Can Saline Pit Lakes Offer Biodiversity Values at Closure?

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Abstract

Saline pit lakes are considered to have few prospects upon closure. However, naturally occurring saline lakes may have outstanding biodiversity values. Therefore, we assessed the limnology and biodiversity of four saline pit lakes (≈3.2-10.5 mS cm^{-1}) from Australia's main coal-producing regions. Nutrients, metals, metalloids and major ions were collected as well as physico-chemical profiles throughout the water column. 'Biodiversity values' of lakes were determined via macroinvertebrate, diatom, and plankton assemblages. Lakes were stratified by temperature but not salinity. Salinity did not appear to drive (nor limit) biodiversity in lakes, and relatively neutral pH indicated opportunity to improve existing biodiversity through rehabilitation. We also discuss the risks and opportunities of using saline pit lakes as ecosystems at closure in this brief presentation.

Keywords: Saline Lake, Hunter Valley, Bowen Basin, Mine Rehabilitation, ANZECC/ARMCANZ

Introduction

Open-cut mining operations create an environmental legacy of large pits throughout the landscape. Many of these open pits are too large or expensive to fill and typically require extensive dewatering operations. Therefore, many of these pits are destined to become large, deep pit lakes. Annual evaporation generally exceeds precipitation in subtropical deserts and semi-desert regions around the Tropics of Cancer and Capricorn. Major mining activities occur within these regions. High evaporation rates within these regions make many pit lakes terminal hydrological sinks. Pit lakes that are terminal sinks are generally predicted via modelling to have increasing salinities over time through evapoconcentration. This salinity may be derived from naturally saline groundwater or surface inflows mobilising salts from overburden, intensified by evapoconcentration.

Australia has a broad range of naturally saline and hyper saline water bodies with unique ecosystems (Timms 2018). We suggest that while high salinity may limit pit lake future uses, saline pit lakes are not necessarily without demonstrable ecological value. Saline mine-pit lakes are unique because they are typically much deeper and may occur in geographical areas that do not naturally have lakes. Unlike naturally occurring saline lakes, little research has been done on the water quality and ecology of saline pit lakes. Further, little is known about rehabilitation of saline pit lakes because most of the research focus worldwide has been devoted to treating acidic pit lakes with high concentrations of metals.

Closure of mines containing pit lakes is problematic because pit lakes are not widely accepted by regulators as a closure option, although this is changing. Therefore, guidance on completion criteria for pit lakes is lacking. Pit lakes may present risks to the wider catchment if they have poor water quality (McCullough and Lund 2006). High salinities are often seen as poor water quality and therefore limits on release of waters from the pit lakes is common, further allowing salinities within the lakes to increase.

Ecological values are the desired measurable attributes of an ecosystem. Measures of community diversity, species abundance, or even the gross attributes of the system itself such as morphology and geographical connectivity could be considered 'ecological values' (Margules and Pressey 2000). There are a range of factors that limit the establishment of ecological values in pit lakes, such as hydrology and bathymetry, as well as nutrient limitation and poor bankside vegetation development (Lund and McCullough 2011).One of the rare published ecological studies on saline pit lakes examined macroinvertebrates in a series of Queensland pit lakes (Proctor and Grigg 2006). The authors found that although naturally co-occurring water bodies had significantly higher macroinvertebrate species diversity than pit lakes, some of the older and less saline pit lakes were "almost as rich in families" (Proctor and Grigg 2006). This research indicates that saline pit lakes can develop ecosystem values although the body of research is extremely limited.

Biodiversity in pit lakes is typically low, however this appears to be due to limited resources rather than directly due to pH or metal toxicity. Pit lakes that are circumneutral tend to have macroinvertebrate diversity and abundance similar to those found in natural lakes (McCullough and Lund 2008; Proctor and Grigg 2006), although limitations in food and habitat can still curtail development (McCullough *et al.* 2009).

Here we briefly report on a year-long study of the ecology and water quality of pit lakes in the major coal mining regions of Australia in New South Wales and Queensland, across a gradient of salinities and mine water uses. We observed the drivers of algal, zooplankton, diatom and macroinvertebrate communities as indicators of biodiversity values in saline pit lakes.

Methods

Study area

Four pit lakes from Australian former coal mines were selected for this study, two (HL1, HL2) from the Hunter Basin (21,500 km^2) in New South Wales, and two (BL1, BL2) from the Bowen Basin (60,000 km^2) in Queensland (Figure 1)(see Blanchette and Lund 2021, for photos and more research). The Hunter Basin is in Köppen climate type Cfa (humid subtropical, mild with no true dry season and hot summers), with rains typically occurring during summer (Peel *et al.* 2007). The Bowen Basin is within Koppen climate type BSa (arid steppe, with hot summer) with predominantly summer rainfall (Peel *et al.* 2007).

Three of the lakes (HL1, BL1, BL2) had no form of rehabilitation at the time of sampling in 2019, and HL2 was a shallow lake (<5 m), that had been rehabilitated although riparian zone vegetation was largely absent. HL1 was actively used for water storage and the other lakes used occasionally for water management. HL1 was approximately 20 years old at the time of sampling, BL1 was 10 years old and BL2 was still filling.

Instrument chains

An instrument chain was installed in three of the lakes (HL1, BL1 and BL2) for the duration of 2019 (beyond the quarterly sampling timeframe) to investigate stratification in the lakes. Chains were installed in all lakes except HL2, as it was <5 m deep and was therefore

Figure 1 *Morphological diversity extremes of Australian saline pit lakes in study: deep lake, no rehabilitation - HL1 (left), shallow lake, some rehabilitation - HL2 (right).*

unlikely to stratify for substantial periods. The chains were described in Blanchette and Lund (2021).

Water quality measurements

The lakes were sampled quarterly (February, May, August and December (not sampled at HL2)) in 2019 at three sites approximately equidistant across each lake which included the deepest location. On each occasion, an *in situ* physico-chemical profile was collected through the entire water column using a Hydrolab Datasonde DS5 multiparameter instrument (Hach, Austin, USA). Water column profile data were: temperature, pH, dissolved oxygen (mg L^{-1} and % saturation; luminescent), electrical conductivity standardized at 25 °C (EC) and oxidation-reduction potential (ORP, platinum electrode).

Water samples were collected at each site on each occasion for metal/metalloid and nutrient analysis at the surface and bottom (max. 20 m). Bottom samples were collected using a 12 V bilge pump (2088-732-244, Shurflo, Cypress, USA) and a 20 m weighted hose or in HL2 using a Teflon Kemmerer bottle. Water samples were processed in the field and lab according to Blanchette *et al.* (2019). On each occasion, samples from the three sites were composited into a single sample for analysis. An unfiltered aliquot was frozen (-12 °C) for later determination of total N and total P. Another aliquot was filtered (0.5 µm Metrigard GF, Pall, USA) and then frozen (-12 °C) for later determination of Cl^- using ion chromatography (Methrohm, Switzerland), nitrate/nitrite (NOx-N), filterable reactive phosphorous (FRP-P) and ammonia (NH_3-N) on a Lachat autoanalyser (Hach, USA), and DOC (measured as non-purgeable organic C) using a total carbon analyser (Shimadzu, Japan). A second filtered aliquot was acidified with nitric acid to pH <2 then stored at 4 °C for determination of select metals/metalloids and S by ICP-AES/MS. All methods were as per APHA (2017) and were conducted at the Edith Cowan University Analytical Chemistry Facility.

Biota collection

At each site (n=3 per lake) a surface water sample was collected for phytoplankton (*ca.* 0.2 m deep) and treated with Lugol's solution. Phytoplankton were counted and identified to genus level by ALS Ltd. Zooplankton were collected at each site via a vertical tow using an 80-µm mesh (0.2 m dia.) zooplankton net at HL2 or using the bilge pump at the other sites to collect water (≈10 L) from the entire water column to 20 m deep, filtering through the same 80-µm mesh (0.2 m dia.) net. The sample was preserved in >50% ethanol and then species were identified and counted by Australian Waterlife Ltd.

At three approximately equidistant sites around each lake's edge (where safe) macroinvertebrates were collected from a 1 × 0.5 m area parallel to the shore using a 250-µm mesh dip net (triangular (0.3 m sides)). The net was passed vigorously throughout the water column and bounced against the sediment for 20 s. Samples were preserved in >50% ethanol before sorting, identification (to Family) and abundance counts. Identifications were based on Gooderham and Tsyrlin (2002).

At macroinvertebrate collection sites, approximately 50 ml of surface sediment (<20 mm deep) was collected for diatoms within 0.5 m distance of the shoreline. A small amount of ethanol was added to each sample to prevent decomposition. Diatoms were counted and identified to species (where possible) by Dr John Tibby, University of Adelaide.

Results and Discussion

Lakes with instrument chain data demonstrated thermal stratification; HL1 was stratified from October to March and mixed during the rest of the year, BL1 and BL2 were stratified during September to March, briefly mixed and then was weakly stratified until September (see Blanchette and Lund 2021, for details). Large rainfall events (≈100 mm per day) at the Bowen Basin sites resulted in mixing in BL2, however in BL1 while hypolimnion temperature increased following the same rainfall even the lake did not mix until surface temperatures matched the warmer hypolimnion.

Salinity in pit lakes ranged from a low of EC ≈3200 µS cm^{-1} in HL1, to ≈3500 µS cm^{-1} in BL2, ≈6400 µS cm^{-1} at HL2 and ≈10,500 µS cm^{-1} at BL1. There were small differences in conductivity according to lake depth which likely interacted with thermal stratification and mixing processes (especially during the high rainfall events). However, these small differences in conductivity with depth did not result in a true halocline (data not shown). Stratification resulted in hypoxia in the bottom waters of HL1, and BL1 (the deepest lake at 32 m) demonstrated a reduction in dissolved oxygen concentrations to ≈70% saturation.

In order to investigate pit lakes as ecosystems at closure, water quality results were compared to the ANZECC/ARMCANZ (2018) trigger values for 95% protection of aquatic ecosystems (Table 1) which are typical of most natural aquatic systems in good condition. Guideline values for nutrients were as per 'freshwater South East Lakes and Reservoirs' in ANZECC/ARMCANZ (2018). Freshwater standards were considered more appropriate than marine standards given the relatively low EC compared to marine waters.

During the study, all four lakes exceeded both trigger values and guideline values (Table 1). High levels of NH_3, NOx and Total N were most likely linked to residual from AMFO blasting during mining (Banks *et al.*

Table 1 *Exceedances of ANZECC/ARMCANZ (2018) trigger values for the 95% Protection of Aquatic Ecosystems for metals and metalloids - guidelines for south-east freshwater lakes and reservoirs. Data from sampled pit lakes. Timing and location of exceedance indicated by top (T) and bottom (B) waters.*

Lake		Al	B	Cr (VI)	Co	Cu	Se	U	NH3	FRP	NOx	Total N
	Trigger/Guideline Values (μg L^{-1})	55	370	1	1.4	1.4	5	0.5	10	5	10	350
BL1	Feb 2019					B	TB	TB			TB	TB
	May 2019					B	TB	TB	B		TB	TB
	Aug 2019				B	T	T	T			TB	TB
	Nov 2019					T	B	B			TB	TB
BL2	Feb 2019					TB		TB	B			
	May 2019					T		TB				
	Aug 2019					T		TB	B		B	
	Nov 2019							T				
HL1	Feb 2019	TB		T	TB	TB		T			TB	
	May 2019				TB	TB			B			
	Aug 2019				TB				TB		TB	
	Nov 2019				TB	B			TB		B	
HL2	Feb 2019	B	B			TB		TB		TB		T
	May 2019		TB					TB	TB			T
	Aug 2019							TB	TB			

Notes:

Al is based on pH>6.5 where it is less toxic

As occurs as both As (III) and As(V) - lowest trigger value is for As(V) about half of As(III)

Cr as measured was not divided into different oxidation states, so exceedances are against the total amount measured versus the trigger value for each oxidation state. The exceedances of trigger values for Cr(VI) therefore represent a worst case scenario, whereas Cr(VI) is generally uncommon in environmental samples.

Mercury due to bioaccumulating - recommended to use guideline value from high level of protection i.e. 99%

Selenium due to bioaccumulating - recommended to use guideline value from high level of protection i.e. 99%

Cadmium, Cr(III), Ni, and Zn trigger values were corrected for hardness as per Warne *et al.* (2018).

***Table 2** Measures of biodiversity in Australian pit lakes. Abbreviations are: 'phyto'; phytoplankton, 'TR'; total richness, 'TR-max'; value of sample with highest richness, 'dom.'; dominant, 'Macro.'; macroinvertebrate. Values are for sample months February, May and August 2019 only.*

Lake	Phyto. (TR-max)	Phyto (dom. Taxa)	Phyto. (restricted taxa)	Diatoms (TR)	Macro. (TR)	Macro. (abun)
BL1	18 (> 13 all seasons)	Chlorophyta Bacillariophyta and Cyanophyta	n/a	84	6	361
BL2	15	Chlorophyta Bacillariophyta and Cyanophyta	n/a	79	6	791
HL1	18	Chlorophyta Bacillariophyta	Cryptophyta	116	5	269
HL2	18	Chlorophyta Bacillariophyta	Cryptophyta, Euglenophyta	108	10	1064

1997). FRP is often limiting in pit lakes and its presence could be useful in stimulating primary production, although prolonged exceedances would increase the risk of algal blooms (Kumar *et al.* 2016). Local geologies were probably responsible for differences in metals/metalloids of concern to different pit lakes, except at HL1 where regular inflows might also have contributed. Exceedances of Cu and U were up to 20 times the trigger values.

Bacillariophyta, Cyanophyta, Chlorophyta, and Cryptophyta were the most abundant phytoplankton (cells mL^{-1}), and relative dominance of taxa was seasonal. BL2 was dominated completely by Cyanophyta in August, whereas HL2 was co-dominated by all four groups variably throughout the seasons. In August, HL1 was dominated by Bacillariophyta and in November by Chlorophyta. The high abundances of Cyanophyta in BL2 (February to August) was due to *Aphanocapsa* sp. Moderate Al concentrations and low total P are known to favour the growth of *Aphanocapsa* sp over other cyanobacteria (de J. Magalhães *et al.* 2019). As characteristic of cyanobacteria, some strains of *Aphanocapsa* sp may be toxic (Buratti *et al.* 2017).

The most abundant and taxonomically rich zooplankton across lakes were the Cladocera and Copepoda. Large bodied *Daphnia cf. carinata* were most abundant in HL2, although present at low numbers in BL2 and HL1 and absent entirely from BL1. High temperatures and salinities approaching the upper limit of known distributions might exclude *D. cf. carinata* from BL1 (Hall and Burns 2002). Ostracods and Harpacticoid copepods are typically benthic but are routinely collected as part of zooplankton sampling when samples are taken close to the sediments.

Briefly, macroinvertebrate taxa collected were cosmopolitan and pollution-tolerant taxa. The least saline lake had the lowest diversity and abundance of macroinvertebrates and the rehabilitated lake had the highest, suggesting rehabilitation may be more important for macroinvertebrates than salinity, although further analysis is needed.

Conclusions

In this brief presentation of biodiversity in saline coal pit lakes, we found a diverse selection of species from plankton to benthic diatoms and macroinvertebrates. Rehabilitation of the pit lake likely influenced aquatic biodiversity. Salinity did not appear to be the major factor driving biodiversity in these saline pit lakes although further analysis is required. Even without rehabilitation, the saline pit lakes did offer ecosystem values in the form of aquatic biodiversity, although there does appear to be considerable opportunity for improvement through rehabilitation. Some challenges include exceedances of ANZECC/ARMCANZ values and cyanobacteria blooms, although these may be due to natural factors. Comparison to naturally occurring saline lakes would be a useful exercise. Where miners can demonstrate that pit lakes are well-established ecosystems with a good range of biodiversity, then relinquishment should be more acceptable from community and regulatory standpoints.

Acknowledgements

This research was funded by the Australian Coal Association Research Program and supported by several mining companies and Edith Cowan University. Blanchette and Lund (2021) previously examined the microbial dynamics of study lakes and water quality from this research as cited in text.

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