Limnology and Ecology of Low Sulphate, Poorly-buffered, Acidic Coal Pit Lakes in Collie, Western Australia

Mark A Lund, Clint D. McCullough

School of Natural Sciences, Edith Cowan University, 100 Joondalup Drive, WA 6027, Australia.
e-mail. m.lund@ecu.edu.au

Abstract

Coal mining in Collie (Western Australia) has produced pit lakes that range in area from <1 to 10 ha surface area, <10 to 70 m depth, 5-48 years in age water quality and the extent of remediation from none to extensive. Collie coal has low sulphur content and upon oxidation produces low amounts of acid mine drainage (AMD). However, low natural alkalinity in regional geologies produces pH as low as 3.5 in some pit lakes. Low pH is accompanied by low metal concentrations in pit lake waters, except for Al which is often at high concentrations and as very toxic species.

Analysis of pit lake water quality data from 1995 to present has shown that in the absence of significant surface acidity inputs, acidity within the pit lakes slowly declines but without commensurate changes in pH. Increases in pH are only accompanied by inputs of circum-neutral groundwater or surface waters. Adits entering some pit lakes are thought to remain an important source of acidity. Experimental additions of organic matter direct the lakes on a different water quality evolution trajectory to neutral water inputs, highlighting that despite comparatively good water quality compared to many pit lakes worldwide, the lakes remain considerably different to their natural counterparts.

Introduction

Collie is located in the south-west of Western Australia and experiences a Mediterranean-style climate of cool wet winters and hot dry summers. Collie is the main coal mining region of Western Australia, with most of extracted coal for electricity generation (Figure 1). Historical and ongoing open cut mining operations have created a number of pit lakes, the oldest nearly 50 years old. Collie black coal has low sulphur concentrations and only produces low amounts of acidity through pyrite oxidation, ferrolysis and secondary mineralization. This low acidity is still sufficient to generate low pH in pit lakes due to low buffering capacity of surrounding geologies. Two of the pit lakes, abandoned in the early 1960s without remediation or rehabilitation, are accessible by the public. These pit lakes have become favoured swimming and water skiing areas (McCullough and Lund 2006). In 1994, one of these lakes (ironically a lake which post abandonment has had most of its surrounds rehabilitated), Stockton Lake was temporarily closed by the Government Agency responsible when pH levels dropped below 4.5 which is the Australasian contact standard (ANZECC/ARMCANZ 2000). Quantities of limestone chip and then sodium hydroxide were added to fix the problem, without success. The publicity surrounding this incident resulted in a number of studies into the lakes, including end-use options, remediation strategies, general ecology and limnology.

End uses investigated for Collie pit lakes have included trials of aquaculture, saline water storage (saline flows in the Collie River are diverted to a pit lake, reducing salt loads to Wellington Dam downstream), use of water for Power Station cooling, and water skiing.

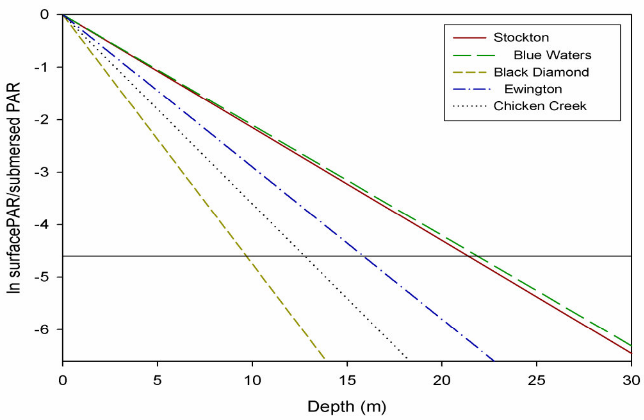
Figure 1 *Location of study area (shaded area indicates coal mining basin)*

A relatively new pit lake (Lake Kepwari) was filled from 1999–2005, first by groundwater and then rapid-filled with Collie River water. Filling followed extensive landscaping contouring and planting of the banks for development as a water recreation park (McCullough et al. in press). Although the high water quality of the pit lakes potentially lends itself to these type of end uses, low pH and high Al concentrations still remain a challenge to remediate (Lund et al. 2006).
This paper will briefly review the status of knowledge on the ecology and limnology of the Collie pit lakes, using published and unpublished data from the authors and other researchers

Methods
Pit lake water quality and physical data was collated for 6 pit lakes from the studies of Phillips et al. (2000) and CSML (2007) (Black Diamond (BD), Blue Waters (BW, also called Ewington 2), Ewington (Ew, also called Ewington No.1), Stockton (S), Chicken Creek (CC) and Lake Kepwari (LK) in the Collie basin. Although data from different studies has been collated, using slightly different methodologies for sample collection and measurement, the data mainly consists of profiles of physico-chemical variables, top and bottom of the water column water samples (analysed for metals, nutrients and sulphate) and benthic aquatic macroinvertebrates collected from the littoral margins. Samples have generally been taken at regular intervals (monthly) from the four oldest lakes and less frequently from newer pit lakes.

Results and Discussion
Acidity in the Collie pit lakes comes from initial *ex situ* pyrite reduction in coal seams followed by *in situ* ferrolysis and secondary mineralisation. Ew sediments contain 4–15% and 0.3% of gibbsite and goethite respectively, and 10% of amorphous material. As a result of loss of Fe, Al and sulphate to the sediment as secondary minerals, Collie pit lakes now have low sulphate concentrations, peaking in CC at 282 mg L^{-1} but <100 mg L^{-1} in other pit lakes, and low Fe concentrations ranging from 11 mg L^{-1} in CC, to <1 mg L^{-1} in all other pit lakes. Low buffering capacity in over- and inter- burdens also limits neutralisation of the low acidity produced. Low buffering capacity is accompanied by low electrical conductivity (0.42 mS cm^{-1} in BD to 2.55 mS cm^{-1} in CC), low P concentrations (Filterable Reactive P typically <2 µg L^{-1}) while concentrations of NOx (NO_2+NO_3) reached nearly 1 mg L^{-1} in LK. Low P concentrations contribute to low Chlorophyll *a* concentrations (<1 µg L^{-1}), although most of the lakes develop a thick benthic algal layer before stratification reestablishes over summer. BD also had the submerged macrophyte *Chara globularis* and *Nitella* sp. growing at the bottom of the lake.
Attenuation of photosynthetic active radiation (PAR) is a limiting factor for benthic primary production, in the deeper lakes (CC, LK). CC has a light compensation point at a depth of 13 m, which is where there is approximately 1% of incident light and algal respiration equals photosynthesis. Below the compensation depth there is insufficient light for net primary production. The shallower or clearer nature of the other mine lakes suggests that there is sufficient light at the sediment to support benthic algae or submerged plants (Figure 2).

Figure 2 *PAR attenuation as a function of depth in Collie mine void lakes. Reference line indicates light compensation point*



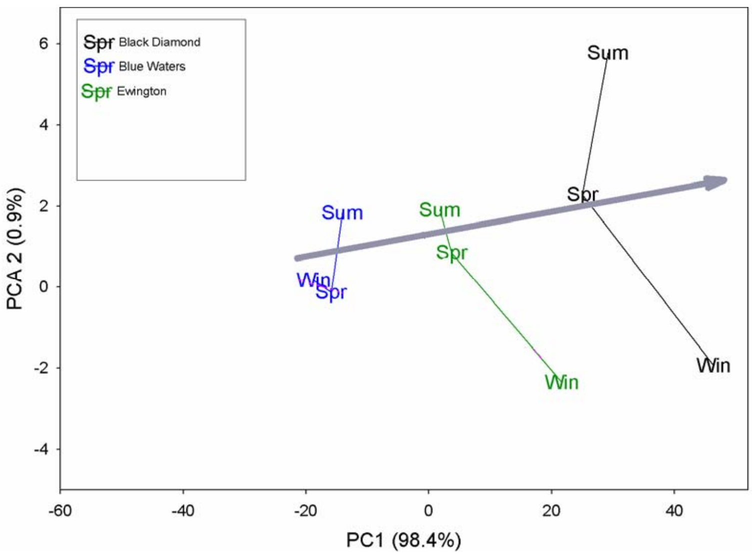
The lakes are warm monomictic, becoming thermally stratified between November and March with the epilimnion extending 6–10 m deep. The hypolimnion becomes anoxic within 1–2 months of stratification occurring. During hypoxia, the benthic algae die and invertebrate fauna (such as the large crayfish – *Cherax tenuimanus*) move to shallow oxic waters. The hypolimnion accumulates ammonia released from the sediments, and nitrogen porewater concentrations decline at this time. Lake sediments have higher pH than overlying water, with sediment pH >6 within 20–30 mm depth. Although sediments contain 10–20% organic matter, the majority of this appears to be coal fragments. Carbon is limiting in both the water and sediments.

Collie pit lakes contain between 20–30 macroinvertebrate taxa, dominated by highly mobile taxa such as Hemiptera, Odonata, Diptera and Coleoptera. This relatively low diversity is coupled with extremely low abundances, reflecting the low productivity of the systems. Fish in Collie pit lakes include the introduced poeciliid pest mosquitofish (*Gambusia holbrooki*), and native western pygmy perch (*Nannoperca vittata*, formerly *Edelia vitta*) and native minnow (*Galaxias occidentalis*) only found in BD and S lakes. All these fish are primarily surface feeders, therefore introduced *Gambusia* probably compete directly with native fish for allochthonous invertebrate foods.

As acidity is higher in CC and LK (~170 mg $CaCO_3$ L^{-1}) compared to the oldest pit lakes (<20 mg $CaCO_3$ L^{-1}, except in BW at ~40 mg $CaCO_3$ L^{-1}) this difference suggests that acidity is reducing over time. Over the same period, there are significant drops in Fe, sulphate and Al concentrations through secondary mineralisation. Secondary mineralisation, however, also generates further acidity. This loss of additional acidity is likely due to albeit limited alkalinity generating bacterial processes (e.g., sulphate and nitrate reduction) (Totsche et al. 2006), primary production (including nitrate assimilation) (Davison et al. 1995) and dilution/neutralisation by groundwater. Remineralisation from secondary minerals is believed to be limited due to continual burial by eroding kaolinite clay washed into the lakes from unstable lake banks. Bacterial processes such as sulphate reduction and denitrification are probably limited by C availability (see Lund et al. 2006) and low sulphate concentrations. The lakes are groundwater flow-thru systems (as per Johnson and Wright 2003), although flow rates are believed to be very slow (Phillips et al. 2000). Ew is known to discharge into the surrounding groundwater during winter and become a sink in summer. BD is known to receive higher inputs of circum-neutral groundwater than other lakes where the groundwater can be acidic (Ew – pH ~5) or high in Fe^{2+} which generates acidity through ferrolysis (e.g., LK). BD has the lowest acidity and highest pH (~6) of the lakes.

Principal components analysis of water quality parameters from the older lakes (*Figure 3*) clearly shows that pit lakes on a trajectory from most (BW) to least acidic (BD). Interestingly, variability in older lakes between seasons also becomes more pronounced, possibly reflecting the greater impact of biological processes as higher pH.

Figure 3 *Principal Components Analysis (PCA) of seasonal water quality data from three of the old pit lakes (Sum= summer, Spr= spring, Win= winter)*



Lund et al. (2006) found that adding organic matter to Ew resulted in Ew moving along a alternative trajectory rather than towards “naturally remediated” BD. Although this is possibly also due to differences in groundwater inputs, it might also suggest that trajectories of natural evolution of Collie pit lakes might not be equivalent to an “actively remediated” lake. On this trajectory, CC is expected to appear to the far left, followed by LK. S would potentially be an outlier as this lake has extensive adits from old underground workings that are likely still generating acidity, combined with surface inflows of circum-neutral dewatering water. Both S and LK have or (in the case of LK, had) increases in pH associated with neutral inputs, but after these inputs cease pH quickly revert back to a typical Collie pit lake (pH 3.5–4.5).

Work to date shows that the Collie pit lakes have generally excellent water quality, with the primary issue remaining toxicity by elevated Al associated with the Al buffering that is occurring within the typical pH range of 4–5.5 (Neil et al. submitted). Neutralisation appears to offer the quickest remediation strategy (despite the previous failure in S), sulphate reduction appears to be very limited by low sulphate concentrations and while processes associated with enhanced primary production (although tested at mesocosm scale (McCullough and Lund 2007)) remain to be tested at a field scale. Importantly, the high quality of Collie pit lake water has led to public expectations of high quality enduses. Nonetheless, previous attempts at remediating water quality in LK suggest that more research is required to create the water quality necessary for these enduses.

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