, Sweden.

Tittel, J. and Kamjunke, N. (2004) Metabolism of dissolved organic carbon by planktonic bacteria and mixotrophic algae in lake neutralisation experiments, Freshwater Biology, Vol. 49, pp. 1062–1071.

van Etten, E.J.B. (2011) The role and value of riparian vegetation for mine pit lakes, in Mine Pit Lakes: Closure and Management, C.D. McCullough (ed), Australian Centre for Geomechanics, Perth, Australia, pp. 91–106.

Weithoff, G., Moser, M., Kamjunke, N., Gaedke, U. and Weisse, T. (2010) Lake morphometry and wind exposure may shape the plankton community structure in acidic mining lakes, Limnologica – Ecology and Management of Inland Waters, Vol. 40, pp. 161–166.

Wetzel, R.G. (2001) Limnology – lake and river ecosystems, 3rd edition, Academic Press, San Diego, United States, 1006 p.

Wollmann, K., Deneke, R., Nixdorf, B. and Packroff, G. (2000) Dynamics of planktonic food webs in three mining lakes across a pH gradient (pH 2–4), Hydrobiologia, Vol. 433, pp. 3–14.