IN-SITU COAL PIT LAKE TREATMENT OF ACIDITY WHEN SULFATE CONCENTRATIONS ARE LOW[1]

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Abstract:Pit lakes (abandoned flooded mine pits) represent a potentially valuable resource to mining companies, the environment and community, if appropriate water quality can be achieved. However, the water is often of low pH with high dissolved metal concentrations. In Western Australia coal pit lakes are acidic (pH 3–5) but with low concentrations of sulfate and metals.

Low sulfate concentrations prevent microbial sulfate reduction from reducing acidity in these lakes. However, stimulation of primary production and associated alkalinity generating processes may provide a cost effective and sustainable solution to the acidity problems. A field-scale experiment (with control) involving the treatment of in-situ macrocosms (~600 m^3) in a small south-west, Western Australian coal mine lake with municipal mulch and phosphorus additions to enhance primary production was undertaken between June 2003 and June 2004. One macrocosm was treated with P additions, another with mulch, a third with mulch and P, and the untreated lake formed the control. Physico-chemical and algal (chlorophyll *a*) sampling of the macrocosms and lake occurred at monthly intervals.

The decomposition of mulch reduced nitrogen concentrations in the macrocosms to very low levels and necessitated supplementation with urea fertilizer. Phosphorus concentrations dropped rapidly after addition as it became bound to iron, organic matter and sediment. Although there was virtually no difference between treatments and control for most physico-chemical parameters measured (including pH), a PCA of the data showed that the addition of mulch sent the macrocosms on a different trajectory to the control. This difference was reflected in observations of increased abundance and diversity of biofilms and macroinvertebrates within the treated macrocosms.

In conclusion, the addition of mulch and phosphorus alone was not sufficient to increase the pH of Collie mine lakes, although it does provide a number of benefits for biota in the water. We therefore recommend that liming be used to increase pH, followed by organic matter and nutrient additions to stimulate primary production.

Additional Key Words: acid mine drainage, nutrients, phosphorus, phytoremediation, primary production.

Introduction

Following cessation of mining, many open-cut mines will refill to create deep pit lakes. Water quality in these pit lakes is highly variable ranging from hypersalinity, high

acidity/alkalinity, heavy metal contamination to high water quality (Geller et al., 1998). High levels of acidity in the pit lakes result from Acid Mine Drainage (AMD) caused by weathering of over-/inter-burden and exposed seams within the lake catchment. The weathering results in oxidation of mineral sulfides (particularly pyrite) to sulfuric acid (Fyson et al., 2003). The impact of this acid generation on the pH of the pit lake will depend on the rate of generation and the buffering available within the catchment. AMD has grown internationally to the largest single environmental issue facing mining both within Australia and internationally (Harries, 1997; Harries, 1998).

Mine pit lakes in Australia have the distinction of having few natural counterparts in terms of water depth and in inland areas, pit lakes represent new and significant water resources (Harries, 1997; Johnson and Wright, 2003). A range of end uses for mine pit lakes are possible dependant on the water quality. Remediation of any water quality issues for proposed enduses could offer significant benefits for the mining industry (e.g., water for dust suppression, washing), local communities (e.g., aquaculture and irrigated horticulture) and the environment (either directly or indirectly by relieving demand on natural water resources) (Doupé and Lymbery, in press).

Passive in-situ treatment of water quality issues in mine pit lakes are attractive to both government agencies and mining companies as they are potentially effective, have lower costs, and offer long term remediation with no/reduced ongoing management. In recent years microbial sulfate reduction has become considered to be an efficient and effective remediation for the treatment of acid mine drainage (AMD), through alkalinity production and precipitation of metals as sulfides (Equation 1) and carbonates (Equation 2; Benner et al., 2002; Dillon et al., 1997; Küsel and Dorsch, 2000; Praharaj and Fortin, 2004). Since Tuttle et al. (1969) first suggested the use of sulfate reducing bacteria (SRB) in the treatment of AMD, treatment has largely focused on *ex-situ* treatment in bioreactors. It is only recently that attention has switched to *in-situ* remediation systems (Castro et al., 1999; Gibert et al., 2002). In-lake neutralization via sulfate reduction is expected to play a key-role in the remediation of acidic mining pit lakes (Kleeberg, 1998).

Equation 1 $\qquad Metal^{2+} + SO_4^{-2} + 2C_{(organic)} \rightarrow MetalS + 2CO_2$

Equation 2 $\qquad Metal^{2+} + CO_3^{-2} \rightarrow MetalCO_3$

A review by Gibert et al. (2002) found that the nature of the organic matter was a prime determinator of the efficacy of the passive treatment system. Consequently, most research into the utility of sulfate reduction processes for ameliorating AMD have focused upon highly labile, and expensive carbon substrates such as ethanol (Kolmert and Johnson, 2001; Martin et al., 2003; McNee et al., 2003), sugar (Frömmichen et al., 2003; Frömmichen et al., 2004; Geller et al., 2003)(Pöhler et al., 2002; Wendt-Potthoff et al., 2002), cow manure (Drury, 1999; Drury, 2000), etc. In many remote mining communities across inland regions of Australia, large masses of labile carbon sources are often difficult to find for practical and economic reasons. Therefore the success on in-situ remediation using additions of carbon will require the use of alternative and more refractory carbon sources, which are available in sufficient quantity locally.

Western Australia has only one commercially exploited coal resource at Collie in the south-west of the State (**Error! Reference source not found.**) (Le Blanc Smith, 1993). The coal is primarily used for power generation, supplying 70% of the electricity used in the south-west of the State. Collie coal has a relatively low sulfur content of <1%, it is a sub-bituminous coal with

low caking and low ash properties. Coal mining commenced underground in 1894, but to meet World War II demands became increasingly open-cut operations. A dispute with the State Government in 1960 saw one of the mining companies abandon its open-cut operations, leaving a small number of mine pit lakes created without any form of remediation (Stedman, 1988). Lund et al (2000) recorded pH in the lakes ranging from 4 to 5.5, but very low levels of sulfate and metals (Table 1). In a series of microcosm experiments, Thompson (2000) found that additions of manure, hay and mulch (chopped garden waste) to water/sediment in intact cores from one of these pit lakes (Ewington Lake) showed that manure and mulch significantly increased pH over 45 days. This was found to be due to the alkalinity introduced directly by the material rather than through SRB activity. It was believed that sulfate levels were too low to sustain SRB activity (see Gyure et al., 1990; Singleton Jr., 1993). Thompson (2000) then tested manure and mulch additions to in a series of artificially constructed ponds adjacent to Ewington Lake. These results showed significant increases in pH that were sustained for 140 days. There was some suggestion that the higher nutrient (particularly P) concentration leaching from the manure was improving water quality. Davison et al (1995) and Findlay et al (1999) have shown that additions of nutrients (particularly P) can stimulate primary production which can produce alkalinity.

Figure 1. Location of Ewington (indicated with an 'X') mine pit lake in Collie, Western Australia.

There is a large body of published data to suggest that bacterially-mediated sulfate reduction processes can ameliorate acidic waters (Tostche et al., 2003; Tuttle et al., 1969; Wendt-Potthoff et al., 2002). The effectiveness of this approach in areas with low sulfate levels is likely to be limited without supplementation of sulfate concentrations. There are also few published reports of field-scale attempts at AMD lake remediation. Furthermore, very little bioremediation work has been carried out in the mining pit lakes of Australia, despite there being an estimated 1 500 pit lakes in Western Australia alone (Johnson and Wright, 2003). As an arid continent with increasing pressure on water resources, there is growing demand for new sources of water to meet a variety of end uses (Doupé and Lymbery, 2005). This study aims to examine using

macrocosms in Ewington mine pit lake to test the effectiveness of organic matter and nutrient (P) additions on remediation of acidic waters with low sulfate concentrations.

Table 1 Water quality parameters (1997-2000) of old mining pit lakes in Collie (not shown as <20 µg l^{-1}: Cadmium, Cesium, Indium, Lead, Lithium, Rubidium, Silver, Titanium, Uranium, and Vanadium; taken from Lund et al, 2000)

		Black Diamond	Blue waters	Ewington	Stockton
Surface area	ha	6	12	1.1	16
Maximum depth	m	8	24	11	47
Conductivity	µS cm^{-1}	421±16	1368±45	1073±29	468±9
pH		5.4±0.1	4.0±0.1	4.4±0.1	5.5±0.1
Sulfate	mg l^{-1}	46.5±1.4	89.6±7.5	30.3±1.2	31.4±1.9
Ammonia	µg l^{-1}	52.0±10.2	19.3±1.3	22±1.6	23.1±4.3
Nitrate/nitrite	µg l^{-1}	163.4±23.2	2.8±0.5	2.8±0.4	17.6±4.3
Filterable reactive P	µg l^{-1}	2.0±0.6	1.8±0.4	1.8±0.3	2.0±0.4
Chlorophyll *a*	µg l^{-1}	0.31±0.1	0.5±0.1	0.6±0.1	0.37±0.06
Aluminum	µg l^{-1}	6±2.6	2047±167	663±29	6±1.7
Boron	µg l^{-1}	25±2.05	24±2.3	26±2.2	17±1.7
Barium	µg l^{-1}	40±2.7	29±5	70±8.9	47±4.0
Calcium	µg l^{-1}	4435±141.1	5973±470	1961±122.5	2289±188.2
Cobalt	µg l^{-1}	<5	32±2.7	<5	<5
Chromium	µg l^{-1}	<100	<100	<100	<100
Copper	µg l^{-1}	<50	<50	<50	<50
Iron	µg l^{-1}	11±2.7	344±45.5	348±29.8	24±3.3
Potassium	µg l^{-1}	1770±112	1646±167	2204±175	1998±196
Magnesium	µg l^{-1}	10573±283	14305±2396	10953±1372	7499±856
Manganese	µg l^{-1}	116±6.05	55.4±4.4	18.8±1.0	66.8±6.8
Sodium	µg l^{-1}	22637±4757	>50000	>50000	>50000
Nickel	µg l^{-1}	3±0.05	34±2.9	5±0.2	3±0.2
Strontium	µg l^{-1}	58±1.2	134±9.9	55±2.8	46±3.7
Zinc	µg l^{-1}	22±1.2	69±12	16±2.2	33±3.0

Methods

Study area

Collie has a Mediterranean climate with hot, dry summers and cool, wet winters (Figure 2) (Varma, 2002). Long-term (105 year) average rainfall is 944 mm, whilst short-term rainfall has declined to 829 mm; a decline by 12% (Commonwealth of Australia Bureau of Meteorology, 05/10/2005).

The Collie Basin is a small sedimentary basin occurring in the Collie River catchment (CWAG, 1996). The Collie Basin is an intra-cratonic and fault-bounded post-depositional basin which contains up to 1200 m of Early- to Middle-Permian and some Cretaceous and Holocene sedimentary rocks overlying a basement of the Archaean gneiss and the granite complex of the Yilgarn Craton (Le Blanc Smith, 1993). The northwest-trending basin covers an area of approximately 225 km^2 and is subdivided into two lobe-shaped sub-basins, the Cardiff Sub-Basin to the west (151 km^2) and the Premier Sub-Basin to the east (74 km^2) which includes Muja, the site of the largest open cut operation (Lord, 1952; Varma, 2002). The northern and

central portions of the Premier Sub-Basin are confined by faults, with maximal fault displacement between 400–500 m.
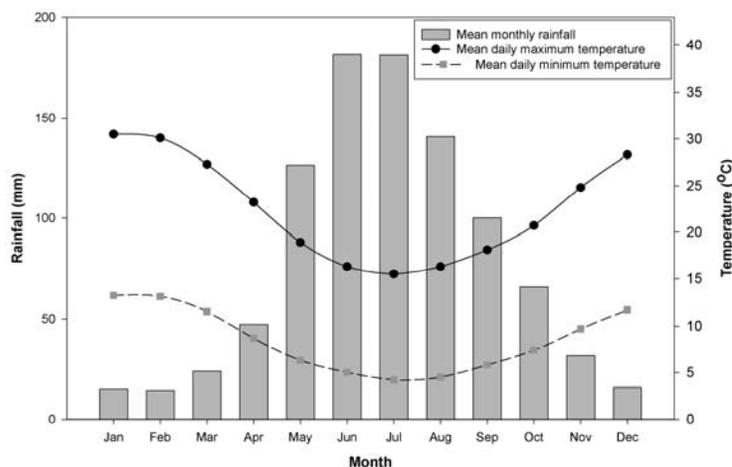
Figure 2. Mean temperature and rainfall climate of Collie (Commonwealth of Australia Bureau of Meteorology, 05/10/2005).

The coal measures are cyclic and consist of sandstone, siltstone, claystone and coal with an erosional base for each cycle. Most coal seams in the basin are less than 4 m in thickness (Sappal et al., 2000). Sandstone dominates the non-coal part of the sequence (Kristensen and Wilson, 1986), varying from coarse to fine sand, moderately to poorly sorted, poorly lithified and containing abundant kaolinitic clays. Kaolinite-rich claystone is interbedded with the sandstone in cyclic sequences. Coal seams do not outcrop and all knowledge of the coal sequence is derived from borehole data and mining exposures with open-cut and underground mines (Sappal et al., 2000; Stedman, 1988).

The Collie basin contains a mainly fresh groundwater resource which is estimated to be in the order of 7,000 GL (Dames and Moore Pty Ltd, 1997). It has also been found that a number of inter-burdens are saline. Deep aquifers extend over the majority of the Premier sub-basin. Interburden and overburden profiles are inter-bedded with shales and coal seams and thus the aquifers are very complicated and multi-layered with great variation in horizontal and vertical permeability (Dames and Moore Pty Ltd, 1997). Collie Basin aquifers are unconfined near the surface and confined at depth. Regional groundwater flow in the Collie Basin and consequent discharge is towards the Collie River, with seasonal fluctuations up to 1 m (Sappal et al., 2000). The pH of groundwater is highly variable ranging from <4 to neutral (Varma, 2002).

Ewington Lake (Ewington No. 1 pit) was a small open cut operation that was abandoned in the early 1960s. It had no remediation prior to natural filling with rainfall and groundwater. It was mined to a depth of 10–15 m (West Australian Forest Department, 1983). Erosion and sedimentation processes are likely to have reduced the angle of the sides; nevertheless, their gradient is still steep leaving only a narrow littoral zone around most of its edges. Littoral rushes and sedges are sparsely distributed with a concentration on the eastern shallow wing (Lund et al., 2000) (Figure 3). Ewington Lake is surrounded by alluvial sands, with fine mud and iron pisoid fluvial sands, organic-rich colluvium and laterite deposits (Sappal et al., 2000). Dumps of inter-

and over-burden remain near the lake and consist predominantly of quartz (89%) and kaolinite (11%) (Sappal et al., 2000).

Ewington Lake currently has an area of about 0.16 km^2 and depths varying from 4 m in the north-west to 11 m in the east and south-east (Sappal et al., 2000). The relatively low pH (3.3–4.6) of the lake is believed to be derived from acidic drainage from the surrounding overburden dumps and from groundwater inflow (Lund et al., 2000). Studies in the Muja area have shown that the overburden is in the 'low acid' range, and that where potential acid toxicity occurs it is primarily a result of the lack of acid neutralising capacity (e.g., a deficiency of $CaCO_3$) rather than via high pyritic sulfur content (Dames and Moore Pty Ltd, 1997). Comparisons to newly filled pit lakes in the region suggest that there has been over the last 45 years a decline in acidity, and Fe, Al and sulfate (SO_4^{-2}) concentrations. This is believed to be due to the formation of secondary minerals in the sediment (e.g. 4-15% gibbsite and 0.3% goethite) (Sappal et al., 2000). Erosion from unstable edges is also believed to have buried secondary minerals in the sediment, reducing possibilities for re-dissolution. The supply of allochthonous nutrients into the lake is probably small. There is also an acidic seep on the south-eastern bank throughout the winter-spring period (Lund et al., 2000).

Figure 3. Ewington mining pit lake. Note blue colour of the water, with a slightly milky appearance due to suspended kaolinitic clays from ongoing bank erosion.

Experimental design

A rectangular side section of Ewington Lake was transversely divided into three approximately equal portions (each with an approximate area of 200 m^2 and a volume of 600 m^3) using a 20 m x 6 m Nylex Aeon XOL Sheet (0.75 mm nominal gauge). Nylex Aeon was used because of its high resistance to acidity, UV, and bacterial action. A hem was heat welded into the top of each sheet. PVC Pipes (32 mm diameter) were placed through the hem. Large polystyrene blocks were attached by cable ties along the hem to hold the sheet out of the water.

The sheets were then held at the sediment and edges of the lake using sand bags filled from the lake margin. Effective seals were obtained as shown in Figure 4; however it is inevitable that on occasion there would have been some transfer of water between the macrocosms. It is considered that the amount of mixing that occurred was minimal.

Figure 4. Photograph taken in May 2003 showing the effectiveness of the barriers in isolating the macrocosms

The experiment used Shire of Collie mulch as a source of organic matter, due to its low cost and availability. The main lake was untreated and used as a control. The following treatments were applied to the macrocosms (Figure 5):

1. Mulch only (12 m^3 of mulch designed to create a layer 50 mm thick on the bottom).

2. Mulch (as above) and phosphorus (17.28 g of superphosphate fertilizer ($Ca(H_2PO_4)_2$, N = 0%; P = 9.1%; K = 0%; traces of carbon and sulphur) designed to increase Total P concentration by 10–15 μgL^{-1}).

3. Phosphorus only (as above)

The quantity of mulch applied was designed to replicate loading rates of mulch used in laboratory experiments by Thompson (2000). Phosphorus additions were designed to double normal P concentrations in the lake without promoting eutrophication. Treatments were added on 11 June, 2003, the day following construction of the macrocosms. Sampling of the macrocosms and lake was conducted at monthly intervals for 12 months starting on 27 June 2003. At each site (approximately middle) in-situ measurements of temperature, specific conductance (conductivity), pH, redox potential (ORP; Ag/AgCl probe) and turbidity were taken from the top (0.1 m deep) using a calibrated YeoKal™ Model 611 Intelligent Water Quality Analyzer. The same instrument was also used to measure the dissolved oxygen and temperature profile at each site. On each occasion, water samples were collected from the surface (0.2 m

deep) at each site (2 sites in macrocosms and 3 sites in each lake pooled). A 500 ml aliquot was transferred to a plastic bottle and another aliquot of known volume was filtered through 0.45 µm glass fibre paper. The filtrate was then transferred to a 250 mL plastic bottle and the filter paper was wrapped in foil and then in a plastic bag. All bottles and filter paper were returned to the laboratory on ice and then frozen (-20°C) until analysed. Unfiltered samples were analysed for Total P, Total N, and acidity as per APHA (1998). Filtered samples were analysed for sulfate, filterable reactive P (FRP), NOx (nitrate/nitrite), and ammonia. Chlorophyll *a* was measured as per APHA (1998) using Dimethylformamide as the solvent as per Speziale et al (1984).

Figure 5. Macrocosms at Ewington mine pit lake. Treatment allocations from left to right are mulch, mulch and phosphorus, phosphorus and Ewington Lake as a control. (Note: mulch floated for 2–3 days before sinking and this resulted in a relatively even distribution across the mulch treated macrocosms).

Statistical analyses

Multivariate nutrient and physico-chemical data was analyzed by Principal Components Analysis (PCA) in the PRIMER software package (PRIMER-E Ltd, 2001). Prior to analysis, draftsman plots were created to determine which variables were highly (i.e., 95% or greater) Spearman rank correlated with each other. These variables were then deleted to leave only a single dummy variable which then represented all of these correlated variables. For example, the two variables dissolved (DO) (%) and DO (mg L^{-1}) were reduced to just DO (%) to form a dummy variable "DO" representing an index of the availability of DO. Data were then $\log_{10}$ transformed to enhance a linear relationship between variables and finally normalized to account for different variable scales (Clarke and Warwick, 2001).

Results and Discussion

Addition of mulch to the macrocosms initially caused an increase in the pH to >6 but this was not sustained for more than 2 months, after which there was no apparent difference in pH between the control and treatments (Figure 6). These findings are similar to those of Thompson (2000). The addition of P did not appear to change pH either alone or in combination with mulch. There appears to be no difference between treatments and control in conductivity with little variation throughout the year, except for a slight increase during the summer probably due to evapo-concentration. Sulfate concentrations, although initially very low in the mulch alone macrocosm, remained very similar between all the treatments and control for the majority of the experiment. This suggests that there was limited SO_4^{-2} reduction occurring in the water column, which was not unexpected given the low SO_4^{-2} concentration, moderate DO levels and positive redox potential (see Thompson, 2000). Dissolved O_2 declined in the both mulch treatments, but remained above 10% at both the surface and bottom of the macrocosms. The addition of such a large mass of organic material to some of the macrocosms might have been expected to have generated a large biological oxygen demand as bacteria started to decompose the material. As the water in the mulch macrocosms remained oxic at the bottom this suggests that the organic material used was strongly refractory and proving difficult to microbially decompose.
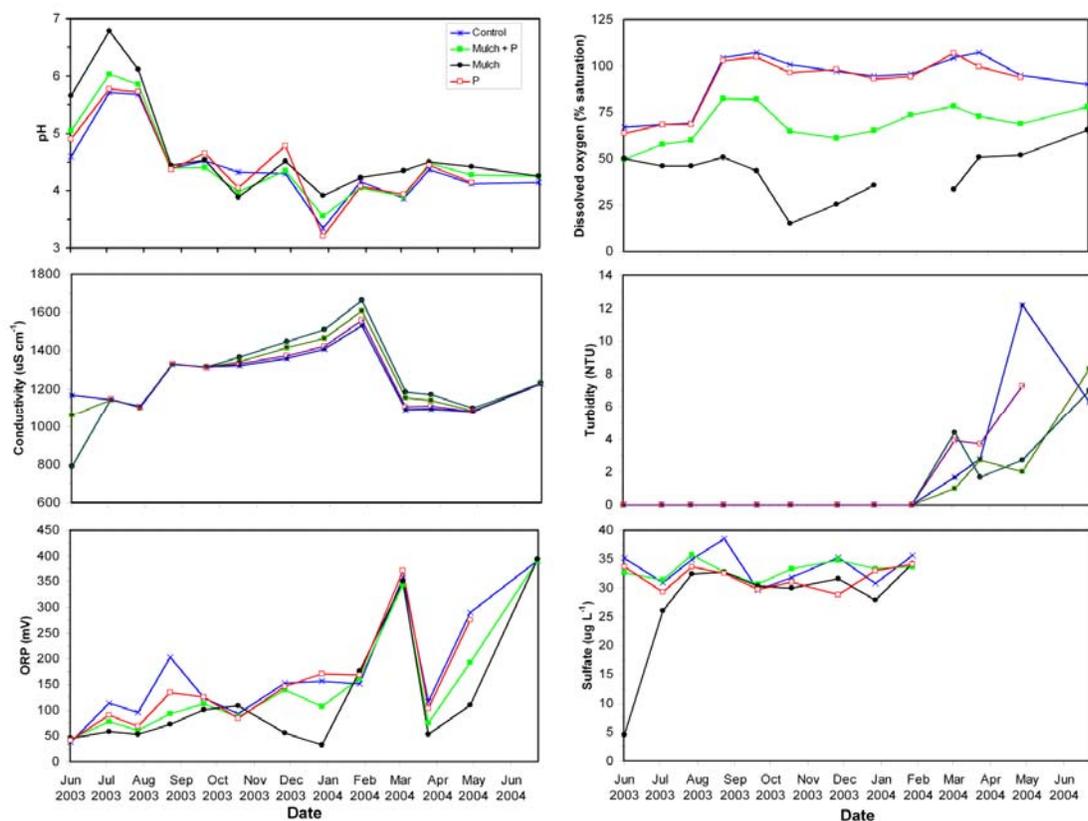
Figure 6. Physico-chemistry from the treatment macrocosms and Ewington Lake (Control) recorded over the course of the experiment.

After March 2004, there was a rise in turbidity of the lake and treatments. This is presumed to be due to re-suspension of kaolinitic clay from the benthic sediments or washed in through

surface runoff following turnover at the end of summer. The temperature profiles show that the lake was mildly stratified (0.5^{o}C difference top to bottom) and the treatments strongly stratified ($3–5^{o}$C difference) between September 2003 and February 2004. However the treatments appear to be mildly stratified for most of the year ($1–2^{o}$C difference). This might be due to reduced mixing as a result of the barriers reducing wind fetch and/or groundwater intrusions that are not mixed to the same extent as in the lake.

The addition of P to the macrocosms increased FRP concentrations by the desired amount (10-15 µg L^{-1}); however, this increase was only maintained for one month after which P levels returned to those of the other treatments and the lake (Figure 7). Interestingly, larger increases in FRP were obtained from the mulch in the first month (>100 µg L^{-1}), although this increase was larger in the mulch alone than in the mulch and P. It is likely that the relatively low iron (0.3 mg L^{-1}) and Al (0.6 mg L^{-1}) concentrations were sufficient to bind with the introduced FRP removing it from the water column. This demonstrates that if P additions are going to be used to remediate even the relatively clean waters of Collie pit lakes that ongoing P additions will be required to maintain elevated FRP concentrations. Total P concentrations were similar between all treatments and the lake.

While appearing to be relatively slow, the decomposition of the mulch created a demand for N, as can be seen in the reduction of Total N, NO$_{X}$ and NH$_{3}$ concentrations to below or close to detection limits in late spring/summer (November 2003 to January 2004). In February 2004 we added a further dose of superphosphate to the P treatments and 32.6 g of urea fertilizer ($CO(NH_2)_2$; 46% N) to all treatments to increase N concentrations by 20-30 µg L^{-1} in response to this. The utilization of available N by decomposition processes was one of the reasons that McCullough et al (2006) chose to utilize both mulch (green waste) and sewage in combination to remediate a mine pit lake. The sewage was included to provide a source of nutrients particularly N to feed the decomposition process. Interestingly, ammonium (NH$_{4}$) concentrations were generally lower in the mulch treatments than in P treatment or lake. In August 2003, there was a peak of NOx in both mulch treatments. This suggests that there may have been an initial release of dissolved organic C in the mulch treatments that supported the nitrification of NH$_{4}$ to NOx, although this was short-lived due to the demand for N by decomposition.

Primary production as measured by Chlorophyll *a* was very low in all macrocosms and the lake, except between February and April 2004, where all treatments showed substantial increases from <2 µg L^{-1} to nearly 8 µg L^{-1}. Interestingly, the treatments with added P showed a reduced response compared to mulch alone, although given that there was no apparent difference between treatments and the lake in FRP and Total P concentrations, this may just reflect between macrocosm variability.

A PCA analysis of the water chemistry data from control and treatment macrocosms accounted for 72.9% of variability within two dimensions (Figure 8). Addition of phosphorus, organic matter and a combination of both appeared to affect the macrocosms in much the same manner. For all seasons, SO$_4^{-2}$, DO, acidity, and N as both NH$_4$ and NOx were all reduced in treatment macrocosms, relative to control. Both FRP and Total P were conversely increased in treatment macrocosms. Temperature, electrical conductivity (EC) and pH were largely unchanged by treatment with either P or mulch, although the former two decreased and the latter increased in winter. Treatment by mulch alone appeared to have more effect on water chemistry than either P alone (little affect) or with mulch and P combined. The mulch-only treatment also appeared to render greater seasonal variability in macrocosm water quality than any of the other

treatments, although the mulch and P treatment was similarly variable. The addition of mulch does appear to have changed the water chemistry of the macrocosms from that of the lake and P only addition, suggesting that the addition was altering water quality. Further work is required to see whether the apparent trajectory of the mulch additions is desirable for remediation. For example, observations of the mulch macrocosms suggest that the additions resulted in increases in abundance and diversity of macroinvertebrates and biofilms. This suggests that without any apparent changes in water quality, the treatments improved biodiversity; this is probably due to the creation of habitat and alternative food sources. Depending on the goals of the remediation program, organic matter additions appear important for the development of more complex biotic communities within the mine lakes.
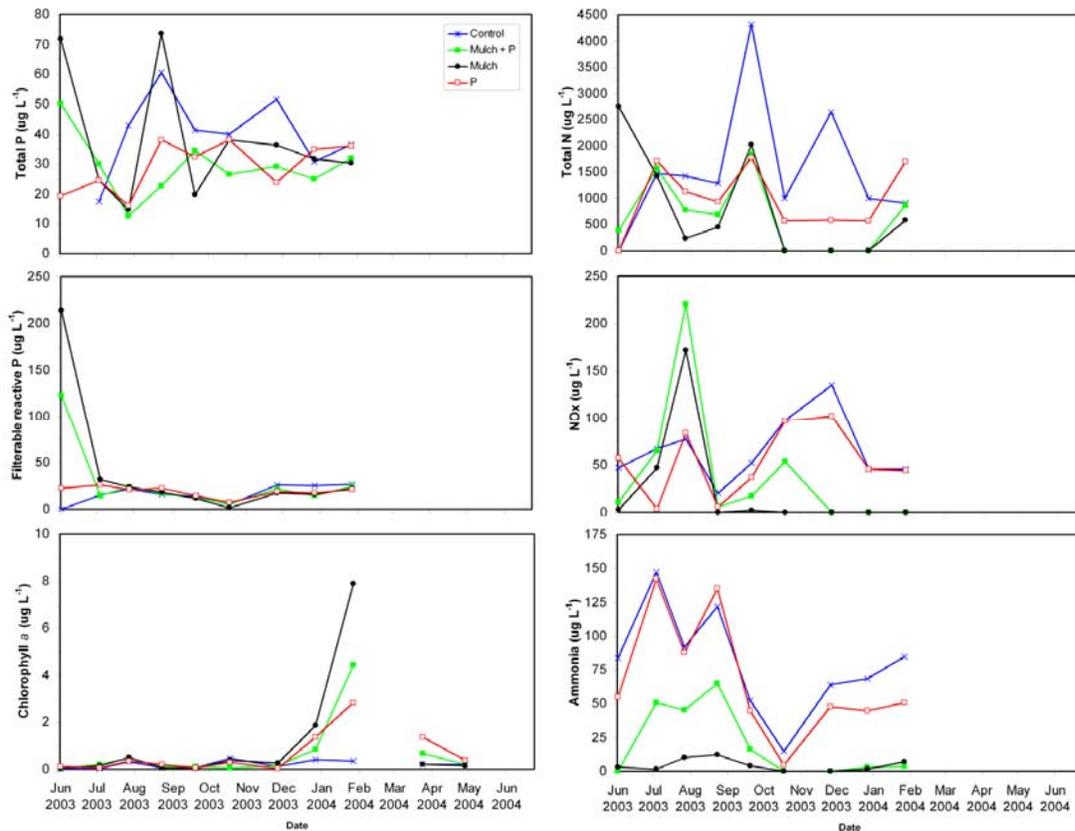
Figure 7.   Nutrient concentrations and Chlorophyll *a* from the treatment macrocosms and Ewington Lake (Control) recorded over the course of the experiment.

Winter groundwater inflow is likely to be responsible for the changes in temperature, EC and pH. Groundwater is likely to play a more important role in these older systems which have come to equilibrium in the hydrogeology and in cases, such as with Ewington Lake, where the ongoing role of overburden contributions to lake water chemistry is minor. Ground water is expected to be of relatively higher pH, yet lower temperature and EC (Varma, 2002).
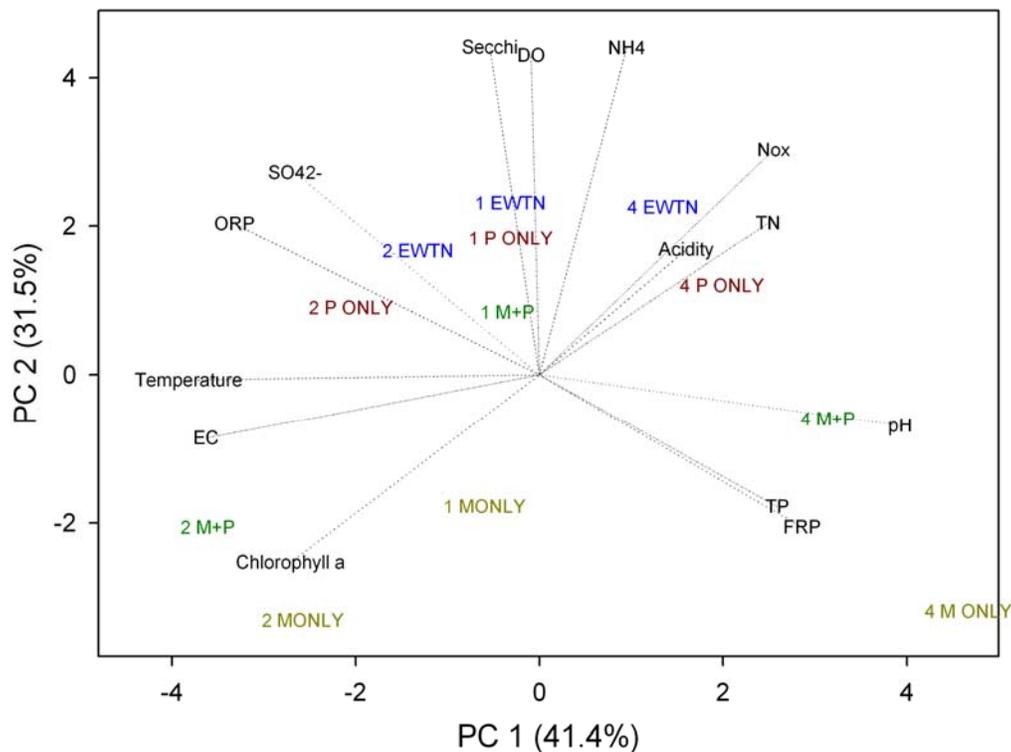
Figure 8. PCA analysis of macrocosms and control lake. (Numbers indicate season with
1 = spring, 2 =summer, and 4 =winter; EWTN = Ewington Lake (control),
P = Phosphorus only, M = Mulch only, M+P = Mulch and P).

Conclusions

Mine water research and management is a very new and rapidly developing field
(Wolkersdorfer, 2004). Much remains to be learnt about remediation of pit lakes, especially in
the Collie region where the pit lakes have low acidity (uncharacteristically for AMD lakes), low
pH and low in SO_4^{-2} and metals. As might be expected there is a loss of predictability of
outcomes when core experiments are scaled to more realistic scales. Therefore reliance on
remediation strategies that utilize SRB does not appear to be appropriate to these lakes. Mulch
appears to be unsuited to mine lake remediation without the addition of other non-refractory
organic materials. These materials are needed to provide carbon and nitrogen for decomposition
processes. The addition of P appears to enhance biotic processes within the lakes, however the P
concentrations need to be maintained as it is rapidly lost to the sediment. The treatments did
however encourage an increase in the abundance and diversity of biofilm and macroinvertebrate
communities.

Current and future projects

Another mesocosm experiment is currently underway. This will focus on the effect of liming
and additions of P, both alone and in combination on water quality in Collie mine pit lakes.
Liming is believed to be necessary to raise the pH, add buffering and to reduce iron and

aluminum concentrations so that additions of P are likely to be more effective at stimulating alkalinity generation through primary production.

In 2006, we are preparing to undertake a remediation of the entire Ewington Lake, using a combination of liming, P addition, and the use of organic materials (probably green waste and a non-refractory source).

Acknowledgements

Literature Cited

APHA, 1998. Standard Methods for the examination of water and wastewater. American Public Health Association, Washington D.C.

Benner, S.G., Blowes, D.W., Ptacek, C.J. and Mayer, K.U., 2002. Rates of sulfate reduction and metal sulfide precipitation in a permeable reactive barrier. Applied Geochemistry, 17(3): 301-320.

Castro, J.M., Wielinga, B.W., Gannon, J.E. and Moore, J,N. 1999 Stimulation of sulfate-reducing bacteria in lake water from a former open-pit mine through addition of organic waste. Water Environmental Research, 71 (2), 218-223.

Clarke, K.R. and Warwick, R.M., 2001. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratory, Plymouth, 144 pp.

Commonwealth of Australia Bureau of Meteorology, 05/10/2005. Collie climate averages.

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

Dames and Moore Pty Ltd, 1997. Groundwater Resource Assessment to June 1997 – Muja, Chicken Creek and Ewington II Mines. Dames and Moore Pty Ltd, Perth, Western Australia.

Davison, W., George, D.G. and Edwards, N.J.A., 1995. Controlled reversal of lake acidification by treatment with phosphate fertilizer. Nature, 377: 504-507.

Dillon, P.J., Evans, H.E. and Girard, R., 1997. Hypolimnetic alkalinity generation in two dilute, oligotrophic lakes in Ontario Canada. Water, Air, & Soil Pollution, 99: 373-380.

Doupé, R.G. and Lymbery, A.J., 2005. Environmental risks associated with beneficial end uses of mine lakes in southwestern Australia. Mine Water and the Environment 24(3): 134-138

Drury, W.J., 1999. Treatment of acid mine drainage with anaerobic solid substrate reactors. Water Environment Research, 71(6): 1244-1250.

Drury, W.J., 2000. Modelling of sulfate reduction in anaerobic solid substrate bioreactors for mine drainage treatment. Mine Water and the Environment, 19(1): 18-28.

Findlay, D.L. et al., 1999. Effects on phytoplankton of nutrients added in conjunction with acidification. Freshwater Biology, 41(1): 131-145.

Frömmichen, R., Kellner, S. and Friese, K., 2003. Sediment conditioning with organic and/or inorganic carbon sources as a first step in alkalinity generation of acid mine pit lake water (pH 2-3). Environmental Science and Technology, 37: 1414-1421.

Frömmichen, R., Wendt-Potthoff, K., Friese, K. and Fischer, R., 2004. Microcosm studies for neutralization of hypolimnic acid mine lake water (pH 2.6). Environmental Science and Technology, 38: 1877-1887.

Fyson, A., Deneke, R., Nixdorf, B. and Steinberg, C.E.W., 2003. Extremely acidic mine lake ecosystems in Lusatia (Germany): characterization and development of sustainable, biology-based acidity removal technology, Sudbury 2003 - Mining and the Environment, Laurentian University - Sudbury, Ontario, Canada.

Geller, W., Klapper, H. and Schultze, M., 1998. Acidic Mining Lakes. Springer, Berlin, 435 pp.

Geller, W., Wendt-Potthoff, K. and Koschorreck, M., 2003. In situ bioremediation of acid mining lakes by addition of organic substrate and lime, Sudbury 2003 - Mining and the Environment, Laurentian University - Sudbury, Ontario, Canada.

Gibert, O., de Pablo, J., Cortina, J.L. and Ayora, C., 2002. Treatment of acid mine drainage by sulphate-reducing bacteria using permeable reactive barriers: a review from laboratory to full-scale experiments. Reviews in Environmental Science and Biotechnology, 1: 327-333.

Gyure, R.A., Konopka, A., Brooks, A. and Doemel, W., 1990. Microbial sulfate reduction in acidic strip mine lakes. FEMS Microbiology Ecology, 73: 193-202.

Harries, J., 1997. Acid mine drainage in Australia. Supervising Scientist Report 125, Office of the Supervising Scientist, Canberra. 104p.

Harries, J., 1998. The OSS/ACMRR study on acid mine drainage in Australia: its extent and potential future liability. AusIMM Bulletin, 1(72-74).

Johnson, S.L. and Wright, A.H., 2003. Mine void water resource issues in Western Australia. 9, Water and Rivers Commission, Perth, Australia.

Kleeberg, A., 1998. The quantification of sulfate reduction in sulfate-rich freshwater lakes - a means for predicting the eutrophication process of acidic mining lakes. Water, Air, and Soil Pollution, 108: 365-374.

Kolmert, Å. and Johnson, D.B., 2001. Remediation of acidic waste waters using immobilised, acidophilic sulfate-reducing bacteria. Journal of Chemical Technology & Biotechnology, 76(8): 836-843.

Kristensen, S.E. and Wilson, A.C., 1986. A review of the coal and lignite resources of Western Australia. In: D.A. Berkman (Editor), Geology and Exploration. 13th Commonwealth Mining and Metallurgy Institute Congress Publication, Melbourne, pp. 87-97.

Küsel, K. and Dorsch, T., 2000. Effect of supplemental electron donors on the microbial reduction of Fe(III), sulfate, and CO_2 in mining–impacted freshwater lake sediments. Microbial Ecology, 40: 238-249.

Le Blanc Smith, G., 1993. The geology and Permian coal resources of the Collie Basin, Western Australia. 38.

Lord, J.H., 1952. Collie Mineral Field: Western Australia Geological Survey. 105 part 1, Perth.

Lund, M., Bills, D., Keneally, T., Brown, S. and Thompson, S., 2000. Bacterial strategies for increasing pH in acidic voids, Final void water quality enhancement: Stage III. ACARP Project Number C8031 report, Perth, pp. 169-222.

Martin, A. et al., 2003. Field-scale assessment of bioremediation strategies for two pit lakes using limnocorrals, 6th International Conference on Acid Rock Drainage (ICARD). Australasian Institute of Mining and Metallurgy, Cairns, Australia.

McCullough, C.D., Lund, M.A. and May, J.M., 2006. Microcosm testing of municipal sewage and green waste for full-scale remediation of an acid coal pit lake, in semi-arid tropical Australia in Proceedings of the 7th ICARD, March 26-30, 2006, St. Louis MO. ASMR, Lexington, KY.

McNee, J. et al., 2003. The physical, chemical and biological dynamics of two contrasting pit lakes: Implications for pit lake bio-remediation, Sudbury 2003 - Mining and the Environment, Laurentian University - Sudbury, Ontario, Canada.

Pöhler, I., Wenderoth, D.F., Wendt-Potthoff, K. and Höfle, M.G., 2002. Bacterioplankton community structure and dynamics in enclosures during bioremediation experiments in an acid mining lake. Water, Air, & Soil Pollution: Focus, 2(3): 111-121.

Praharaj, T. and Fortin, D., 2004. Indicators of microbial sulfate reduction in acidic sulfide-rich mine tailings. Geomicrobiology Journal, 21(7): 457-467.

PRIMER-E Ltd, 2001. PRIMER. Plymouth Marine Laboratory, Plymouth.

Sappal, K., Zhu, Z.R., Rathur, Q. and Hodgkin, T., 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. ACARP Project Number C8031 report, Perth, pp. 11-68.

Singleton Jr., R., 1993. The sulfate-reducing bacteria: an overview. In: J.M. Odom and R. Singleton Jr. (Editors), The sulfate-reducing bacteria: contemporary perspectives. Springer Verlag, New York, USA, pp. 1-20.

Speziale, B.J., Schreiner, S.P., Giammatteo, P.A. and Schindler, J.E., 1984. Comparison of N,N-Dimethylformamide, Dimethyl sulfoxide, and acetone for extraction of phytoplankton chlorophyll. Canadian Journal of Fisheries and Aquatic Sciences, 41: 1519-1522.

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

Thompson, S., 2000. Managing the acidity of abandoned water filled coal mining voids in Collie (Western Australia) using organic matter. M.Sc. Thesis, Edith Cowan University, Perth, 205 pp.

Tostche, O., Fyson, A. and Steinberg, C., 2003. Neutralizing extremely acidic mining lakes by chemical and microbial treatment - mesocosm studies., Sudbury 2003: Mining and the environment, Laurentian University - Sudbury, Ontario, Canada.

Tuttle, J.H., Dugan, P.R. and Rendles, C.I., 1969. Microbial sulfate reduction and its potential utility as an acid mine water pollution abatement procedure. Applied Microbiology, 17: 297-302.

Varma, S., 2002. Hydrogeology and groundwater resources of the Collie basin, Western Australia. HG 5, Water and Rivers Comminission, Perth.

Wendt-Potthoff, K., Frömmichen, R., Herzsprung, P. and Koschorreck, M., 2002. Microbial Fe(III) reduction in acidic mining lake sediments after addition of an organic substrate and lime. Water, Air, & Soil Pollution: Focus, 2(3): 81-96.

West Australian Forest Department, 1983. Collie Coal Basin: Status of coal mining operations: proposals and priorities for rehabilitation, West Australian Forest Department, Perth.

Wolkersdorfer, C., 2004. Mine water literature in ISI's Science Citation Index Expanded™. Mine Water and the Environment, 23: 96-99.