Importance of catchment vegetation and design to long-term rehabilitation of acidic pit lakes

Mark A. Lund[1], Eddie J.B. van Etten[1], Clint D. McCullough[1,2]

[1]Mine Water and Environment Research Centre (MiWER), School of Natural Sciences, Edith Cowan University, 270 Joondalup Drive, WA 6027, Australia; m.lund@ecu.edu.au
[2]Golder Associates, West Perth, Western Australia 6005, Australia

Abstract Lakes are an extension of their catchment and neither should be considered in isolation. However, pit lakes have typically small catchments that have rarely been designed for their ecological significance to the lake. This paper discusses a preliminary assessment of the vegetation of catchments around selected pit lakes of the Collie Lake District. We examine how effectively modern and historical catchment revegetation techniques contribute organic matter to the pit lakes. Overall, there appear to be a number of areas where modified rehabilitation and revegetation in pit lake catchment design at closure could lead to enhanced ecological values in the lakes.

Keywords Water quality, catchment, ecology, pit lake, end-uses, mine closure.

Introduction

A lake is a product of its catchment. Natural lakes connected to drainage lines often have large catchments relative to the lake surface area. Catchments provide lakes with sources of water (surface and subsurface), nutrients and allochthonous (external to the lake) carbon. Natural catchments also show a gradient of vegetation into the lake, moving from terrestrial communities, through riparian to fringing vegetation assemblages (Van Etten *et al.* 2012). In many regions, shallow areas connected (fully or partially) to the lake (wetlands) provide a range of ecosystem services including nutrient retention as well as transformation, and sources of biological diversity and propagules (see Mitsch and Gosselink 2007). In contrast, pit lakes which are formed upon cessation of mining, when open-cut voids that extend below the water table fill with groundwater and surface runoff, are rarely rehabilitated to incorporate all these natural features (Van Etten *et al.* 2011).

For many mine pit lakes, the catchment area to lake area ratio is relatively low at <4:1. Surface inflows may bring high quality rainwater into the lake which can help maintain water quality against evapo-transpiration and solute inputs. However surface runoff, from the catchment is often deliberately minimised to reduce the potential inflow of acid and metalliferous drainage (AMD) from the mine waste in the catchment (Müller *et al.* 2011). Oxidation of sulphidic minerals in exposed mining waste in the presence of water and bacteria can lead to AMD when there is limited neutralisation capacity in the pit lake catchment.

Prior to relinquishment, catchments are often shaped to geotechnically stable slopes and revegetated to or below the waterline. However, many pit lakes fail to attain riparian (water influenced terrestrial vegetation) or fringing (located in the lake water) vegetation, even many years following closure (Lund and McCullough 2012). This is mainly due to a lack of planting of riparian species, unstable pit lake margins, low nutrient concentrations in the soils and rapidly changing pit lake water levels during filling (van Etten 2012). The contribution of organic carbon (C) by 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.

In this study, we aimed to quantify the organic matter generated by pit lake catchments and investigated the transfer of this material into the pit lakes in the Collie Lake District (Western Australia).

Methods

Study Site

The town of Collie (population over 10,000) is located on the north western rim of the Collie Coal Basin within the Collie River catchment. Collie lies nearly 160 km south-southeast of Perth and is the centre of coal mining in Western Australia (Fig. 1). The major land uses in the catchment are coal mining, timber production, power generation and agriculture. Approximately 79 % of the catchment is production forest. The Collie Coal Basin covers an area of approximately 225 km^2. It is 27 km long by 13 km wide and elongated in a north-west to south-east direction. The basin consists of two lobe-shaped sub-basins, the Cardiff sub-basin (151 km^2) to the west and the Premier sub-basin (74 km^2) to the east, in part separated by a faulted basement high, known as the Stockton Ridge (Moncrieff 1993). Collie coal is a sub-bituminous coal with a relatively low sulfur content (0.3 – 0.9 %), and low caking and low ash (4–9 %) properties (Le Blanc Smith 1993). Low amounts of acidity are generated through pyrite oxidation, ferrolysis and secondary mineralization. This acidity is still sufficient to generate low pH in the pit lakes due to the low buffering capacity of the surrounding rock.

Collie is situated in an area of Mediterranean climate, with hot, dry summers (range 12–29 °C) and cool, wet winters (range 4–15 °C; Commonwealth of Australia Bureau of Meteorology, 25/02/2009). 75 % of the rainfall occurs during the five months from May to September. The 100 year mean annual rainfall for the Collie Basin is 939 mm (Commonwealth of Australia Bureau of Meteorology, 25/02/2009), although this has decreased to an average of 690–840 mm over the past 20 years (Craven 2003).

Several pit lakes of various sizes have created a Lakes District within the Collie Coal Basin. Four pit lakes (Stockton, WON9, Lake Kepwari and Black Diamond) and a sumpland formed around an overburden pile adjacent to

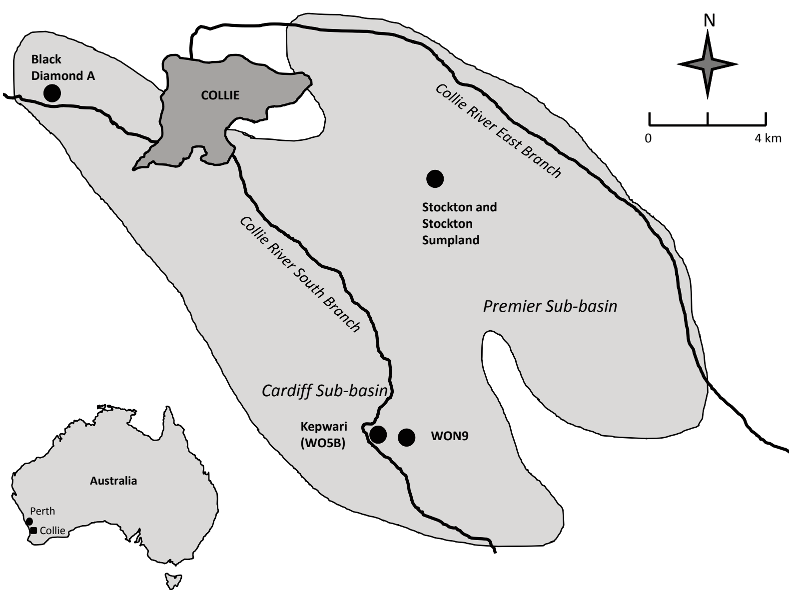

Fig. 1 *Map showing location of the Collie Coal Basin and pit lakes sampled.*

Stockton Lake were sampled. More details of the pit lakes can be found in Lund and McCullough (2012).

Sampling Methods

Five sites including four pit lakes and a nearby sumpland were sampled in June 2013. At each site, a 5 m wide belt transect was run perpendicular to the shore to the top of the catchment through each vegetation community. The transect extended into the lake, with samples taken at 5 m in from the shore. Between two to five transects were taken at each site, with at least one transect placed in each vegetation cover type. Every tree in the belt transect was identified and its diameter at breast height measured. At least at 5 m intervals, in the middle of the transect, % litter cover and depth were assessed. Within 2 m of the lake shore and in the middle of the transect a 0.25 × 0.25 m quadrat was used to collect all surface leaf litter, and soils 0–50 mm deep. Google Earth and ground-truthing were used to determine catchment areas and areal extent of vegetation communities. Litter and soils were air dried, then dried at 80 °C to constant weight. Loss on ignition (LOI) was used as an assessment of organic matter, following burning at 550 °C to constant weight.

Results and Discussion

Stockton Sumpland and WON9 had catchment to lake area ratios that were just above 4, while Black Diamond A was approximately 3 and Stockton and Kepwari <2 (Table 1). All the lakes had no major surface inflows other than runoff, although Kepwari was rapidly filled by the Collie River (Salmon *et al.* 2008). Stockton has received dewatering water from the nearby Ewington mine via a small stream in the past, although this is not currently occurring and so has been excluded from the estimate of the catchment area. The catchments of WON9 and Kepwari were revegetated using a typical upland jarrah (*Eucalyptus marginata*) forest seed mix (jarrah forest is the dominant forest ecosystem in the area). WON9 had no riparian or fringing vegetation, the older (50+ years) lakes of Stockton and Black Diamond all had small patches of fringing vegetation (<20 % of perimeter) but no true riparian, Stockton Sumpland (50+ years) was almost completely surrounded by fringing vegetation but no riparian. Lake Kepwari is starting to show development of patches of both riparian and fringing vegetation believed to be due to entry of propagules during a river breach (see McCullough *et al.* 2012).

The two Lake Stockton catchments are covered in relatively few jarrah trees (self-established, after ≈ 50 years without formal rehabilitation), but these trees are large and overall these catchments resemble old growth jarrah forest in terms of stocking rates (Table 2).

The Lake Kepwari catchment is almost entirely covered in ≈ 10-15 y.o. rehabilitation and in terms of tree density resembles 50–80 y.o. regrowth jarrah forest (McCaw 2011), although

Lake	Lake Area	Catchment Area	Lake: Catchment Area Ratio	Revegetation	Jarrah Forest	Plantation	Sparse
Stockton	15	23	1.5				7.3
Stockton Sumpland	1.9	75	4.0				5.6
WON9	7.8	31-	4.0	23			
Black Diamond A	4.9	15	3.0		4.5	1.7	3.9
Kepwari	99	150	1.5	50			

Table 1 *Area (ha) of the pit lakes, catchments and major vegetation communities*

Lake	Tree Density		Tree Basal Area		Surface Litter	
	trees ha^{-1}	trees $catchment^{-1}$	m^2 ha^{-1}	m^2 per catchment	t ha^{-1}	t $catchment^{-1}$
Stockton	330	2400	27.0	197	7.6	55
Stockton Sumpland	310	1800	14.8	84	1.9	11
WON9	166	3900	0.4	9	0.9	21
Black Diamond A	660	6700	12.7	128	12.8	129
Kepwari	702	35000	8.3	417	9.5	480
Old Growth & Long Unburnt Jarrah Forest#	200-500		30-50		15-25	
Regrowth & Prescribed Burned Jarrah Forest#	500-1000		20-30		5-10	

data based on (Abbott and Loneragan 1986; Stoneman et al. 1997; McCaw 2011)

Table 2 *Tree density, basal area and surface little coverage for the pit lake catchments compared to natural and revegetated jarrah forest.*

stocking in terms of basal area per hectare is lower than regrowth at this early stage. The WON9 catchment is also post-mine rehabilitation but is only a few years old and trees are all less than 100 mm in diameter. The low density of these small trees suggests mature tree density will be very low in this catchment (*e.g.* compared to Kepwari catchment). The Black Diamond A catchment is covered in a variety of distinct vegetation types (regrowth jarrah forest, dense plantations and sparse/disturbed jarrah forest). On average, it is similar to jarrah regrowth in terms of tree density, but has substantially lower basal area per hectare than jarrah forest.

When scaled up to whole catchments, there are thousands of trees in the pit lake catchments, with around thirty five thousand trees in the largest Kepwari catchment (Table 2). This is however several orders of magnitude lower than might be expected in natural jarrah forest catchments. The size of jarrah forest catchments varies widely depending on stream and catchment position, in the range of 1000 to several 100,000 ha (Borg *et al.* 1987), but are typically much larger than the Collie pit lake catchments.

Surface leaf litter quantities per hectare in mine pit catchments are generally similar to that found in regularly burned jarrah forest, with the exception of WON9 (yet to see much litter build up) and the Stockton sumpland catchment (which has a lot of bare ground). They are lower than long unburnt jarrah forest however (Table 2). Litter per hectare is typically less near lake edge compared to interior of vegetation. For instance, 18 t ha^{-1} of surface litter is found inside Kepwari rehabilitation, on average, whereas in rehabilitation closest to the edge of lake it only averages 1.1 t ha^{-1}. This suggests that litter either doesn't make its way down to the lake edge (via surface water flows as well as gravity), doesn't accumulate here because of low tree density, or is readily lost from this zone.

The relatively young age of the pit lakes is reflected in the low carbon contents (Loss on Ignition) of the sediments near the shore (Table 3). The only exception was Stockton which had levels starting to approach those of natural sediments in the local area (>30 %).

Lake	Soil	Water
Black Diamond A	3.4±1.0	4.1±1.6
Lake Kepwari	1.8±0.6	2.2±0.2
WON9	5.4±1.8	5.4±1.6
Stockton	3.9 (*n*=2)	24.1±10.9
Stockton Sumpland	-	4.3 (*n*=2)

Table 3 *Loss on Ignition in soil and sediment collected within 5 m of the shoreline at 0–50 mm depth for soil and 0–10 mm depth for sediment at the pit lakes.*

This however may not truly reflect organic matter inputs as loss on ignition also includes coal particles which occur in some samples. Equally poor organic matter concentrations were found in the catchments, despite some being of reasonable age and both WON9 and Lake Kepwari being rehabilitated with stored topsoil.

Conclusions

Rehabilitation of pit lake catchments achieves values of trees, biomass and litter that approximate those of natural forest within 10–15 years compared to 50 years at unrehabiliatated sites. Pit lake catchments are very small compared to comparable natural systems, typically at least 10 times smaller. Therefore despite the relatively high production of leaf litter and other plant debris, the total quantity available will be similarly smaller. Observations at the pit lakes studied, noted that horizontal ripping created potential barriers to litter transport to the lakes. This was overcome partially by the steep slope of pit lake catchments and that surface runoff utilises the contour rips as drainage lines. As no defined flow paths have been engineered into the pit lake catchment, surface flow collects along the rip lines it eventually overtops and creates an erosional gully into the lake. This gully cuts through all the carefully layered overburden and potentially exposes acid generating materials. We recommend that hydrological studies be made and that drainage lines be engineered into the catchment prior to revegetation; ideally with detailed erosion considerations such as bio erosion modelling with SIBERIA or similar model (Willgoose 2005). There is little evidence that the leaf litter produced in the catchment enters the lake, although this could be simply be due to the low quantities produced. Riparian species need to be included in seed mixes around the lakes edge to stimulate the growth of this important aquatic community, which after 50 years is still absent around the pit lakes studied (McCullough and Van Etten 2011; Van Etten *et al.* 2012). Connection to natural waterways, where this can be achieved safely, has the advantage of introducing a range of propagules that stimulate the development of riparian and fringing communities. This study highlights that current practices of minimising catchment areas around pit lakes may work against their long term natural remediation.

Acknowledgements

This study was jointly funded by Australian Coal Association Research Program (Project C21038) and Premier Coal Yancoal Ltd. The authors are grateful to Dr Digby Short at Premier Coal and the Department of Environment and Conservation for access to the lakes. Thanks to Mark Bannister (ECU) for chemical analysis.

References

Abbott I, Loneragan OW (1986) Ecology of Jarrah (*Eucalyptus marginata*) in the northern Jarrah forest of Western Australia. Dept. of Conservation and Land Management., Perth.

Borg H, Stoneman GL, Ward CG (1987) Stream and Ground Water Response to Logging and Subsequent Regeneration in the Southern Forest of Western Australia: Results from Four Catchments. Dept of Conservation and Land Management, Perth.

Craven E (2003) Acid Production in the Overburden of Lake WO5B, Collie. Environmental Engineering Project 640.406, Thesis, University of Western Australia, Australia, Perth.

King DL, Simmler JJ, Decker CS and Ogg CW (1974) Acid strip mine lake recovery. Journal of the Water Pollution Control Federation 46: 2301–2315

Le Blanc Smith G (1993) The geology and Permian coal resources of the Collie Basin, Western Australia. Western Australian Geological Survey Report 38. 86 p

Lund MA, McCullough CD (2012) Meeting environmental goals for pit lake restoration – factoring in the biology. In: Mine Pit Lakes: Closure and Management, McCullough CD (ed) Australian Centre for Geomechanics, Perth, 83–90 pp

Lund MA, McCullough CD, Kumar RN (2012) The Collie Pit Lake District, Western Australia: An Overview. In: McCullough CDL, M.A.; Wyse, L. (Ed.) International Mine Water Association Symposium. Bunbury, Australia, IMWA, p 287 – 294

McCaw WL (2011) Characteristics of jarrah (*Eucalyptus marginata*) forest at FORESTCHECK monitoring sites in south-west Western Australia: stand structure, litter, woody debris, soil and foliar nutrients. Australian Forestry 74: 254–265

McCullough CD, Kumar RN, Lund MA, Newport M, Ballot E and Short D (2012) Riverine breach and subsequent decant of an acidic pit lake: evaluating the effects of riverine flow-through on lake stratification and chemistry. In: International Mine Water Conference. Bunbury, Western Australia, IMWA, p 533–540

McCullough CD, Van Etten EJB (2011) Ecological restoration of novel lake districts: new approaches for new landscapes. Mine Water and the Environment 30: 312–319

Mitsch WJ, Gosselink JG (2007) Wetlands. 4th edn, John Wiley & Sons Inc, Hoboken, NJ.

Moncrieff JS (1993) Hydrogeology of the Collie Basin, Western Australia: Western Australia Geological Survey. 129–153 p

Müller M, Eulitz K, McCullough CD and Lund MA (2011) Model-based investigations of acidity sinks and sources of a pit lake in Western Australia. In: Rüde TR; Freund A and Wolkersdorfer C (Eds.), Proceedings of the International Mine Water Association (IMWA) Congress. Aachen, Germany, p 41–45

Salmon SU, Oldham CE, Ivey GN (2008) Assessing internal and external controls on lake water quality: Limitations on organic carbon-driven alkalinity generation in acidic pit lakes. Water Resources Research 44: W10414

Stoneman GL, D. S. Crombie, K. Whitford, F. J. Hingston, R. Giles, C. C. Portlock, J. H. Galbraith and Dimmock. GM (1997) Growth and water relations of *Eucalyptus marginata* (Jarrah) stands in response to thinning and fertilization. Tree Physiology 17: 267–274

Van Etten EJB (2012) The role and value of riparian vegetation for mine pit lakes. In: Mine Pit Lakes: Closure and Management, McCullough CD (ed) Australian Centre for Geomechanics, Perth, 91–106 pp

Van Etten EJB, McCullough CD, Lund MA (2011) Setting restoration goals for restoring pit lakes as aquatic ecosystems: a case study from south west Australia. In: Proceedings of the Heavy Minerals 2012 Conference. Perth, Australia, p 339–350

Van Etten EJB, McCullough CD, Lund MA (2012) Importance of topography and topsoil selection and storage in successfully rehabilitating post-closure sand mines featuring pit lakes. Mining Technology 121: 139–150