The Collie Pit Lake District, Western Australia: An Overview

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Abstract

Open-cut mining can create pit lakes that form distinct lake districts. Localised factors at the lake level ensure that individual pit lakes develop different water qualities and ecological values. The Collie Lake District is formed from open cut coal mining operations in the south-west of Western Australia. The limnology and water quality of 13 of these lakes were investigated in 2009. All of the deep pit lakes appeared to be thermally stratified over the summer but many had, or were close to, mixing by autumn. The lakes were mainly Al buffered, with pH ranging from 2.5 to 6.4. Most lakes could be considered oligotrophic but some contained high N and moderate P concentrations. Dissolved organic C and metal concentrations were generally very low.

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

Introduction

On cessation of mining, open-cut voids that extend below the water table can fill with groundwater and surface runoff to form a pit lake. Mining operations can generate a number of pit lakes located relatively close together, forming a pit lake district; this has now occurred in a number of international mining regions (McCullough and Van Etten 2011). This paper focuses on a key Australian pit lake district where pit lakes uniquely cover the spectrum from abandoned without rehabilitation, to those with rehabilitated catchments approaching relinquishment back to the state for conservation, recreation or commercial development. Of the 15 pit lakes in Collie, of these, Ewington has been re-mined, and Black Diamond B is located on private property. The remaining 13 pit lakes were investigated in this study.

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 (Figure 1). The Lake District is located in the Collie Coal Basin in Western Australia.

The major land uses in the catchment are coal mining, timber production, power generation and agriculture. Approximately 79% of the catchment is state forest. The recreation and nature conservation values of the forest areas are highly regarded along with the recreational opportunities provided by the Wellington

Reservoir and other surface waters, including some pit lakes. These values have led to increased promotion of the area for tourism by the local business community and the Shire of Collie.

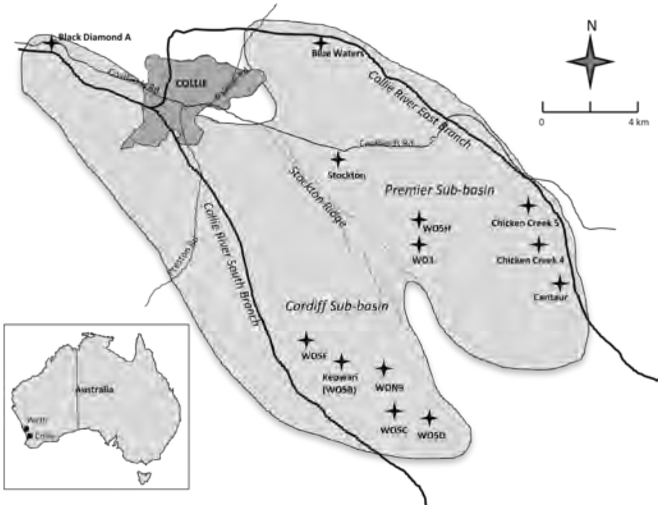

Figure 1. *Map showing location of the Collie Coal Basin and pit lakes sampled.*

The Collie Basin is located in south-west Western Australia and 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).

The Collie coal basin is relatively small, containing up to 1400 m of Permian sedimentary rocks, covered by a thin layer of Cretaceous rocks. (CWAG 1996). The base layer of pebbly mudstone is covered by layers of sandstone, shale and coal. There are up to 55 significant coal seams, which are typically 1.5 to 5 m thick, although the Hebe seam can reach 13 m thick. There are an estimated 1330 Mt of coal resource in the basin, of which extractable reserves account for 482 Mt (Varma 2002).

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). Seventy-five percent 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).

Groundwater resources of the Collie basin are fresh and discharge towards the Collie River in the west, with seasonal fluctuations up to 1 m (Sappal, Zhu et al.

2000). The pH of the groundwater is highly variable, ranging from <4 to neutral (Varma 2002). The hydrogeology of the Collie basin is complex, with multiple aquifers due to aquicludes and faulting (Varma 2002).

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 (Stedman 1988). 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.

Sampling Methods

The 13 pit lakes were sampled in April and November 2009, although Blue Waters was only sampled in April and Centaur only in November. A single vertical profile (1 m intervals) in the middle/deepest part of each lake for temperature, pH, electrical conductivity (EC), oxidation-reduction potential (ORP), turbidity (NTU), dissolved oxygen (concentrations and % saturations) and chlorophyll *a* was taken with a Hydrolab Datasonde 4A (Hach, USA). Previous unpublished data found no significant spatial heterogeneity in water physico-chemistry. WO5C and WO5D were only sampled close to the shore as boat access was not possible.

At each profile site, a surface (about 0.1 m deep) water sample was collected. An aliquot of each water sample was filtered (0.5 µm glassfiber, Pall Metrigard) in the field. An aliquot of the filtrate was acidified to 1% with analytical grade concentrated HNO_3 for analysis of metals. Filtrate was analyzed for dissolved organic carbon (DOC) using a total carbon analyzer (Shimadzu, Japan) and NH_3/NH_4^+ (NH_3), NO_2^-/NO_3^- (NO_x) and filterable reactive phosphate (FRP), as per APHA (2005). Sulphate was analyzed by ion chromatography (Methrohm, Switzerland). Metals (Al, Ba, Be, Ca, Cd, Cr, Co, Cu, Fe, Mn, Na, Ni, Sb, Sn and V) were measured by ICP-OES (Varian, USA). Total phosphate (TP) and total nitrogen (TN) were measured in unfiltered samples, following persulphate digestion, as per APHA (2005).

Results and Discussion

The pit lakes of Collie range from 4.5 ha to 98.5 ha in area and 8 to 81 m deep (Figure 2). One group of lakes consists of those abandoned in the 1960's with no shaping or attempts at rehabilitation (Blue Waters, Stockton and Black Diamond), another includes relatively new lakes (<10 years old) that have been contoured and have had catchments revegetated (Lake Kepwari, WO5H, WO5F, WON9, WO5C, WO5D). The Chicken Creek lakes (4 and 5) are new lakes that have not been rehabilitated (due to possible re-mining). WO3 and Centaur are historic and have not been rehabilitated.

These pit lakes were mainly naturally filled with groundwater and surface runoff, apart from Lake Kepwari, which was rapidly filled with Collie River water. Chicken Creek 4 was final-filled with approximately 3 GL of saline Collie River Water (containing about 13,000 t of salt) in 2005/06. Stockton has sometimes received circum-neutral dewatering water from the Ewington mine. WO5H receives saline waters collected from plant and localised sources around Wesfarmers Plant. Centaur is directly connected to the seasonal Chicken Creek. Some of the pit lakes discharge to natural waterways (ultimately the Collie River); these include Black Diamond A, WO5H, Stockton, Lake Kepwari (2011 onwards, described in McCullough, Kumar et al. 2012), Centaur, and formerly Ewington.

Pit lakes in Collie are typically flow-through lakes (as per Commander et al. 1994); however, Sappal et al (2000) found that in winter, the Ewington lake was supercharged with water and discharged back to the groundwater, whilst in summer it acted as a groundwater sink due to the high evaporation rates during this time. Ewington is a small pit lake, so this phenomenon may not apply to the larger lakes. Models prepared for Lake Kepwari also show the importance of groundwater flows into and out of the lakes (Müller et al. 2011)

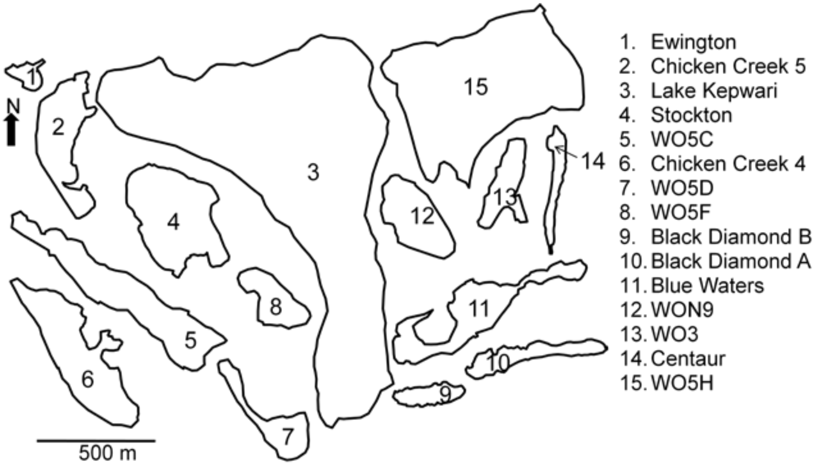

Figure 2: *Pit lakes of the Collie Lake District showing correct orientation and identical scale, with no spatial representation.*

Most of the pit lakes are in the Al buffering range; only WO5C, Chicken Creek 5, WO5H consistently have pH <3.5 (Table 1). Only Stockton, WO5F and Blue Waters were consistently pH >4.5, with Black Diamond A and Kepwari very close. Compared to most other pit lake districts, EC was generally high, typically between 1 and 2 mS cm^{-1}, with only Black Diamond A, WO5F and WO5D below this. The high salinities of Kepwari, Chicken Creek 4 are directly attributable to artificial inputs of saline water from the Collie River.

Sampling occurred at the most likely periods for lake turnover and whilst there was strong thermal stratification (>10 °C difference, top and bottom) in some of the deeper pit lakes, most showed evidence of weakening stratification or turnover (e.g., Kepwari in April 2009). Another feature of the stratified lakes was the noticeable increase in surface salinity (typically by 0.2 mS cm^{-1}) in the epilimnion, presumably due to evapo-concentration. Unusually, there was no evidence of anoxia or low (<100 mV) ORP recorded for any of the hypolimnia, as recorded in previous studies (Phillips, Evans et al. 2000).

Collie pit lakes are oligotropohic in terms of productivity, with no submerged plants (except for *Chara globularis* and *Nitella* sp in Black Diamond) and very low chlorophyll *a* (<1 µg L^{-1}, except for Centaur and WO3 with 1.6 and 6 µg L^{-1} respectively). Table 2 shows the mean nutrient and sulphate concentrations recorded in 2009. Sulphate concentrations tended to be lowest in the historical pit lakes at <100 mg L^{-1}, rising to a maximum of 906 mg L^{-1} recorded in WO5C. DOC was low at <10 mg L^{-1} in all pit lakes except for WO5F, which reached 38 mg L^{-1} during filling. Nitrogen was often high compared to comparable local systems, and exceptionally high in WO3, with a NH_3 concentration of 18,145 µg L^{-1}. FRP was relatively low but still detectable. Recent work has suggested that despite these concentrations, P is still the main limiting nutrient in these lakes (Radhakrishnan et al. 2011).

Aluminium concentrations in surface waters ranged from <0.1 to 76 mg L^{-1} in WO5D, and was typically highest in the newer pit lakes. The following metals were below detection: As, B, Cu at <0.05 mg L^{-1}, Se at <0.2 mg L^{-1}, Cd, and Cr at <0.01 mg L^{-1}. Iron concentrations were highest in Chicken Creek 5, the most acidic lake at 19.2 mg L^{-1}, but was <10 mg L^{-1} in all other lakes. Peak metal concentrations for other metals were cobalt at 0.7 mg L^{-1} (WO5D), Mn at 2.36 mg L^{-1} (WO5H), Pb at 0.1 mg L^{-1} (Stockton), U at 0.18 mg L^{-1} (Chicken Creek 5) and Zn at 3.94 mg L^{-1} (Stockton).

Table 1: *Physico-chemical parameters (surface waters) for Collie Pit Lakes as measured in April and November 2009 (T= thermally stratified with depth of eplimnion indicated; N = not stratified; ? indicates stratification is very weak; nd = no data collected; * still filling)*

	Depth (m)	pH		EC (mS cm^{-1})		Stratification		Bottom DO (%)	
		April	Nov	April	Nov	April	Nov	April	Nov
WO5C	49	3.24	3.13	1.67	1.57	nd	nd	nd	nd
WO5D	22	3.88	4.21	0.88	0.59	nd	nd	nd	nd
Chicken Creek 4	41	4.3	3.34	7.55	7.3	T 8 m	T 4 m	76	86
Chicken Creek 5	24	3.24	2.54	2.97	2.75	T 11 m	T 3 m	75	90
Stockton	47	5.28	4.53	0.47	0.47	T 21 m	N	67	89
WON9	33	3.81	3.56	1.33	1.22	T 5 m	T 4 m	95	91
Black Diamond A	8	5.34	4.38	0.58	0.47	N	N	107	97
Centaur	9	nd	6.55	nd	2.76	nd	T 2 m	nd	40
WO5H	81	3.13	3.08	1.50	1.35	T 19 m	T 9 m	119	42
WO3	8	4.03	3.79	2.14	1.7	T? 7 m	T 3 m	113	42
Kepwari	65	4.94	4.34	3	2.85	N	T 4 m	130	95
WO5F	2*	6.40	5.11	0.44	0.21	N	N	89	102
Blue Waters	24	5.80	nd	1.5	nd	T? 3 m	nd	117	nd

Table 2: *Nutrient and sulphate mean surface concentrations (n=1 or 2) for the Collie pit lakes in 2009.*

	TN $\mu g\ L^{-1}$	**TP** $\mu g\ L^{-1}$	**DOC** $mg\ L^{-1}$	**FRP** $\mu g\ L^{-1}$	**NOx** $\mu g\ L^{-1}$	NH_3 $\mu g\ L^{-1}$	SO_4 $mg\ L^{-1}$
WO5C	2592	44	1	17	113	1979	906
WO5D	650	38	2	4	12	18	361
Chicken Creek 4	477	67	2	16	61	336	221
Chicken Creek 5	1389	50	7	19	76	1085	506
Stockton	125	46	4	4	44	69	64
WON9	412	97	1	27	31	53	670
Black Diamond A	269	205	1	3	159	60	72
Centaur	651	73	10	10	30	115	55
WO5H	689	44	3	16	141	471	572
WO3	22717	112	3	11	2428	18145	542
Kepwari	1083	44	2	5	610	64	195
WO5F	864	35	38	2	482	155	60
Blue Waters	237	102	5	5	181	37	98

Conclusions

In the Australian landscape, lake districts such as Collie may provide numerous environmental and social benefits and understanding these systems will be useful in several ways. The Collie Lake District can be a significant water resource but has problems associated with low pH, low nutrients and some elevated metal concentrations. These issues limit the end-uses that these systems can be used for. Among the existing pit lakes, it is likely that Blue Waters, and Chicken Creek 4 and 5 will be dewatered and re-mined in the next few years. New pit lakes in the Collie basin are likely to be larger and deeper and fewer in number. Current practice tries to avoid pit lake formation; however, new pit lakes remain inevitable in Collie.

Acknowledgements

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References

APHA (2005). Standard methods for the examination of water and wastewater / prepared and published jointly by American Public Health Association (APHA), American Water Works Association and Water Environment Federation, Washington, D. C.: APHA-AWWA-WEF, 2005.

Commander, D. P., C. H. Mills, et al. (1994). Salinisation of mined out pits in Western Australia. Conference Proceedings of the XXIV Congress of the International Association of Hydrogeologists, Adelaide, South Australia.

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

CWAG (1996). Strategies for water resources management in the Collie Basin. Perth, Collie Water Advisory Group.

McCullough, C. D., R. N. Kumar, et al. (2012). Riverine breach and subsequent decant of an acidic pit lake: evaluating the effects of riverine flow-through on lake stratification and chemistry. International Mine Water Conference, Bunbury, Western Australia, IMWA.

McCullough, C. D. and E. J. B. Van Etten (2011). "Ecological restoration of novel lake districts: new approaches for new landscapes " Mine Water and the Environment **30**: 312-319.

Moncrieff, J. S. (1993). Hydrogeology of the Collie Basin, Western Australia: Western Australia Geological Survey. **34:** 129–153.

Müller, M., K. Eulitz, et al. (2011). Model-based investigations of acidity sinks and sources of a pit lake in Western Australia. International Mine Water Association (IMWA) Congress. Aachen, Germany, International Mine Water Association**:** 41-45.

Phillips, B., L. Evans, et al. (2000). Final void water quality enhancement: stage III. Perth, Australia.

Radhakrishnan, N. K., C. D. McCullough, et al. (2011). Evaluating the factors limiting algal biomass in acidic pit lakes of the Collie Lake District, Western Australia. International Mine Water Association Congress, Aachen, Germany, IMWA.

Sappal, K., Z. R. Zhu, et al. (2000). Subsurface geology, hydrogeological and geochemical analysis of the Ewington Open Cut No 2 lake area, Collie Basin. Final void water quality enhancement: Stage III. Perth, ACARP Project Number C8031 report**:** 11-68.

Stedman, C. (1988). 100 years of Collie coal. Perth, Australia, Curtin Printing Services.

Varma, S. (2002). Hydrogeology and groundwater resources of the Collie Basin, Western Australia. Perth, Water and Rivers Commission**:** 80.