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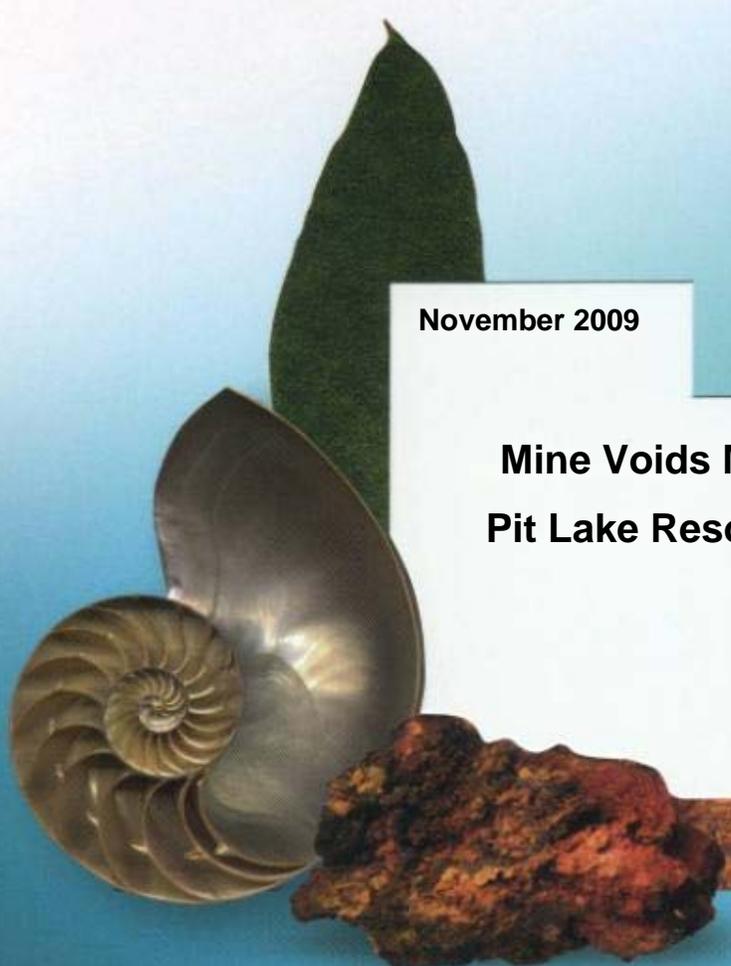


**EDITH COWAN  
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November 2009

**Mine Voids Management Strategy (I):  
Pit Lake Resources of the Collie Basin**

By, Dr. C. D. McCullough  
Assoc. Prof. M. A. Lund  
Dr. L. Y. L. Zhao



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between ecology & management to help  
environmental problems*



**CENTRE FOR ECOSYSTEM MANAGEMENT**





November 2009

## Mine Voids Management Strategy (I): Pit Lake Resources of the Collie Basin

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*Prepared for,*

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*Frontispiece*



**Figure 1.** Paul Irving, Environmental Officer, Griffin Coal Mining Company Pty Ltd, water quality sampling in Blue Waters Lake, April 2009.

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## **Executive Summary**

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1. Pit lakes can form in open cut mining pits, which extend below the groundwater table. Once dewatering ceases, then groundwater, surface water and direct rainfall contribute to the formation of a pit lake.
2. Pit lakes are common in the Collie Basin in Western Australia (WA). They formed a lake district consisting of 15 lakes, although two were re-mined in late 2009. As other mine operations in the Basin finish further pit lakes are anticipated, many of these potentially much larger than existing pit lakes (e.g., Muja). It is estimated that the total volume of water in Collie pit lakes will exceed 200 GL.
3. Collie pit lakes have different physico-chemical characteristics than natural lakes, such as a small catchment vs. relatively great depth, less nutrients, low pH but high metal concentrations.
4. The current demand for water in WA and its increasing scarcity means that Collie pit lakes represent a potentially valuable resource to both the environment and the community.
5. This study reviews and collates existing information on pit lakes in the Collie Basin. Historic data and contemporary data chemistry and ecology information have been collected, analysed, compared and evaluated. Our aims are summarise the currently available information on pit lakes, to identify knowledge gaps and to make preliminary assessments as to the potential end uses for Collie pit lakes.
6. The historical data were collected from research institutions, such as Centre for Ecosystem Management, ECU, Centre for Sustainable Mine Lake, Curtin University and University of WA; from government agencies, Department of Water and Department of Environment; and from the mining industry, Wesfarmers Premier Coal Limited and Griffin Coal Mining Company Pty Ltd. As the lakes have not had any regular monitoring, this has led to a disparate range of

data being collected both in terms of parameters measured, monitoring approach (i.e., sample replication and location) and sampling frequency.

7. Water quality extends back until 1991, however ecological data were not recorded until 1997 and there are still few records after this point. Pit lake ecological data is dominated by macroinvertebrate surveys, although some diatom and plankton surveys have been made by students.
8. The data set was extended with contemporary data collected in 2009, which covered physico-chemical parameters, major and trace elements, nutrients and ecological species and structural analysis.
9. Water quality data was collated back to 1991 for Blue Waters, Ewington and Stockton Lake, with Lake Kepwari and Stockton Lake having the longest series of data. Black Diamond B has only 1 sampling occasion recorded from 1994; while WON9, WO3, WO5C, WO5D, WO5F only have the data collected in this study from 2009. The most comprehensive data sets come from Philips et al. (2000) covering the historical lakes between 1997 and 1999. A total of 3263 individual records (including records for each site and each depth). In 2006, Chicken Creek was the most frequently sampled lake with a total of 45 sampling occasions. The most common parameters measured were dissolved oxygen (2506 records), followed by temperature (2324) and pH (1078), nutrients (N, P and C all forms) were recorded in <300 records each. Mg (669) was the most commonly measured metal followed by Fe (654), with all other metals recorded <500 times.
10. Primary and secondary productivity in the voids is extremely low and this appears to be largely due to low availability of carbon sources and low filterable reactive phosphorus concentrations
11. The pH within pit lakes is relatively stable over time once equilibrium is reached, although acidity (buffering capacity) slowly declines over time in some pit lakes.

12. Charophytes (*Chara* and *Nitella* spp.) appear capable of colonising and growing in the pit lakes if pH is raised to around 5.
13. Although most metals in the water are at low concentrations, certain metals such as aluminium occur at toxic levels for a range of end-uses. There are also other individual metals of concern in specific pit lakes. Unfortunately as much of the metal data does not have very low detection limits and is restricted to only a few samples the full risks posed by metals cannot be ascertained.
14. The input of large amounts of neutral pH water appears successful in maintaining higher pH in the Collie pit lakes. However, this neutralising effect appears relatively short-lived once the incoming flow of higher pH water is stopped.
15. The dataset is large but heavily reflects the disparity of sources and the various aims of collectors. As a result there is a dearth of information on the long term water quality trajectories of these systems. This study was also the first to record water quality and biological data on a number of the newer pit lakes.
16. A comprehensive water quality and biological monitoring program is strongly recommended for these pit lakes in order to be able to predict and manage risks and best utilises the opportunities provided by the pit lakes for the Collie region and south-west Australian economy. The development of a suitable programme will form Task 4 of this research programme.
17. The water in the pit lakes is potentially suitable for a range of high quality end-uses although in most cases some form of remediation would be required to ensure the water reaches the appropriate standard or guideline value.
18. Given the likely use of the pit lakes for a range of end-uses and the need for remediation, the need for research into the types of remediation that could be undertaken as well as the likely costs is essential.

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## 1 Background

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### 1.1 Pit lake formation

Open cut mining operations have become common practice over the last few decades in Australia, as a method of extracting commercially useful ore found near the surface. Since backfilling is normally unfeasible practically or economically, an open pit after completion of extraction operations is left. This is called a mine void. After mine operations are discontinued and dewatering ceases, most of those that extend below the natural groundwater table, fill by inflow of groundwater, direct rainfall, and runoff from adjacent drainage basins and the void catchment. Natural filling may take many years to complete. To reduce oxidation of mining waste and wall rocks, to inhibit the activity of acidophilic sulphur-oxidizing bacteria, and to promote anoxic conditions at the lake bottoms which may minimize the formation of acids and dissolved metals, some pit lakes are rapidly filled with stream or river diversions. The water qualities in such pit lakes depend on the filling water and geological catchments and are highly variable. Although the water level may continue to fluctuate as it equilibrates or as climate and local groundwater levels alter, once containing water, the empty mine void has now become a pit lake.

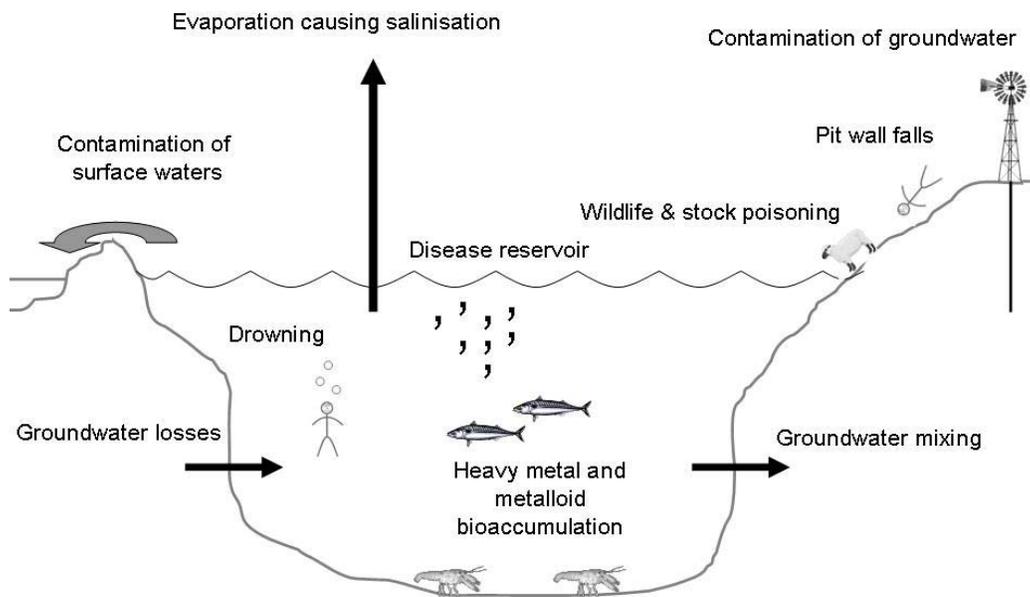
During the first half of the twentieth century, most pit lakes formed as a result of coal mining were located in North America. With the introduction of high-powered steam shovels in 1911, the surface mining industry became a major source of coal in the United States (Gibb & Evans, 1978) and left hundreds of pit lakes. Since the implementation of the federal Surface Mining Control and Reclamation Act of 1977, the formation of coal pit lakes in the United States has virtually stopped. However, coal pit lakes are still allowed and are sometimes desirable, considering that backfilling is normally unfeasible practically or economically. Also the needs of communities and ecology may allow pit lakes. There are some pit lakes being constructed at coal-mining sites in Canada (Sumer *et al.*, 1995) to serve as fish and wildlife habitat and for recreational use.

New mining technologies have led to a large increase in open cut mining of gold, silver, uranium, and base metals (Miller *et al.*, 1996). Open cut mining is currently in use mainly in Australia, Bulgaria, Canada, Chile, Colombia, Indonesia, Kyrgyzstan,

Mongolia, Namibia, Peru, Portugal, Russia, South Africa, United Kingdom, United States, and Zambia. The number of future open cut mines is likely to continue with current and predicted demands for minerals and energy, the global financial crisis notwithstanding. Except for those in the most arid areas, deep open cut mines are likely to develop pit lakes when mining operations end. Given the large number of pit lakes that will form worldwide and the large volume of water they will contain, the quality of the water in these lakes will be of profound importance, especially in areas with scarce water resources.

## **1.2 Pit lake characteristics**

Pit lakes differ physically from natural lakes in having a markedly higher ratio of depth to surface area (Figure 2). This is described by percent relative depth, which is defined as the percentage of a lake's maximum depth compared to its width calculated from its surface area by assuming the lake is approximately circular. A typical natural lake has a relative depth of less than 2%, although some may exceed 5%. Pit lakes commonly have relative depths between 10 and 40% (Doyle & Davies, 1999). This causes pit lakes easily stratify with the consequential changes in chemical characteristics with depth. Total dissolved solids and electrolytic conductivity tend to increase with depth; values near the bottom are often several times those at the surface. The hypolimnion (lower stratum) of a stratified lake has the tendency to contain low dissolved oxygen concentrations, if enough oxygen demand (chemical and/or biological) is high enough. The existence of a sub-oxic or anoxic (no oxygen) layer in a pit lake can have significant effects on the lake's chemical and biological characteristics and thus on its potential for remediation.



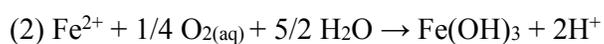
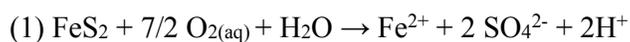
**Figure 2.** A conceptual model of the risks of pit lakes (after McCullough & Lund, 2006).

Where pit sides are battered for public access or to promote development of riparian (fringing vegetation) zones, deep pits will still have a bathymetry unlike natural lakes with steep sides below the battering. The size of mining pits in Australia ranges from relatively small urban borrow pits of about 100 m in diameter, to enormous open cut operations such as Mount Whaleback mine in the Central Pilbara, (WA) which will have final pit dimensions of 5.5 km by 2.2 km and a depth of 500 (Johnson & Wright, 2003). These new mining pit lakes have few natural counterparts in Australia, especially in depth. Furthermore, as the water level in the pit lake equilibrates, it is frequently deep within the walls of the open-cut, creating very little opportunity for natural slopes to the water surface; this also influences water mixing due to sheltering from winds (Huber *et al.*, 2008).

As pit lakes typically have limited catchments, inflows of surface water tend to be small which may be useful in preventing worsening water quality from exposed geologies. However, where exposed geologies are not problematic, it may desirable

for pit lake water quality to capture clean surface waters and small catchments may limit this. Pit lake water quality can be highly variable; particularly for acidity, salinity, hardness and metal concentrations which are primarily governed by the pit lake catchment hydrology and geochemistry (Miller *et al.*, 1996). For example, pit lake water quality may become acidic, through oxidation of reactive iron-bearing geologies as Acid Mine Drainage (AMD) (Klapper & Geller, 2002). Such acidic mine waters are often toxic to aquatic biota (Spry & Wiener, 1991; Doyle & Davies, 1999; Storer *et al.*, 2002; Stephens & Ingram, 2006). Pit lakes waters affected by salinity and acidity may also adversely influence nearby and regional groundwater resources and receiving environments, e.g., wetlands with contaminated plumes from flow-through pit lakes extending large distances down-gradient. The extent of such an impact may vary from insignificant in low hydraulic conductivity rocks and groundwater systems already saline, to considerable in high hydraulic conductivity rocks and naturally low-salinity groundwater environments (Commander *et al.*, 1994; Johnson & Wright, 2003). The majority of pit lake studies conducted in Australia have focussed on physical and chemical characteristics of water quality (Boland & Padovan, 2002; Jones *et al.*, 2008). These studies have demonstrated that pit lake water quality is influenced by many factors including climate, groundwater quality, depth, pit filling method and local mineralogy.

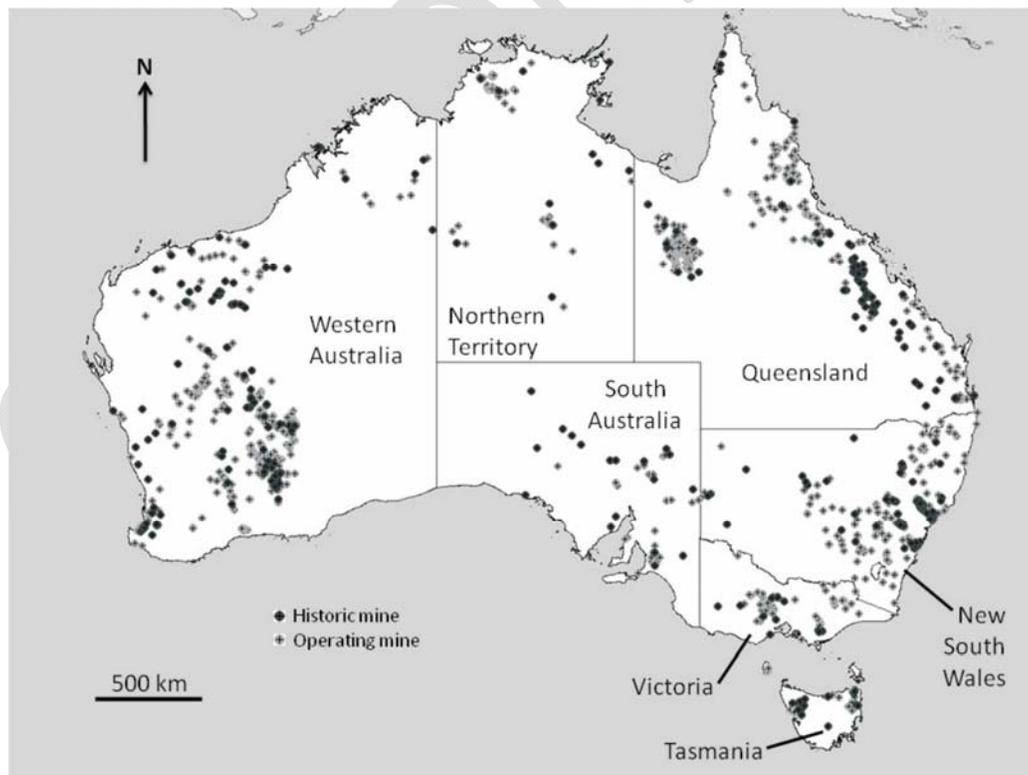
Many pit lakes contain high levels of acid, sulphate, and dissolved metals/metalloids. The chemical characteristics of a lake depend on the alkalinity of the local groundwater, the composition of the wall rocks, the chemistry of the surrounding vadose zone, and the quality and quantity of runoff from the surrounding land (Plumlee *et al.*, 1992; Davis *et al.*, 1993). Rock that is exposed to oxidizing conditions during dewatering can be a major source of acid, even though it lies below the water table before mining operations begin and after the lake fills (Miller *et al.*, 1996). The most common set of reactions producing acidity in mine lakes is the oxidation of sulphide and iron in pyrite ( $\text{FeS}_2$ ) in the following two reactions (Castro *et al.*, 1999).



In natural systems pH is typically buffered by a carbonate buffer system (at pH of 6 to 8.5); however pit lakes of lower pH are often buffered by aluminium complexes (pH 4.5–5.5) or iron complexes (pH 2.0–4.0).

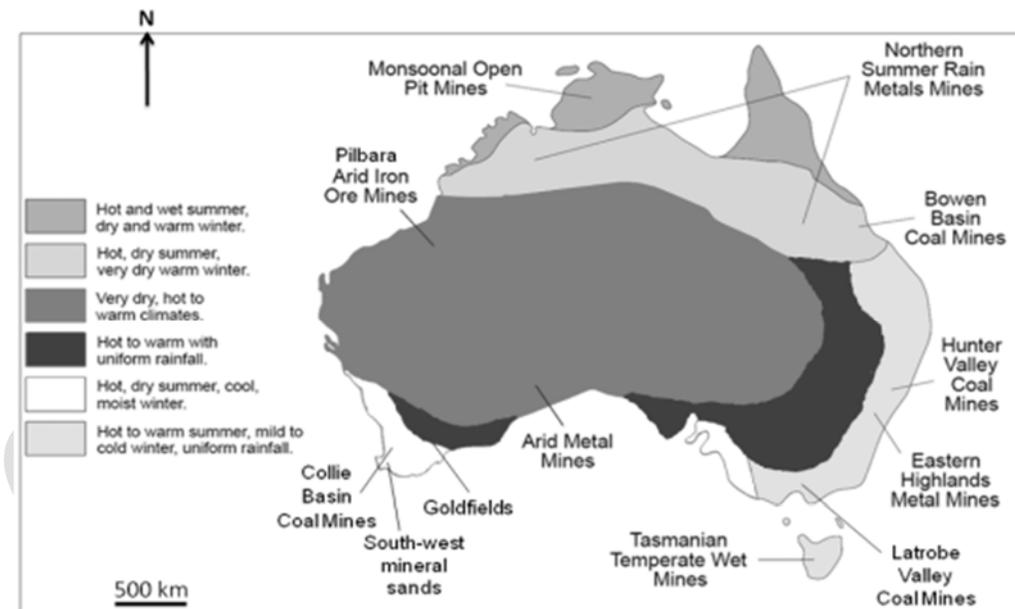
### 1.3 Australian pit lakes

Australia is among the top producers for many of the world's most important minerals (Mudd, 2007; Geoscience Australia, 2008). Major mining resources include diamonds, uranium, black coal, iron, gold, copper, lead, zinc, bauxite and mineral sands. Pit lakes occur in all states and territories in Australia. However, most historic and contemporary mining activity is centred on the states of Western Australia (WA), Queensland and New South Wales (NSW) (Figure 3). Tasmania, Victoria, South Australia (SA) and Northern Territory (NT) are generally only important for certain minerals i.e., copper, gold, uranium, etc. (Mudd, 2007).



**Figure 3.** Distribution of historic and operating mines in Australia (after Kumar *et al.*, in press).

The mining areas also occur across a broad range of climatic regions (Figure 4). Approximately one-third of Australia is arid with rainfall less than 250 mm per year and another one third is semi-arid (250–500 mm per year). There are few areas where rainfall exceeds evaporation on an annual basis (Bell, 2001). Low rainfall and high evaporation rates exist in most parts of the country which may lead to net evaporation and the formation of hyper-saline pit lakes. Furthermore the groundwater in many parts of inland Australia is naturally brackish to hyper-saline. Low annual rainfall delays filling rates for new pit lakes facilitating oxidation of measures. A limited range of rivers and streams also limits opportunities for river rapid fill of pit lakes in many areas. However, surface discharge from pit lakes is also unlikely, which reduces a major source of environmental impact often seen in wetter climates. Contamination of regional groundwater in many arid areas can also often be a minimal risk as high evaporation rates ensure the pit lake remains a groundwater sink.



**Figure 4.** Australian pit lake classification after Mallet and Mark (1995), Johnson and Wright (2003) and (Kumar *et al.*, in press).

As one of the driest continents in the world and with the demand for water resources by industry and an increasing population, Australia may find pit lakes to be of

significant potential use for both industry and surrounding communities (McCullough & Lund, 2006). It is not known how many pit lakes exist in Australia, since there is no database for pit lakes at State or Commonwealth level. However, it was estimated in 2003 that there were 1,800 mine pits in Western Australia which potentially could form pit lakes (Johnson & Wright, 2003). Additionally, there are active or not-relinquished mining operations which add uncertainty to the number of pit lakes. Companies retain their leases over pit lakes with an option to over-mine as technology and economics alter the viability of their remaining resources.

A survey of mining operations in Australia found that 317 out of 517 mining operations contained potentially acid generating wastes (Harries, 1997). The same survey reported of the 176 mines that answered the questionnaire, 60 mines had water filled pits, but the pit lake water was similar to pre-mining groundwater. Nevertheless, seven sites had a total of  $0.06 \times 10^6 \text{ m}^3$  of acidic water at a pH of 2.5–3.5.

Australian pit lakes fall into four main categories in terms of their water quality. These are acidic (AMD affected), saline (can co-occur with AMD), neutral pH (but with some degree of contamination), and good water quality (but not necessarily comparable to natural regional water bodies) (Kumar *et al.*, in press).

1. **Acidic** – As examples, water quality of pit lakes of Collie (WA), Collinsville and Mt Morgan (both Queensland) are all degraded by AMD. Nevertheless, Collie pit lakes have low pH and toxic concentrations of Al primarily due to low buffering rather than high acidity inputs. Collinsville and Mt Morgan show similar classic AMD conditions of extremely low pH and very high metal concentrations. These latter pit lakes also show effects of ongoing salinisation.
2. **Saline** – In drier regions where net evaporation exceeds precipitation, and surface inflow to the pit is largely restricted to direct precipitation, can result in dramatic increases in salinity leading to brackish through to hyper-saline lakes. Such hyper-saline pit lakes of degraded value may also contaminate valuable regional groundwater resources in the future. For instance, in semi-arid regions such as the Collinsville region, high rates of evapo-concentration result in significant increases in pit lake salinity each year (McCullough *et al.*, 2008b).
3. **Neutral** – Mary Kathleen and Thalanga (Queensland), Ranger (Northern Territory) and Wedge Pit (WA) pit lakes have generally good water quality that is

nevertheless contaminated by one or more metals; in these cases Cu, Zn, U and As respectively. Nevertheless, these pit lakes remain well suited to a variety of end-uses as individual contaminants can often be more readily remediated or treated than more complex pit lake chemistries. For example, As contaminated water is extracted from bores a few meters away from Wedge Pit, treated and used to supply potable water to Laverton.

4. **Good water quality** – Kemerton (WA) is a silica sand mining operation with few geological considerations or mining processes that result in contamination of pit lake waters, hence water quality is very good. However, there remain significant differences in lake shape and water quality compared to shallow naturally acidic wetlands nearby (McCullough & Lund, 2008).

#### 1.4 Pit lake water quality over time

Water quality in pit lakes plays a dominant role in determining the range of end uses the lake can be used for (McCullough & Lund, 2006). The chosen end use will necessitate a certain water quality within the pit lake and remediation technologies will be needed in many cases to achieve the required end use water quality. Research is therefore required into water quality development in pit lakes by incorporating hydro-geological, limnological, biological and biogeochemical processes.

Current predictive models do not adequately account for sufficient of these processes for pit lakes to allow for useful predictions to be made (Jones, 1997). Instead, such models are likely to provide information for advancing current conceptual models and provide advice of pit lake response to different management scenarios (McCullough *et al.*, 2009). There are no Commonwealth or state guidelines for developing pit lakes as useful water resources. For instance, acidic and/or saline pit lakes influenced by AMD with acidic and metal contaminated water will need to be remediated using either chemical or biological methods (McCullough, 2007; McCullough *et al.*, 2008a; Neil *et al.*, 2009). Pit lakes contaminated with one or two metals but otherwise with good water quality can be used for a range of activities following chemical treatment such as selective precipitation. On the other hand, pit lakes with good water quality can be used immediately for uses such as aquaculture, water sports and recreation, etc.

Even partial remediation of highly acidic and saline waters can allow this water to be used for activities such as dust suppression, potentially reducing demands on other higher quality water sources (McCullough & Lund, 2006). However, despite the potential and existing examples of possible beneficial end uses for pit lakes, there are many pit lakes across the Australian continent with no planned end uses (Farrell, 1998).

The potential use of pit lake water remains dependent on the pit lake water quantity and quality (Doupé & Lymbery, 2005). However, there is no central database of existing or future pit lakes currently available in Australia. There has also been very little research on pit lakes in general with a detailed literature review for this chapter producing little information. What published information that is available is typically in the form of *ad hoc* opportunistic studies across a diverse range of disciplines including environmental engineering, geology, chemistry and aquatic ecology. Although many State and Federal primary industry and environmental agencies do collate mining data, including sometimes those of pit lakes and their characteristics, these data are generally limited to current or only recently decommissioned pit lakes. Many Australian pit lakes are on un-relinquished mining leases. This situation makes the long-term acquisition of data required to study the evolution of the quantity and quality of pit lake water a very challenging exercise. Furthermore, it is suspected that many pit lakes are considered commercially sensitive and are therefore not generally available for sampling and data collection. Such lack of detailed data of pit lake water quantity and quality for many regions currently renders it impossible to assess the risk and opportunities presented by pit lakes to Australia. Moreover, there are no guidelines for 'pit lakes' at the level of Federal government to be followed. In the Federal government's recent 'Mine Rehabilitation Handbook' guidelines (DITR, 2007) pit lakes are not mentioned.

## 1.5 Current study

Joint funded by the Department of Water, Western Australia and the Australian Government under its \$12.9 billion Water for the Future plan, this project is focussed toward the management and use of pit lakes that have formed within the Collie Basin

(the Collie Lakes District). The outcomes of this work are intended to support water resource planning and management in the Collie River catchment.

In late 2008, the Department of Water tendered a request for management of a research programme that would support and advise future water management in the Collie Basin in the south-west of Western Australia. A team lead by Edith Cowan University and comprising senior researchers from Mine Water and Environment Research Group (MiWER) and Centre for Ecosystem Management (CEM) at Edith Cowan University (ECU) and the School of Population Health, University of Western Australia (UWA) provided the successful tender for this research programme. This group of scientists have developed expertise in the area of environmental effects of mining over many years of specialist research and consultancy. Leading the mine water side of this research programme was Dr. C. McCullough, Associate Professor Mark Lund with Dr Lu Zhao of MiWER (Mine Water and Environment Research Group). Dr. Andrea Hinwood, Dr. Jane Heyworth and Mrs. Helen Tanner contributed considerable experience on human health issues and epidemiology to the health component of Task 2. All staff involved were successful researchers who have significant experience and a growing publication record in the mine water and environment and health area. The combined experience of the research team is unique within Australia.

The research programme activities were expected to run from March 2009 to May 2010. Altogether, 5 tasks were part of this research programme including:

1. Developing an inventory of pit lakes' data including history, storage, hydrology, water quality, water source and ecology and preparing a summary report that includes a preliminary assessment of end-use options for each pit lake and highlights gaps in existing data sets;
2. An assessment of the current effects of pit lakes on human health;
3. Development of a monitoring strategy for pit lakes and connected waters with special attention to those of the Collie Lakes District;
4. Production of a report outlining conceptual models of Environmental risk assessment, ecological limitations and health and grouping Collie pit lakes with regard to their geo-hydrology; and,

5. Geo-chemical modelling of water chemistry within pit lakes under different management scenarios to support management decisions.

This report fulfils Task 3 of this Collie Pit Lake research programme by developing a monitoring strategy for pit lakes, particularly designed toward the requirements of data collection from pit lakes within the Collie Basin. These data include hydrology, water quality, water source and ecology. Recommendations are also given as to how this data is analysed and reported. Knowledge gaps in existing monitoring strategy recommendations are indicated and recommendations are made into the continuous refinement of an ongoing monitoring programme for the 13 lakes in the Collie Lake District.

The purpose of this document is to recommend state-of-the-art monitoring design and sampling methodologies for environmental monitoring of pit lakes and their immediate catchments in the Collie Lake District, south-western Australia. This report gives an overview of regional and international environmental issues related to pit lakes, current national guidelines and best practice international operations and recommendations for monitoring pit lakes aquatic ecosystems. The purpose of monitoring selected indicators and their field sampling and analysis methods and techniques are described, and the practical temporal and spatial issues targeting episodic events are discussed in detail. Strategies for data analysis and reporting are also suggested for maximising data value and for enabling during further strategy development during long-term monitoring. Based on these general principles of monitoring, quality assurance, health and safety and budget recommendations are included as well.

The water quality and other environmental legacies of pit lakes following completion of mining operations is one of the most significant environmental issues facing the mining industry. The Collie region now has a Lake District of 13 pit lakes from historic (*ca.* 1960) and current open-cut mining activities. The current demand for water in the south-west of WA and its increasing scarcity means that Collie pit lakes represent a potentially valuable resource to both the environment and the community. Many of these lakes represent relatively good water quality that could be of risk to local and regional environments; and conversely of benefit to local communities if their environs are develop or managed to these ends (Zhao *et al.*, 2009). As a result, a

monitoring strategy for these pit lakes is required in order to achieve more stringent demands on pit lake conditions at relinquishment made by state and federal regulation and the desired end uses of local communities (McCullough *et al.*, 2009).

Targeting the environmental issues specific for pit lakes, this report is divided in three main parts:

- 1) Introduction to cover a review of the status and environmental issues of pit lakes, its related guidelines and the purpose of a monitoring strategy for pit lakes;
- 2) Discussion on monitoring water quality of pit lakes by applying the monitoring program, including objectives, water quality indicators, sampling and analysis quality assurance, health and safety and budget considerations.
- 3) Documentation and interpretation on the data obtained from a pit lake monitoring program, including data management and QA/QC, data analysis and assessment, programmatic evaluation and recommendations.

To obtain systematic water quality data of pit lakes incorporating hydro-geological, limnological, and biogeochemical processes, a monitoring strategy is needed. However, there are currently no Commonwealth, state or industry guidelines for monitoring lakes in lieu of better management and realisation of water resources. Internationally, a single brief chapter on broad guidelines has only recently been published in a US pit lake handbook that provides little guidance to development of a monitoring strategy for the purposes of particular lake types, regions and proposed end uses (Gammons, 2009).

This document is based on the experience of developing an inventory of Collie pit lake data and a preliminary assessment of existing dataset gaps. To support further water quality research, such as conceptual and numerical modelling, the design and recommendations of this water quality monitoring program will provide a good overview on historic and current parameter status and their predicted change and evolution. Also, the strategy report targets episodic events and gives short-term and long-term monitoring solutions, which will support water management and related decision making for pit lakes.

The intention of this work is, therefore, to develop and present *ad hoc* monitoring strategies for pit lakes, with particular regard for those of the south-west of Australia.

This report attempts to answer these questions: “Why monitor water quality of pit lakes? How should a monitoring program designed? What needs to be measured and analysed, and how? How to report and interpret monitoring results?” This report should provide a solid reference for researchers to consider the investigations on pit lakes. It will also provide a useful overview of considerations and a generic approach useful for environmental officers in industry and governmental agencies with to arrange and process a practical monitoring project for pit lakes.

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## 2 The Collie Coal Basin

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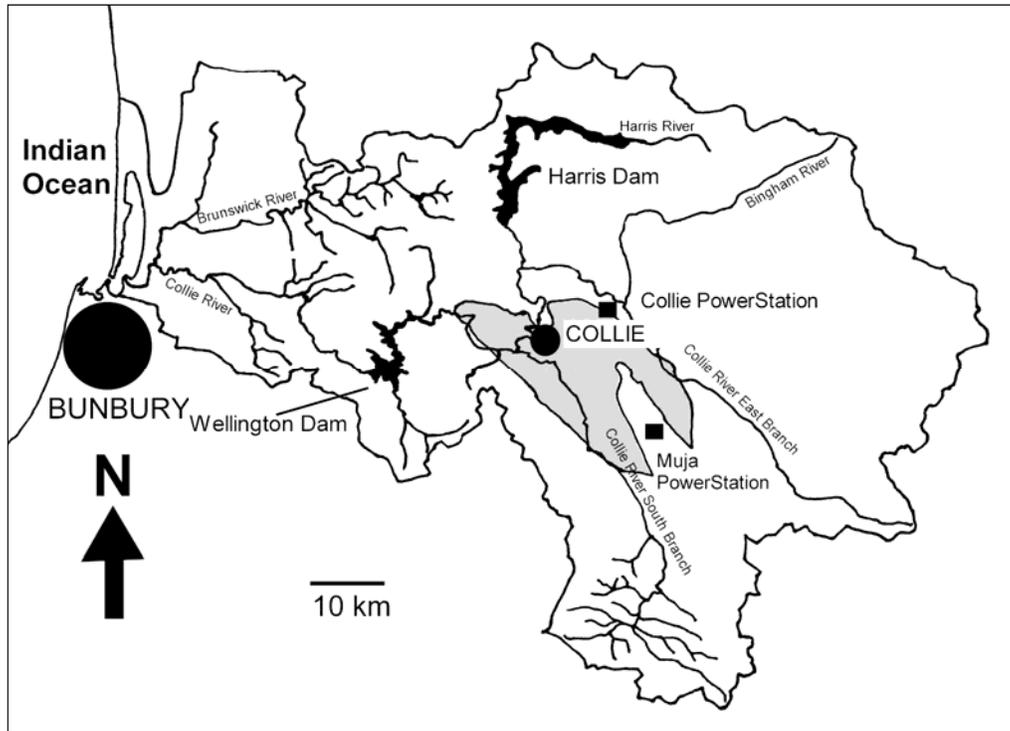
### 2.1 Background

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 160km south-southeast of Perth, and is the centre of coal mining industry in Western Australia (Figure 5). 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.

### 2.2 Geology

The Collie Basin covers an area of approximately 224 km<sup>2</sup>, 27 km long by 13 km wide and elongating in a north-west to south-east direction. The basin consists of two lobe-shaped sub-basins, the Cardiff sub-basin (151 km<sup>2</sup>) to the west and the Premier sub-basin (74 km<sup>2</sup>) to the east, in part separated by a faulted basement high, known as the Stockton Ridge (Moncrieff, 1993).

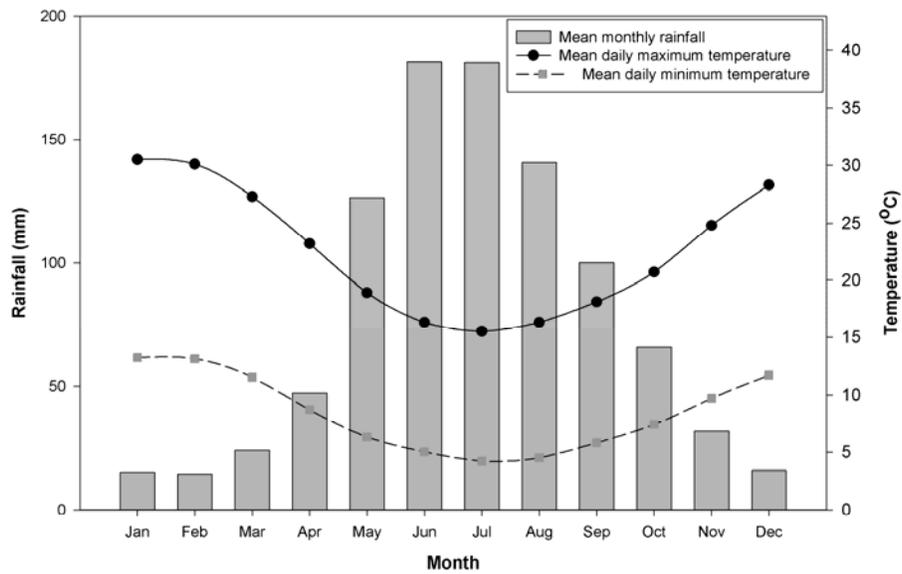
The Collie coal basin is a small sedimentary basin occurring in the Collie River catchment (Figure 5; (CWAG, 1996)). The Basin contains up to 1400 m of Permian sedimentary rocks, covered by a thin layer of Cretaceous rocks. The base layer of pebbly mudstone is covered by layers of sandstone, shale and coal. There are up to 55 significant coal seams which are typically 1.5 to 5 m thick although the Hebe seam reaches 13 m thick glacial sediments and coal measures. There are an estimated 1,330 Mt of coal resource in the basin of which extractable reserves account for 480 Mt (Varma, 2002).



**Figure 5.** Location of the Collie Basin (after Neil *et al.* 2009).

### 2.3 Climate

Collie is located in the south-west of Western Australia. 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 rainfall occurs in the five months from May to September (Figure 6). 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).



**Figure 6.** Mean temperature and rainfall climate of Collie (Commonwealth of Australia Bureau of Meteorology, 05/10/2005).

## 2.4 Groundwater

Groundwater resources of the Collie basin are fresh and discharge 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).

Groundwater (in abstractable quantities) in the Collie basin is mainly contained within the sandstone of the Muja Coal Measures, Premier Coal Measures, Allanson Sandstone, Ewington Coal Measures and Westralia Sandstone of the Collie Group; within the sand and sandstone of the Nakina Formation; and in the surficial sediments (Varma, 2002). The hydrogeology of the Collie basin is complex, with multiple aquifers as a result of aquicludes and faulting (Varma, 2002).

## 2.5 Collie River

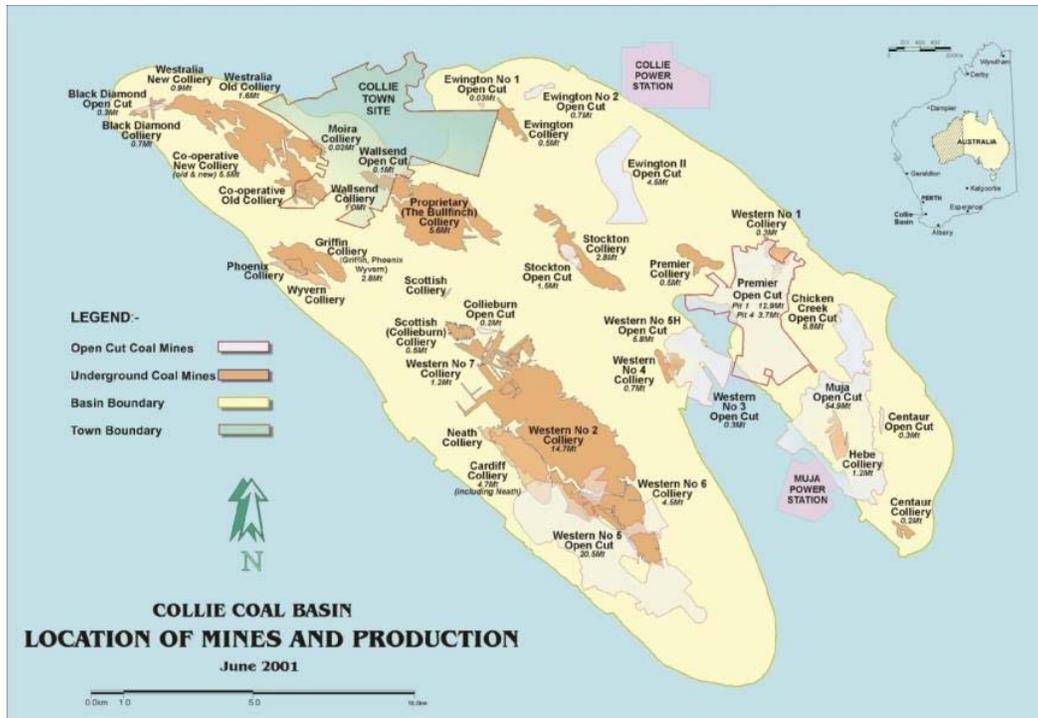
The Collie River is the main river system of the Collie basin, running almost 100 km westward to the Indian Ocean. It was once fresh but due to clearing of the upper catchment for agriculture, the salinity has risen to over 1000 mg L<sup>-1</sup> (Mauger *et al.*,

2001). Total phosphorus levels were recorded at over  $18 \mu\text{g L}^{-1}$  in July of 2004 (Salmon, UWA, unpublished data). The south branch of the river was diverted around the former WO5B (Lake Kepwari) mine pit during operations and has been used to fill the void when winter flows were sufficient.

Wellington dam was built on the Collie river, 35 km from the Collie townsite, in 1933 as a source for irrigation for the coastal plain (Mauger *et al.*, 2001). The dam was raised to its current capacity of 185 GL in 1960 and used for drinking water. Rising salinity in the river meant the dam was no longer suitable for drinking water and was replaced in this capacity by the Harris dam in 1989 (Mauger *et al.*, 2001).

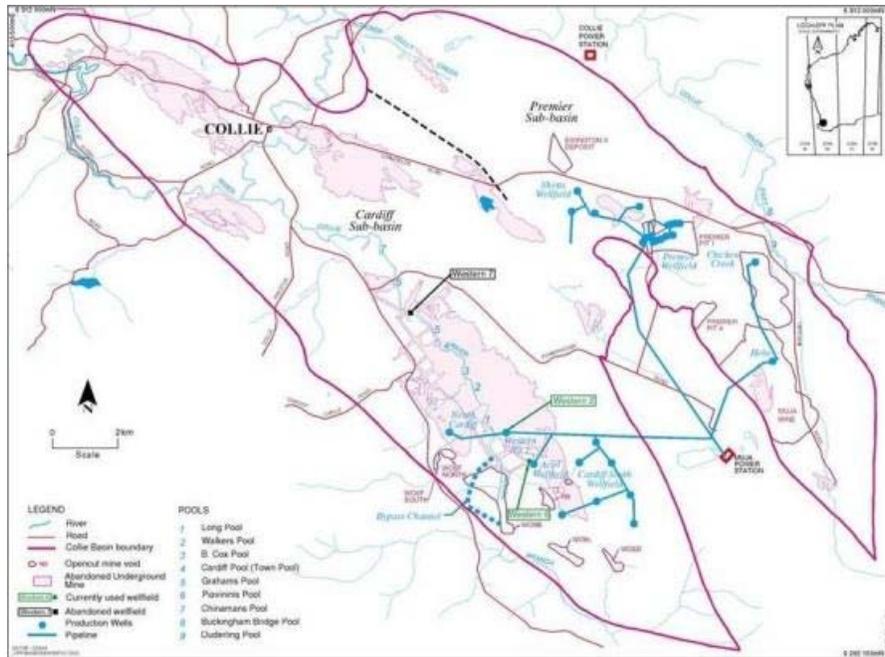
## 2.6 Mining in Collie

Underground and open cut coal mining has taken place in the Collie basin since 1898. Until the mid 1990's coal mining was predominantly in the Cardiff sub-basin. In 1997 mining in the Cardiff sub-basin ceased and since then mining has taken place in the Premier sub-basin at the Muja, Ewington and Premier mines. The history of Collie coal mining is detailed in Stedman (1988). As a result of a dispute with the Government, six open cut pits were abandoned in 1950s and 1960s, which went on to form Stockton Lake, Ewington Lake, Blue Waters, Black Diamond (A & B) and Wallsend (used for landfill) (Figure 7).



**Figure 7.** Historical mine workings in the Collie Basin (source unknown).

Currently two mining companies (Wesfarmers Premier Coal Pty Ltd and Griffin Coal Pty Ltd) have active mines in the Premier sub-basin. Wesfarmers Premier Coal Pty Ltd is currently rehabilitating or developing end uses for finished pits in the Cardiff sub-basin (Figure 8).



**Figure 8.** Current mining activities in the Collie Basin (source unknown).

## 2.7 Collie Pit Lakes

In 2009 there were 15 mine lakes in Collie, with surface area between 1–10 ha, depth between 10–70 m, age between 1–50 years and pH 2.4–6.8 (Figure 9). Two lakes (Blue Waters and Ewington 1) have now been dewatered and redeveloped by 2010. Water quality of pit lakes of Collie is degraded by AMD, mainly in terms of low pH and elevated concentrations of selected metals.

Collie black coal has low sulphur concentrations (0.3–1%) (Le Blanc Smith, 1993) and only produces low amounts of acidity through pyrite oxidation, ferrollysis and secondary mineralization. This low acidity is still sufficient to generate low pH in pit lakes due to low buffering capacity of surrounding geologies. These pit lakes also have very low nutrient concentrations of carbon, particularly in historic lakes where it may be at detection level of  $<1 \text{ mg L}^{-1}$  (Kumar *et al.*, 2010). The few ecological studies made on Collie pit lakes highlight nutrient limitation restricting algal productivity and hence lake foodwebs (Lund *et al.*, 2000; Lund *et al.*, 2006; Thomas & John, 2006; Salmon *et al.*, 2008).



**Figure 9.** Location of current Collie pit lakes (sourced from Google Earth). Note: Wellington Dam is a reservoir.

### 3 Data Collection

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#### 3.1 Collation of existing data

##### 3.1.1 Water Quality

Historical data were collected from research institutions, such as the Centre for Ecosystem Management (Edith Cowan University), Centre of Excellence for Sustainable Mine Lakes, Curtin University, and University of Western Australia. Government agencies including, Department of Water and Department of Environment and Conservation made contributions of data. The mining industry, Wesfarmers Premier Coal Limited and Griffin Coal Mining Company Pty Ltd provided extensive monitoring datasets (Table 1).

All the data of physical, chemical, nutrients and major and trace elements were input to an Excel 2007 (\*.xlsx) spreadsheet and coded to a primary key relating to order of data input. The final water quality database contained more than 29,000 separate data points from over 4,200 separate sampling events. Metadata was created to allow reference back to original data sources. Parameter units were standardized by converting to  $\mu\text{g L}^{-1}$  to  $\text{mg L}^{-1}$ ,  $\text{dS m}^{-1}$  to  $\text{mS cm}^{-1}$  and so on. Système Internationale (S.I.) units were used as default. Some assumptions/decisions were inevitably made as to the relevance of data to each other, such as surface water data referring to the data of depth 0 m, and the data from water samples only labelled as 'lake bottom' referring to the data of maximum depth for that lake. A process of QA/QC was taken to identify outliers. Removal of outliers was based on expert judgement of recent sampling data and the fit of data to the overall data trend when plotted, with regard to seasonal and other considerations.

Due to the diversity of objectives in the very disparate studies recorded in the database, data collated did not cover all pit lakes and not all physico-chemical parameters were recorded at any one time. Some data were also not able to be used in the database as their sampling location was unclear. Other data such as the extensive dewatering datasets were not considered relevant to pit lake water conditions as evidence by their much higher pH values. Some local natural resource data for nearby and highly relevant water bodies such as the Collie River and Chicken Creek were

kept in the database as useful references to baseline and pre-mining local water quality conditions.

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**Table 1.** Summary of water quality data collated in this study and its sources.

Data source	Authors	Source File Name	Years	n	Data type	Lakes covered
MiWER, ECU	McCullough et al.	collie_DOW.xlsx	2009	195	Physico-chemical	All
MiWER, ECU	McCullough et al.	Void limnology.xls	2004	168	Physico-chemical Solute	Black Diamond, Stockton, Ewington, Blue Waters, Chicken Creek 4
Griffin Coal	Irving et al	Sample locations at Bluewaters void - Depth Sampling - 16 September 2008.pdf	2008	16	Physico-chemical	Blue Waters, Ewington
MiWER, ECU	McCullough et al.	collie database.xls	2003–2004	606	Physico-chemical Solute	Black Diamond, Stockton, Ewington, Blue Waters
Centre for Ecosystem Management, ECU	Yuden et al.	Yuden's data (database)2.xls	2003–2004	5	Physico-chemical Solute	Black Diamond, Stockton, Ewington, Blue Waters
Centre for Ecosystem Management, ECU	Lund et al.	Collie Monitoring Latest.xls	1995–1999	856	Physico-chemical Solute	Black Diamond, Stockton, Ewington, Blue Waters
Centre for Ecosystem Management, ECU	Lund et al.	Collie Monitoring Data_from Mark.xls	1994-1999	1,082	Physico-chemical Solute	Black Diamond, Stockton, Ewington, Blue Waters
MiWER, ECU	Radhakrishnan et al.	Radhakrishnan 09-01.xls	2009	45	Solute	All
MiWER, ECU	Radhakrishnan et al.	AUSIMM tour.xls	2009	4	Physico-chemical	All
Curtin University	Tsvetnenko et al.	Tsvetnenko progress	2005	19	Bioassays chemical	Chicken Creek 4

Conceptual Models of Collie Basin Pit Lakes

Data source	Authors	Source File Name	Years	n	Data type	Lakes covered
		report_UCurtin_2005.pdf			analyses	
Department of Environment	Kelly et al.	DOE Kepwari water chem..doc	2004–2005	17	Solutes	Lake Kepwari
Department of Water	Kelly et al.	DOWbunbury_5BVOID QUALITY.xls	1999–2002	36	Physico-chemical Solutes	WO5B
Department of Water	Kelly et al.	DOWbunbury_DR25181-Collie R East - Mine Void-All WQ data.xls	2005–2007	73	Physico-chemical Solutes	River and other related sites
Department of Water	Kelly et al.	DR24963 Site Details & WQ.xlsx	1985–2007	311	Physico-chemical Solutes	Lake Kepwari
Griffin Coal	Irving et al.	2008 4312254 File Note - 2nd Dec 2008 - depth sampling at Little (baby)Blue- Ewington 1.doc	2008	6	Physico-chemical	Ewington
Griffin Coal	Irving et al.	ARL_Report 23816-30 Bluewaters lake Quality Data_2 October 2008.pdf	2008	25	Solutes	Bluewaters
Griffin Coal	Irving et al.	2008 3496 GCM Surface Water Quality Spreadsheet MASTER.xls	2008	1,393	Physico-chemical Solutes	Centuar, Chicken Creek 4 and 5, Ewington and Blue Waters
UWA	Salmon et al.	WO5B Jul05 data.xls	2005	11	Physico-chemical Solutes	WO5B
UWA	Salmon et al.	Salmon et al. 2008.pdf	2005–2008	2	Physico-chemical	Lake Kepwari

*Conceptual Models of Collie Basin Pit Lakes*

<b>Data source</b>	<b>Authors</b>	<b>Source File Name</b>	<b>Years</b>	<b>n</b>	<b>Data type</b>	<b>Lakes covered</b>
Wesfarmers Premier Coal Limited	WPCL	WPCL Water Monitoring 5H 5B voids.xls	2007–2009	178	Physico-chemical Solutés	WO5H, WO5B

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### 3.1.2 Aquatic Biota

Aquatic biota data from the Collie pit lakes was collated and summarised. Data was primarily sourced from the extensive Edith Cowan University datasets resulting student and staff projects by Assoc. Prof Mark Lund and Dr. C. McCullough dating back to 1997 (Table 2).

Other aquatic biota data was also sourced by a literature search and review of journal publications and theses and from database information provided by the different organisations already listed.

**Table 2.** Summary of aquatic biota data collated in this study and its sources.

Data source	Authors	Source File Name	Data Type	Notes
School of Natural Sciences, ECU	Lyons	Invertebrate1.xls	Excel sheet	3 <sup>rd</sup> year project data 1997 - Macroinvertebrates
Royal Society of Western Australia	Thomas & John	Diatoms and macroinvertebrates as biomonitors of mine-lakes in Collie, Western Australia	pdf	Journal paper 2006 – Diatoms and macroinvertebrates
ACARP	Evans et al.	Centre for Sustainable Mine Lakes	pdf	Published report
MiWER, ECU	Yuden	Yuden's data (database)2	Excel sheet	MSc thesis data 2000 - Macroinvertebrates
School of Natural Sciences, ECU	Lund et al	ACARP 8031 data	pdf	Published report 1997-2000 - Macroinvertebrates
MiWER, ECU	McCullough et al.	Collie Monitoring Latest.xls	Excel sheet	2003-2009 – Macroinvertebrates and finfish

### 3.2 Contemporary pit lake water quality data collection

#### 3.2.1 Water Quality

Ten different pit lakes were sampled for water quality in May and November 2009. These lakes included the following (Table 3).

**Table 3.** Summary of Collie pit lakes sampled in the 2009 contemporary sampling.

Historic Lakes	New Premier Lakes	New Cardiff Lakes
Black Diamond	Chicken Creek 4	WON9
Blue Waters*	Chicken Creek 5	WO5C
Stockton		WO5D
Centaur**		WO3
		WO5F
		WO5H
		WO3B (Kepwari)

\*Data from May only

\*\*Data from November only

A vertical profile of the water column was taken in the centre of each lake in April and November 2009. Temperature, pH, specific conductance (EC), oxidation-reduction potential (ORP, platinum reference electrode), turbidity (NTU), dissolved oxygen (DO, % saturation and mg L<sup>-1</sup>) and chlorophyll *a* were measured at 1 m intervals using a Hydrolab Datasonde 4a multi-parameter meter.

A water sample was collected for analysis of nutrients and metals from the lake surface as well as another from *ca.*0.30 m above the benthos using a Kemmerer bottle. Upon collection, half of the water sample was filtered through 0.5 µm glassfibre filter paper (PAL Metrigard, USA) and the other half left unfiltered. Filtered samples were halved again with one filtrate half analysed for ammonium, NO<sub>2</sub><sup>-</sup>/NO<sub>3</sub><sup>-</sup> (NO<sub>x</sub>), and filterable reactive phosphate (FRP) after APHA (1998). Part of the filtered aliquot was analysed for SO<sub>4</sub><sup>2-</sup> by ion chromatograph (Dionex ICS-1000). Another portion of the filtered sample was analysed for dissolved organic carbon (as NPOC) using a Total Carbon Analyser. Aliquots were stored in clean high-density polyethylene bottles and frozen prior to analysis (within 1 month of collection).

The remaining filtered sample was then acidified with reagent grade HCl on return to the laboratory and stored at 4°C until analysed within 2 weeks of collection for selected metals/metalloids by Inductively Coupled Plasma Atomic Emission Spectrophotometry (ICP-AES; Al, Ba, Be, Ca, Cd, Cr, Co, Cu, Fe, Mn, Na, Ni, Sb, Sn and V).

Unfiltered samples were digested using a persulfate digestion and then analysed by discrete analyser for total P and total N after APHA (1998).

### 3.2.2 Aquatic Biota

A new data collection was also made for aquatic benthic macroinvertebrates and finfish of the Collie pit lakes so as to extend these existing datasets for previously studied lakes, and so as to extend pit lake ecology knowledge to lakes never studied before e.g., most of the Cardiff sub-basin pit lakes (Table 4).

**Table 4.** Summary of aquatic biota data collated in contemporary study. ✓ = data collected, – = data not collected.

Pit lake	Fish	Macroinvertebrates
Black Diamond	✓	✓
Blue waters	–	✓
Centaur	✓	✓
Ewington	–	–
Stockton	✓	✓
Chicken Creek 4	–	✓
Chicken Creek 5	–	✓
Kepwari (WO5B)	✓	✓
WON9	–	✓
WO3	–	✓
WO5C	–	–
WO5D	–	–
WO5F	–	✓
WO5H	–	✓

#### 3.2.2.1 Macroinvertebrates

Each lake was sampled with three replicates around the littoral fringe. Aquatic macroinvertebrates were collected with a 250 µm mesh sweep net for 1 m<sup>2</sup> quadrat. Macroinvertebrate sorting began with a big-pick from the 2 mm fraction. The sample filtrate was then placed into a four-channel Bogarov tray and sorted by two passes with an Olympus SZ-STU2 stereo microscope. Macroinvertebrates from both the larger fraction CPOM sieving and from the smaller fraction sorting tray were identified and counted

under this same microscope. Initially all uncommon (<200 individuals) were sorted, identified and counted. The remaining sample was then 20% subsampled for common taxa (>200 individuals) which were sorted, identified and counted. Subsampling was by volumetric dilution in beakers after Wrona *et al.* (1982). Prior to removal, samples were well shaken in the subsampler to break up organic clumps and increase the random nature of particle settling (Lund, 1999).

#### 3.2.2.2 *Finfish*

A contemporary survey for finfish was made in November 2009. Although the same broad range of historic and new pit lakes were surveyed as per the November 2009 water quality sampling, health and safety issues due to steep banks reduced the number of lakes able to be effectively sampled to four lakes; three historic, one new Cardiff lake. These were lakes Black Diamond, Centaur, Stockton and Kepwari. Two beach transects at each pit lake were taken with a 10 m Japanese seine (5 mm mesh). Fish recovered to the beach were immediately placed into a bucket of clean water, anaesthetised with Aqui-S, then identified and then returned live back to the lake.

### 3.3 Analysis

#### 3.3.1 Water quality data

Data for each lake were graphed by their surface physico-chemistry where the datasets were inevitably the strongest. This gave the most robust interpretation of trends of water quality over time. Water quality data were then tabulated, where all site data (regardless of depth) were combined. For example, water quality parameter means and 95% confidence intervals were therefore based upon the entire water column mean dataset for that parameter

In some instances where the data trend was clearly not linear, robust smoothing techniques were utilised to tease out if there was a signal from the often very highly variable time-series water chemistry data (Cleveland, 1979; ANZECC/ARMCANZ, 2000e). For this study, smoothing of highly variable data was accomplished within the software SigmaPlot using a single-factor negative exponential polynomial, with a sampling proportion of 0.10 (Cook & Peters, 1981; SPSS Inc., 2000). Otherwise, least-wise linear regression was used to establish a trend line of best fit through the data cloud.

Outlier points that biased the resulting dataset and plot for just some seasons e.g., regression ‘tails’ being dominated by summer sampling events were removed to establish a trend that better represented mean seasonal sampling events for that parameter for that year.

### 3.3.2 Macroinvertebrates

Analyses of multiple parameter datasets (multivariate data) (e.g., pH dissolved oxygen and temperature all considered together) were made using the PRIMER v6 software package (Clarke, 1993). These multivariate analyses followed a procedure of data transformation, graphical exploration and then statistical analysis. The key to the multivariate techniques is that the software represents on an ‘ordination’ graph the degree of similarity between lakes and times based on datasets such as water quality or macroinvertebrate assemblages; the closer together the symbols are on the ordination graph indicates the more relatively similar the datasets for water chemistry or macroinvertebrate assemblages were. Therefore on the graphs similar sites group closely together are very similar; those far apart are very different to each other.

Principal Components Analysis (PCA) was used to produce ordination graphs of water quality data to illustrate how lakes differed from each other and over different sampling times. Ordination graphs of multivariate macroinvertebrate assemblage data were made using the Bray-Curtis dissimilarity matrix (Faith *et al.*, 1987) and non-metric Multi Dimensional Scaling (nMDS). The statistical significance of differences between lakes or sampling times shown by the ordination graphs were tested using the ANalysis-Of-SIMilarity (ANOSIM) method (Clarke & Gorley, 2001). Water quality parameters and macroinvertebrate species most contributing to the differences seen between lakes and sampling times in the ordination graphs were determined by the SIMilarity-PERcentages (SIMPER) routine (Clarke, 1999). A transformation matching that of the ordination and consequent ANOSIM analysis was made for SIMPER analysis of biological variables with Bray-Curtis dissimilarity. The BIO-ENV procedure was then used to determine the combination of water quality parameters that seems to best explain the lake’s macroinvertebrate assemblages (Clarke & Ainsworth, 1993). These are the water quality variables that are most likely to be important in limiting macroinvertebrate life in the lakes e.g., through toxic effects. Prior to BIO-ENV analysis, water quality variables were normalised to the maximum value encountered (Olsgard *et al.*, 1997; Clarke & Warwick, 2001). Water quality data were always  $\log_{10}$  transformed.

Transformations of abundance data for multivariate analysis were used to reduce the effect of difference in macroinvertebrate abundances when the actual species composition was not very different (Faith *et al.*, 1987; Austen & Somerfield, 1997; Stark, 1998). The actual data transformation chosen for macroinvertebrate assemblage data was those which gave the greatest returns of most statistically powerful ANOSIM results (Olsgard *et al.*, 1997).

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## **4 Collie Pit Lake Water Quality**

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### **4.1 Introduction**

In 2009 there were 15 mine lakes in Collie, with surface areas between 1–100 ha, depth between 2–70 m, age between 1–50 years and pH 2.4–6.8 (Chapter 2). Pit lakes in Collie can be divided into three broad groupings based on history, rehabilitation and location: historic lakes, which were all abandoned with no rehabilitation between 1953 and 1960 (Stedman, 1988), the new generally rehabilitated lakes of the Cardiff sub-basin, and the mainly un-rehabilitated lakes of the Premier sub-basin.

Water quality data is highly variable in terms of intensity and seasonal and interannual spread (Table 5). Generally within a lake, only a single central sample site has been used. Where multiple sites have been sampled, there are no discernable differences between them suggesting the lakes are well mixed spatially. Many sampling programs have simply collected metals and nutrient data at the surface and close to the bottom. There is at least an oxygen/temperature profile for all lakes except WO5C and WO5D.

**Table 5.** Summary of the collated water quality data for pit lakes in Collie, showing number of individual sampling occasions and total number of records (includes multiple sites and depths).

Lake	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total Records	
Black Diamond A			9	5			9	4					7	8	1					3	245
Black Diamond B				1																	24
Blue Waters	2			1	2		9	30	10				5	8	2				4	3	1203
Centaur											1					3	6	4	2		41
Chicken Creek 4														3	1	45	29	7	2		222
Chicken Creek 5							1									4	8	6	2		79
Ewington	2			1	2		9	13	10				7	6	2				3		347
Lake Kepwari									4	11	13	12	12	16	16	12	12	14	7		198
Stockton Lake	2			3	2		14	22	16	12	9	7	4	9	12	11	11	12	7		675
WO3																				2	24
WO5C																				3	5
WO5D																				3	5
WO5F																				2	13
WO5H												10	12	12	13	12	11	13	6		151
WON9																				2	31

Collie coal has a relatively low sulfur content of <1%, it is a sub-bituminous coal with low caking and low ash 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 low buffering capacity of surrounding geologies. These pit lakes also have low nutrient concentrations particularly of carbon (mean±s.e; DOC 4.2±1.4 mgL<sup>-1</sup>) and phosphorus (FRP 5.3±0.5 µgL<sup>-1</sup>; Salmon *et al.*, 2008). The few ecological studies made on Collie pit lakes highlight nutrient limitation restricting algal productivity and hence lake foodwebs (Lund *et al.*, 2000; Lund *et al.*, 2006; Thomas & John, 2006; Salmon *et al.*, 2008).

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## 4.2 Historic Lakes

### 4.2.1 Background

Over the last decade the majority of research effort on Collie pit lakes has been devoted to understanding the physical and chemical processes occurring within the historic pit lakes (Phillips *et al.*, 1999). The pits of the historic lakes were all mined by the Amalgamated Collieries Company, which closed in 1960 following changes to the Government coal procuring procedures which saw the Company lose all Government contracts (Stedman, 1988). All of these lakes had no remediation prior to natural filling with rainfall, surface flows and groundwater. Although erosion and sedimentation processes have reduced the angle of the lake sides, their gradient is typically steep leaving only a narrow littoral zone around most of the lake sides. The supply of allochthonous (external) nutrients into the lakes from the limited catchments is small (Lund *et al.*, 2006).

The historic pit lakes in the Collie Basin are Lake Ewington, Blue Waters, Lake Stockton, Black Diamond A and B and Lake Centaur (Table 6). All are located towards the edge of the Basin apart from Lake Stockton which is located in the centre.

**Table 6.** Physical dimensions of the historical Collie pit lakes

Lake	Area (Ha)	Perimeter (m)	Maximum Depth (m)
Black Diamond A	4.6	1500	8
Black Diamond B	2.5	800	Unknown
Blue Waters	13.7 (includes a 2.1 Ha island)	2260	24
Ewington Lake	1.3	540	11
Stockton Lake	15.4	1740	47
Lake Centaur	4.5	1590	~7

### 4.2.2 Black Diamond A and B

#### 4.2.2.1 History and development

Black Diamond is located near the original coal discovery site at Allanson (Figure 10). Black Diamond commenced operation in 1948 and closed in 1953 after producing 344,530 tonnes of coal (Stedman, 1988). As mining progressed the void was backfilled which would eventually produce two pit lakes (Black Diamond A and B). It was abandoned without any rehabilitation and is now on Crown land. Neither the Shire of

Collie nor state government agencies appear to accept responsibility for management of the lake (*Collie Mail*, 19<sup>th</sup> Nov 2009). Black Diamond A and surrounds are actively used for public recreation including swimming, marroning and camping. The eastern end of this lake lie partially on private land and water from the lake is used by these householders (Figure 11). In 2009, a bush fire resulted in a small underground coal fire on the northern side of the lake. This lake has seen several serious injuries and a death (of a tourist in 2008) and signage and fencing has been installed along some of the cliffs to reduce the risk. Black Diamond B is on private land and appears to be used by the household for recreation and for watering cattle. Black Diamond A overflows into the Collie River at the end of winter in most years.



**Figure 10.** Black Diamond A (09/2009) looking north.

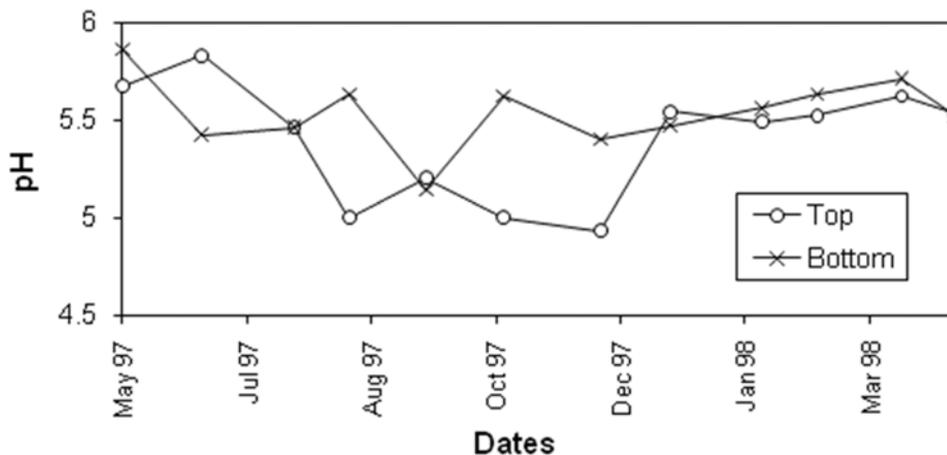


**Figure 11.** Aerial photograph of Black Diamond (A – right; B – left) Lakes (image from Google Earth, dated 2007) (top of picture is north).

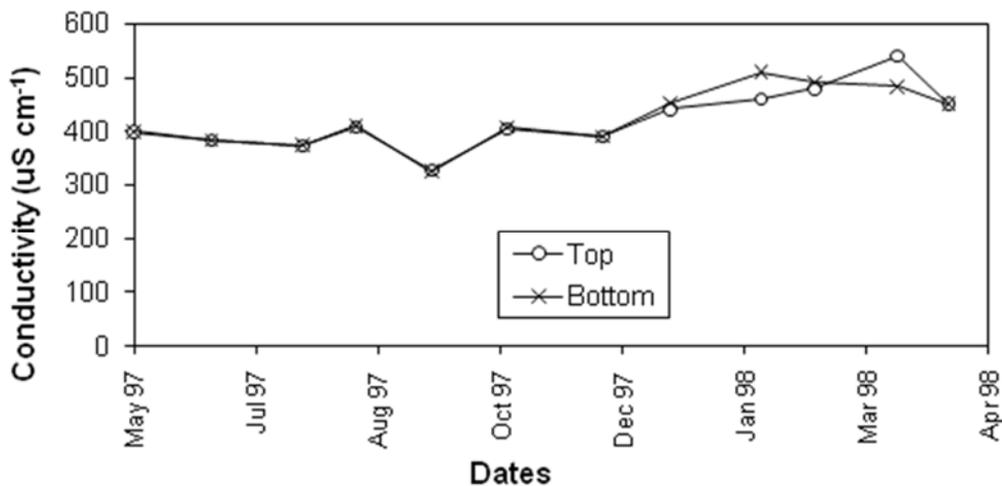
#### 4.2.2.2 Trends in water quality

Black Diamond Lake is the least acidic of the historic pit lakes, the pH of the bottom of the Lake during summer is higher than that of the surface (Figure 12a). The presence of charophyte algae on the bottom, probably accounts for this difference, with pH increased as a result of photosynthesis by the plants. Conductivity varies little throughout the year but is slightly higher during the summer months as a result of evapo-concentration effects (Figure 12b).

a) pH



b) Electrical conductivity



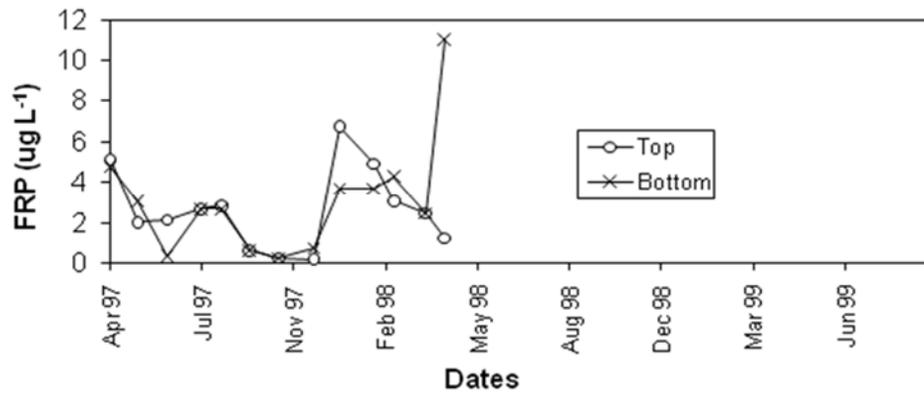
**Figure 12.** Seasonal changes in a) pH and b) conductivity in Lake Black Diamond (1997-1998).

Nitrate levels in Black Diamond are very high compared to the other historic pit lakes (Figure 13). There is a decrease in ammonia and FRP as Black Diamond Lake approaches summer, while NO<sub>x</sub> levels increases slightly. The most probable explanation for this decrease in ammonia is the growth of charophyte algae towards summer. The charophyte algae utilise ammonia and at the same time bacterially-mediated nitrification probably occurs in the water column under warmer water temperatures.

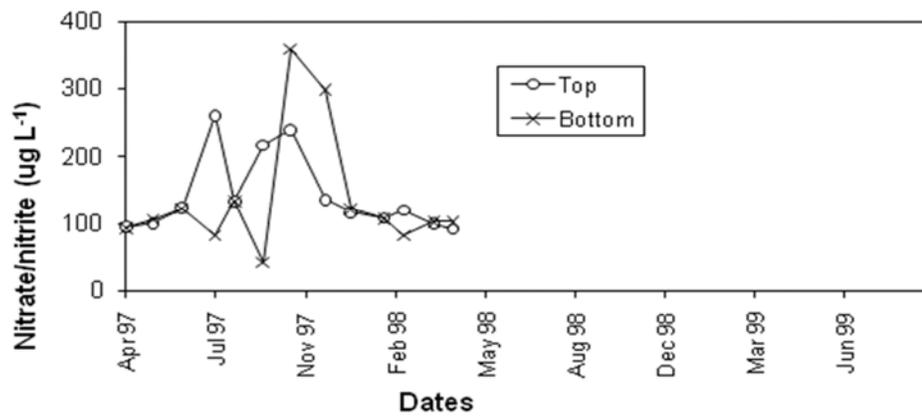
The shallow nature of the Lake appears to prevent prevents any seasonal stratification or associated bottom anoxia from occurring (Figure 14). Primary productivity of benthic (aside from charophytes) or planktonic algae is extremely low in Black Diamond (Figure 15)

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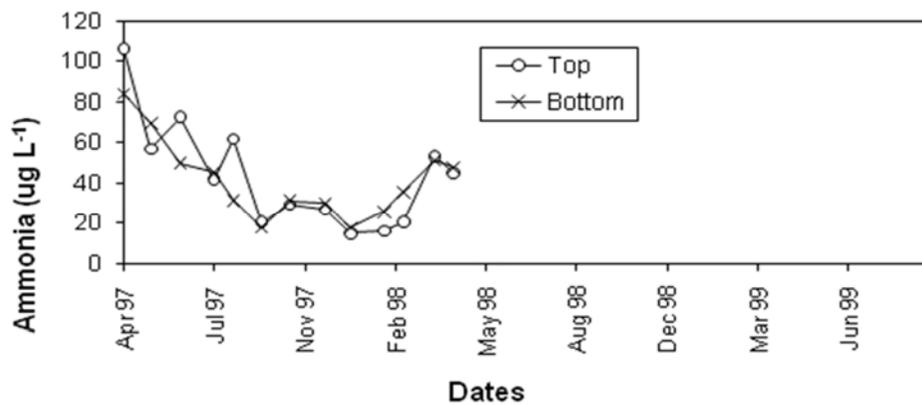
a) FRP



b) NOx

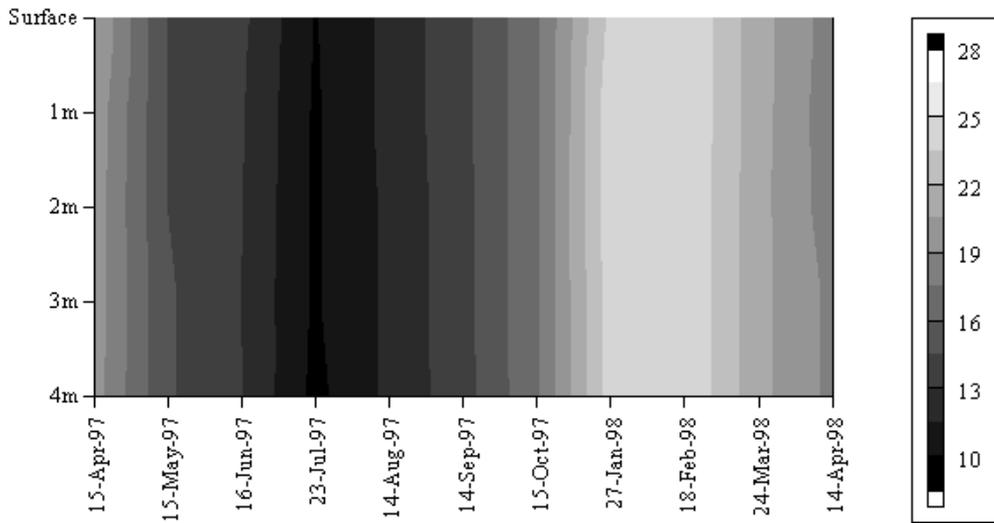


c) Ammonia

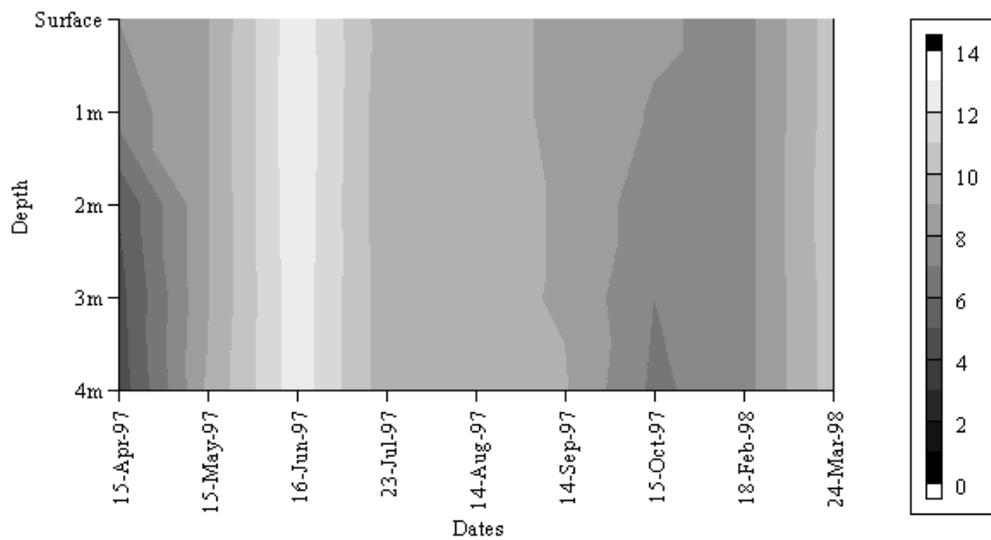


**Figure 13.** Seasonal changes in a) FRP, b) NOx and c) ammonia in Lake Black Diamond (1997-1999).

a) Temperature (°C)  
Black Diamond

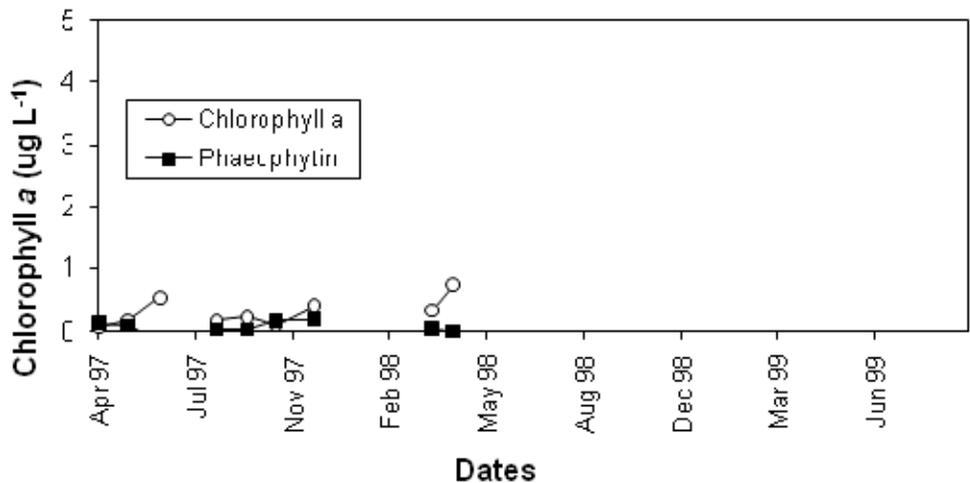


b) Dissolved oxygen (mg L<sup>-1</sup>)  
Black Diamond

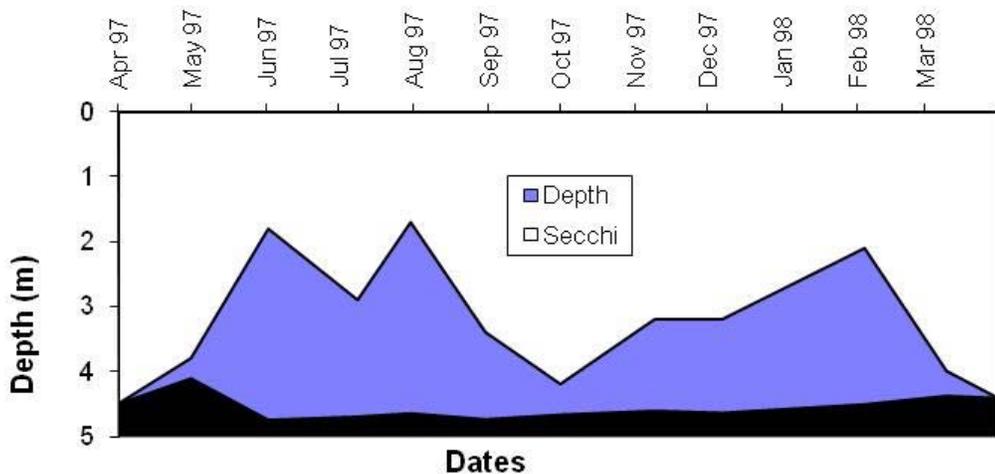


**Figure 14.** Changes in a) temperature and b) in Black Diamond A (taken from Phillips et al, 2000) over 1997-98 and depth.

a) Chlorophyll *a*

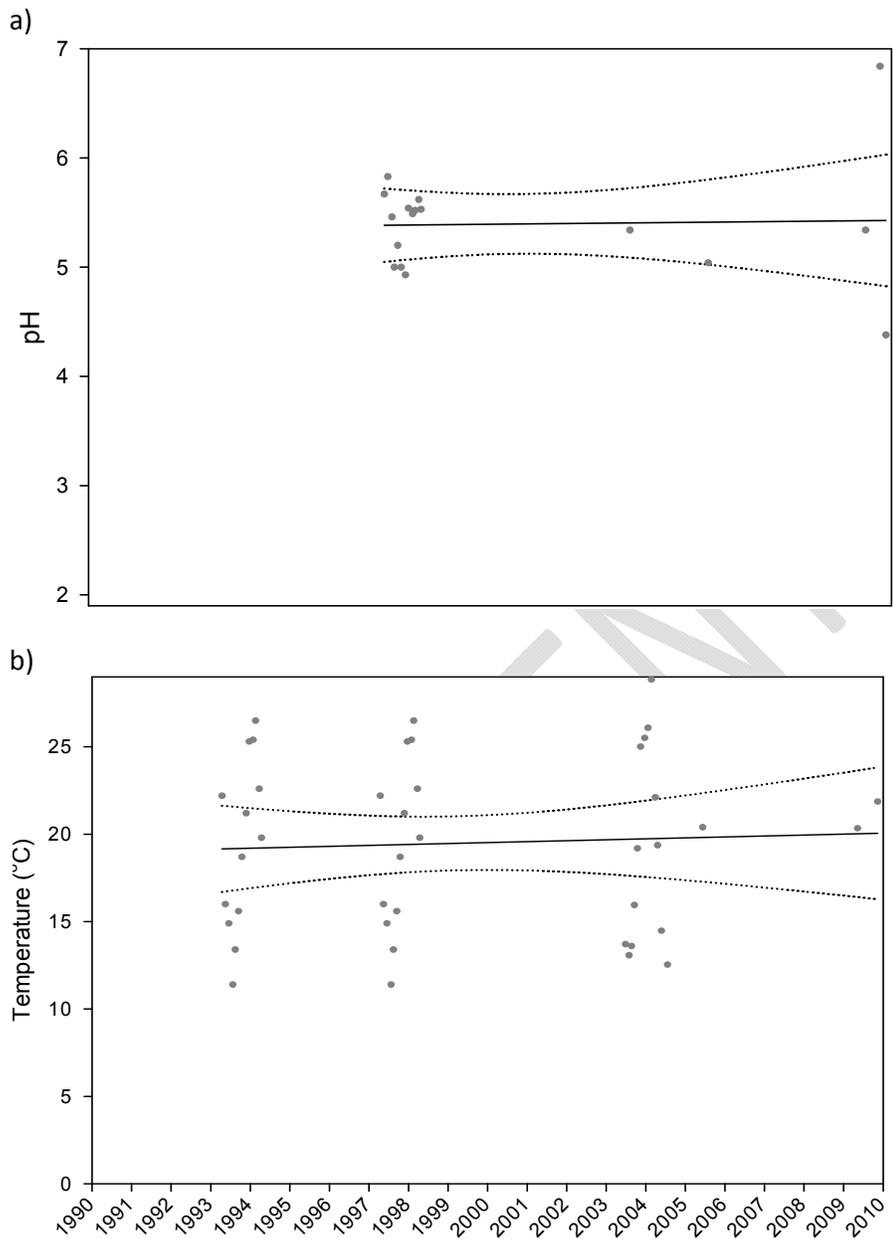


b) Secchi depth

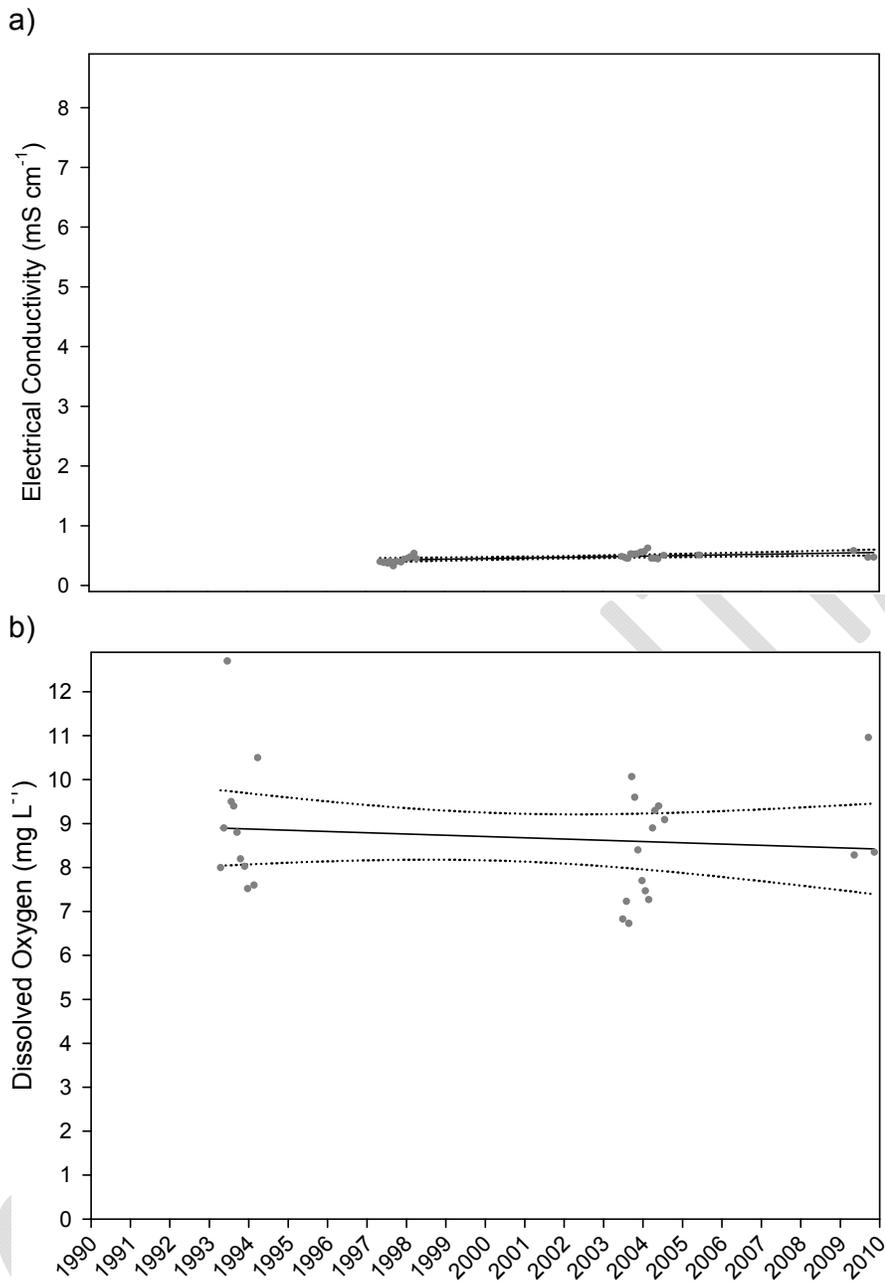


**Figure 15.** Changes in a) chlorophyll *a* (top and bottom of the water column) and b) Secchi depth (black = bottom, Blue = water below Secchi depth) in Black Diamond between 1997-98

Black Diamond shows no significant ( $P > 0.05$ ) change in surface water pH over time (Figure 16a) ( $n = 17$ ,  $r^2 = 0.001$ ). However, the apparent slight upward trend is almost certainly influenced by a single data point of 6.8 collected in September 2009 at the end of very heavy winter rains. The lake was overflowing from the western side into an arm of the nearby Collie River at this time and this dilution is likely to have contributed to the abnormally high pH of this record. Surface water temperature of Black Diamond Lake show no significant ( $P > 0.05$ ) trends over the last 17 years of data collection (Figure 16b)



**Figure 16.** Long term changes in a) surface water pH and b) temperature in Lake Black Diamond. Grey dots represent individual sample points, dashed black line represent smoothed data plot, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.



**Figure 17.** Long term changes in surface water electrical conductivity a) and dissolved oxygen b) in Lake Blue Waters. Grey dots represent individual sample points, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.

( $n = 17$ ,  $r^2 = 0.003$ ). As with the other physico-chemical variables, electrical conductivity in Black diamond lake also showed a weak but significant ( $P < 0.05$ ) increase over time (Figure 17a) ( $n = 29$ ,  $r^2 = 0.34$ ). If surface water temperatures were rising this could

explain increased conductivity and increased pH simply by evapo-concentration. Black Diamond dissolved oxygen (measured as mg L<sup>-1</sup>) showed no significant ( $P > 0.05$ ) change over time (Figure 17b) ( $n = 27$ ,  $r^2 = 0.02$ ).

Although there are some significant data gaps with Black Diamond mean annual water quality, the data do suggest that nitrogenous nutrients, SRP and TSS concentrations are increasing (Table 3). TSS may be increasing in the form of algae, although there are few chlorophyll *a* data to confirm this.

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**Table 7.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Black Diamond Lake. — = no data available for that year.

Parameter	1993	1994	1997	1998	2003	2004	2005	2009
Temperature (°C)	16.4 $\pm$ 1.3 (9)	23.6 $\pm$ 1.5 (4)	17.6 $\pm$ 1.5 (9)	23.6 $\pm$ 1.5 (4)	18.0 $\pm$ 2.0 (7)	20.8 $\pm$ 3.2 (5)	20.4 (1)	21.1 (2)
pH	—	—	5.3 $\pm$ 0.1 (8)	5.5 $\pm$ 0.0 (4)	5.3 (1)	—	5.0 (1)	5.5 $\pm$ 0.7 (3)
EC (mS cm <sup>-1</sup> )	—	—	0.391 $\pm$ 0.012 (8)	0.483 $\pm$ 0.020 (4)	0.507 $\pm$ 0.015 (7)	0.521 $\pm$ 0.035 (5)	0.510 (1)	0.509 $\pm$ 0.037 (3)
Salinity (ppt)	—	—	—	—	0.2 $\pm$ 0.0 (7)	0.3 $\pm$ 0.0 (5)	—	—
TDS (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Dissolved oxygen (%)	—	—	—	—	85.9 $\pm$ 7.0 (7)	93.8 $\pm$ 2.3 (5)	—	93.9 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	8.8 $\pm$ 0.6 (9)	9.1 (2)	—	—	8.1 $\pm$ 0.5 (7)	8.4 $\pm$ 0.4 (5)	—	9.2 $\pm$ 0.9 (3)
ORP (mV)	—	—	—	—	94 $\pm$ 14 (7)	211 $\pm$ 63 (5)	78 (1)	207 $\pm$ 19 (3)
Turbidity (NTU)	—	—	—	—	0.0 $\pm$ 0.0 (7)	4.2 $\pm$ 2.4 (5)	—	0.7 (2)
TSS (mg L <sup>-1</sup> )	—	—	—	—	54.8 $\pm$ 8.5 (7)	52.5 (2)	—	—
Chlorophyll a ( $\mu$ g L <sup>-1</sup> )	—	—	0.2 $\pm$ 0.1 (7)	0.5 (2)	0.4 $\pm$ 0.1 (7)	1.1 $\pm$ 0.3 (3)	—	0.0 (2)
Chlorophyll b ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Chlorophyll c ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Phaeophytin ( $\mu$ g L <sup>-1</sup> )	—	—	0.1 $\pm$ 0.0 (6)	0.0 (2)	9.2 (1)	—	—	—
KdPAR	—	—	—	—	—	0.23 (2)	—	—
Alkalinity	—	—	—	—	1 (1)	—	—	—
Acidity	—	—	—	—	5.5 $\pm$ 0 (7)	3.8 (2)	—	—
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	—	47 $\pm$ 1 (7)	—	48 $\pm$ 2 (7)	48 (2)	—	72 (2)
Cl (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	116 (2)
TP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	30 $\pm$ 18 (6 1)	15 $\pm$ 8 (4)	—	205 (2)
FRP ( $\mu$ g L <sup>-1</sup> )	—	5 $\pm$ 1 (8)	0 (2)	—	4 $\pm$ 1 (7)	8 $\pm$ 3 (4)	—	3 (2)
TN ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	2344 $\pm$ 494 (7)	1148 (2)	—	269 (2)
NO <sub>x</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	149 $\pm$ 26 (7)	29 (2)	—	159 (2)
NH <sub>4</sub> ( $\mu$ g L <sup>-1</sup> )	—	31 $\pm$ 1 (8)	52 $\pm$ 10 (8)	—	26 $\pm$ 7 (6)	54 $\pm$ 9 (4)	—	60 (2)

Parameter	1993	1994	1997	1998	2003	2004	2005	2009
NO <sub>3</sub> (µg L <sup>-1</sup> )	—	106 ± 9 (3)	188 (2)	—	—	—	—	—
DOC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	1 (2)
DIC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	1 (1)
As (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<50 (0 2)
Al (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	0.1 (2)
Ag (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
B (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<50 (0 2)
Ba (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Be (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Ca (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	5.2 (2)
Cd (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<10 (0 2)
Co (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<10 (0 2)
Cr (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<10 (0 2)
Cs (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Cu (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<50 (0 1)
Fe (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	0.1 (2)
Hg (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	241.2 (1 1)
K (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	1.4 (1 1)
Li (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Mg (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	10 (2)
Mn (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	134 (2)
Mo (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Na (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	24 (2)
Ni (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	37.5 (2)
P (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
Pb (µg L <sup>-1</sup> )	72.3 (2 3)	8.4 ± 2.9 (6)	5.0 ± 0.0 (4)	3.7 ± 0.7 (3)	5.0 (1)	2.5 (1)	—	<100 (0 1)

Parameter	1993	1994	1997	1998	2003	2004	2005	2009
S (mg L <sup>-1</sup> )	—	100 (1)	—	—	—	—	—	45 (1)
Sb (µg L <sup>-1</sup> )	0.01 (1 1)	0.01 (1 1)	—	—	—	—	—	—
Se (µg L <sup>-1</sup> )	<5 (0 2)	<1 (0 2)	—	—	—	—	—	<200 (0 1)
Si (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—
SiO <sub>2</sub> (mg L <sup>-1</sup> )	9 (1)	7 (1)	—	—	—	—	—	—
Sn (µg L <sup>-1</sup> )	<0.1 (0 2)	<0.1 (0 2)	—	—	—	—	—	—
Sr (µg L <sup>-1</sup> )	365.6 (2)	410.8 (2)	—	120.3 (1)	—	—	—	—
Ti (µg L <sup>-1</sup> )	<10 (0 2)	<5 (0 2)	—	0.2 (1)	—	—	—	—
U (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	<50 (0 1)
V (µg L <sup>-1</sup> )	<10 (0 3)	<1 (0 2)	—	0.0 (1)	—	—	—	—
Zn (µg L <sup>-1</sup> )	236.7 ± 128.7 (3 2)	289.2 ± 109.0 (6)	102.5 ± 42.1 (4)	87.5 ± 34.7 (3)	5.0 (1)	20.0 (1)	—	<50 (0 1)

### 4.2.3 Blue Waters

#### 4.2.3.1 History and development

Blue Waters (Ewington No. 2) lake was formed after mining operations (operated by Amalgamated Collieries) ceased in 1959 (Figure 18). The name ‘Blue Waters’ comes from the name of the farm and was used colloquially to avoid confusion with Ewington lake (Ewington No. 2). The mine commenced in 1952 and produced 683,121 tonnes of coal. Griffin Coal Mining Company own the land and for many years it has been leased for cattle farming. The lake is surrounded by steep eroding cliffs and collects runoff from two substantial overburden dumps nearby (Figure 19; Lund *et al.*, 2000b). The waters of the lake have been used to supply drinking water to the farm as well as water to the New Collie PowerStation. The lake is currently being drained in preparation for re-mining in 2010 by Griffin Coal Mining Company.



**Figure 18.** Blue Waters (09/2005) looking north.

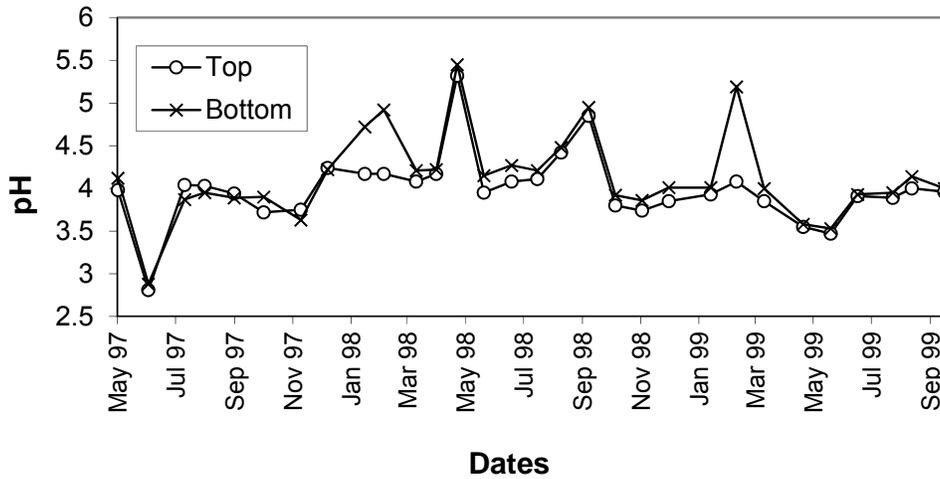


**Figure 19.** Aerial photograph of Blue Waters taken from Google Earth (imagery dated 2007/2008) (top of picture is north).

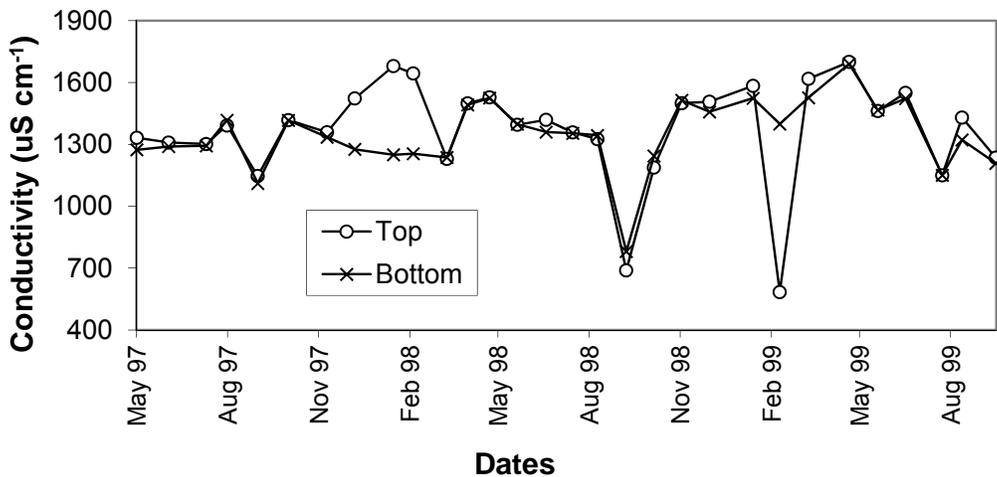
#### 4.2.3.2 Trends in water quality

pH varied slightly throughout the year, but was higher in the bottom waters during stratification (Figure 20). This suggests that some SRB activity may be occurring. The erratic changes in pH over the seasons may be influenced by the extraction of large quantities of water for testing purposes for the new Collie PowerStation. The conductivity may also be influenced by water extraction, although during stratification, evapo-concentration of the epilimnion is probably responsible for the differences between top and bottom (Figure 20).

a) pH



b) Electrical conductivity



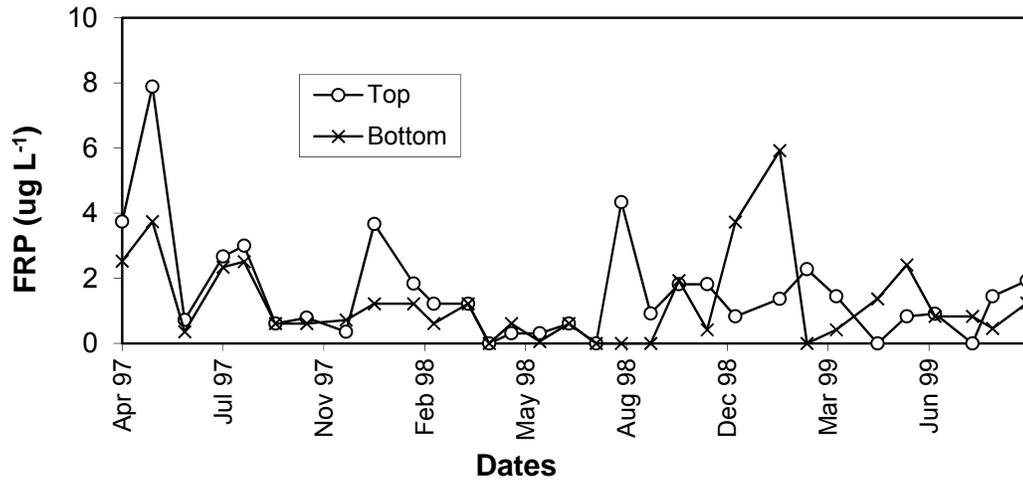
**Figure 20.** Seasonal changes in pH in Lake Black Diamond.

Nutrient concentrations were low throughout the year, but during periods of bottom anoxia, levels of ammonia increased in the bottom waters (Figure 21). This increase cannot be explained by denitrification of NO<sub>x</sub> to ammonia as nitrate levels changed little but is probably due to flux from the sediments, resulting in low ammonia levels in the pore-water. Furthermore nitrification (conversion from ammonia to nitrate) is inhibited at low pH. Under anoxic conditions there also appears to be a small flux of

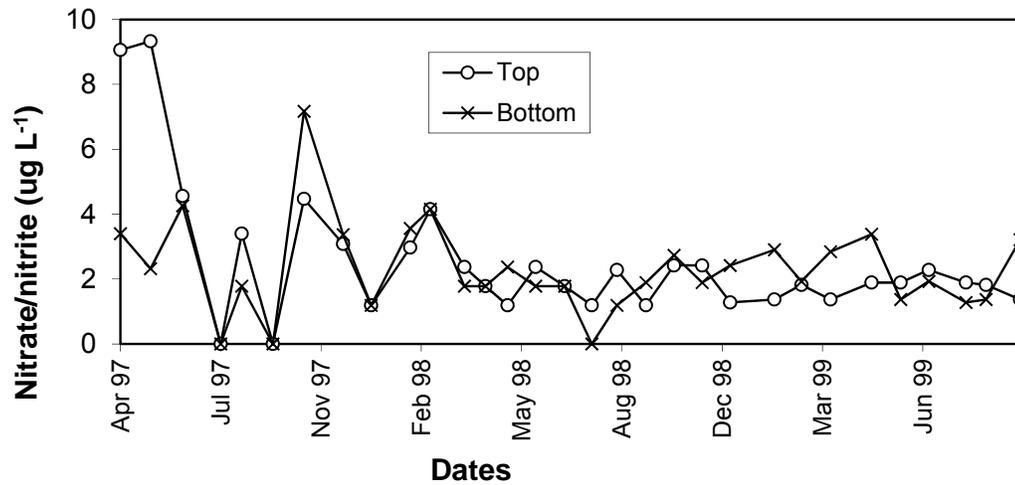
FRP from the sediment, although the low concentrations involved make it hard to ascertain for certain.

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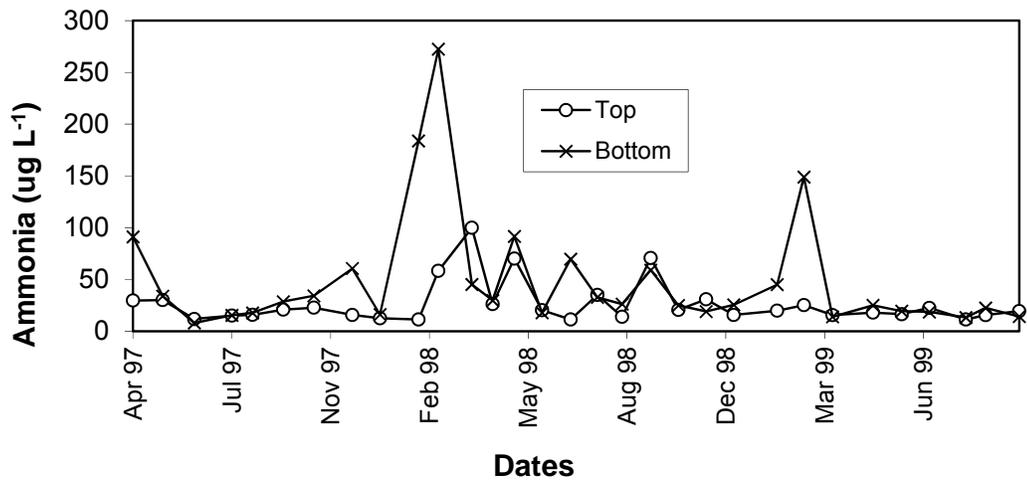
a) FRP



b) NOx



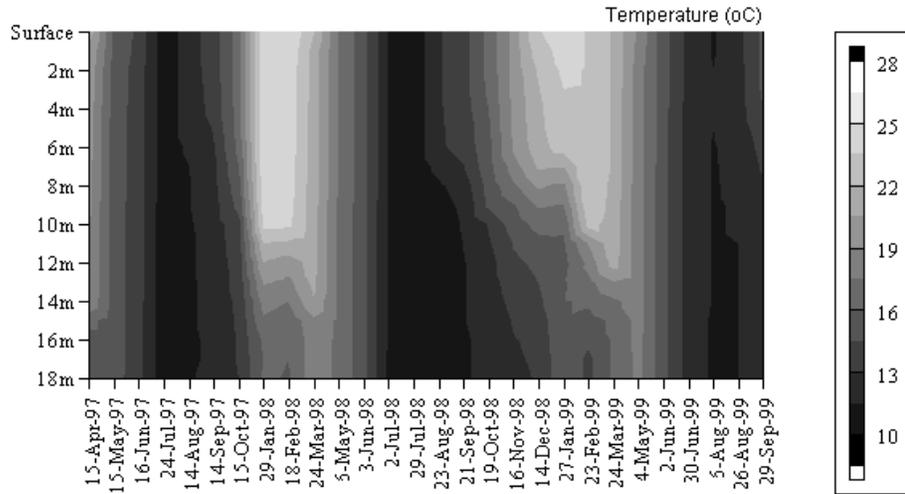
c) Ammonia



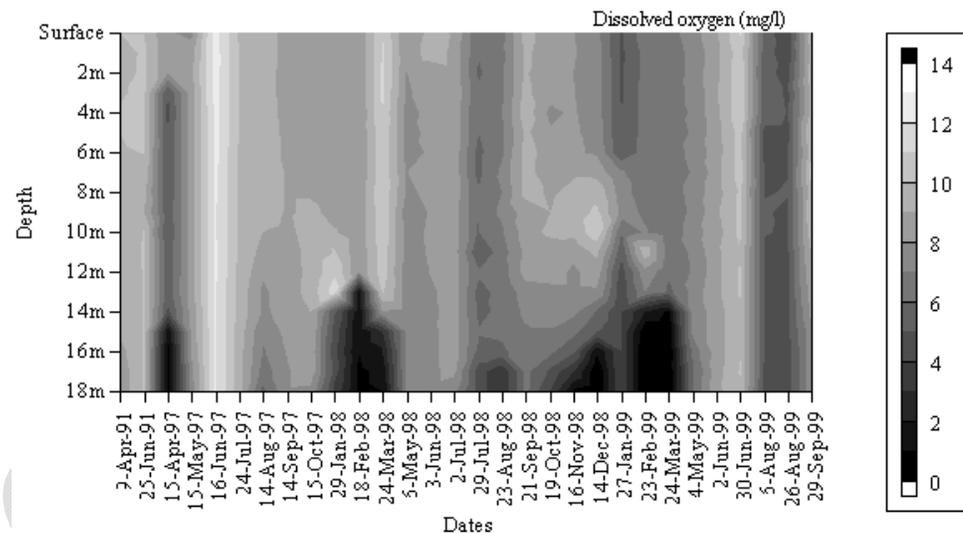
**Figure 21.** Seasonal changes in a) FRP, b) NO<sub>x</sub> and c) ammonia in Blue Waters lake between 1997 and 1999.

Blue Waters was typically stratified between August and March 1997 and 1999 then mixed throughout the rest of the year (Figure 22a). The epilimnion extends from 3–5 m and metalimnion from 3–5 m to 11–12 m. The hypolimnion was anoxic between January and March each year 1997 to 1999 (Figure 22b).

a) Temperature (°C)  
Blue Waters



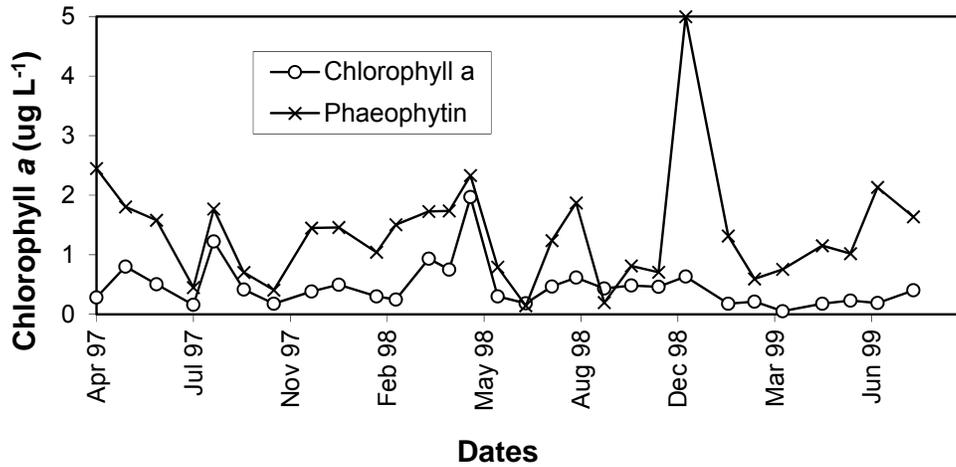
b) Dissolved oxygen (mg L<sup>-1</sup>)  
Blue Waters



**Figure 22.** Changes in a) temperature and b) in Blue Waters (taken from Phillips et al, 2000) over time and depth.

Algal productivity was extremely low, although there appears to be a slight increase after the lake mixes, (Figure 23a) increasing FRP levels in the surface waters. Masses of benthic algae have been seen by the authors on occasion in the lake. Secchi depths are greatest following mixing of the lake; however, the mechanism involved remains unclear (Figure 23b).

a) Chlorophyll *a*



b) Secchi depth

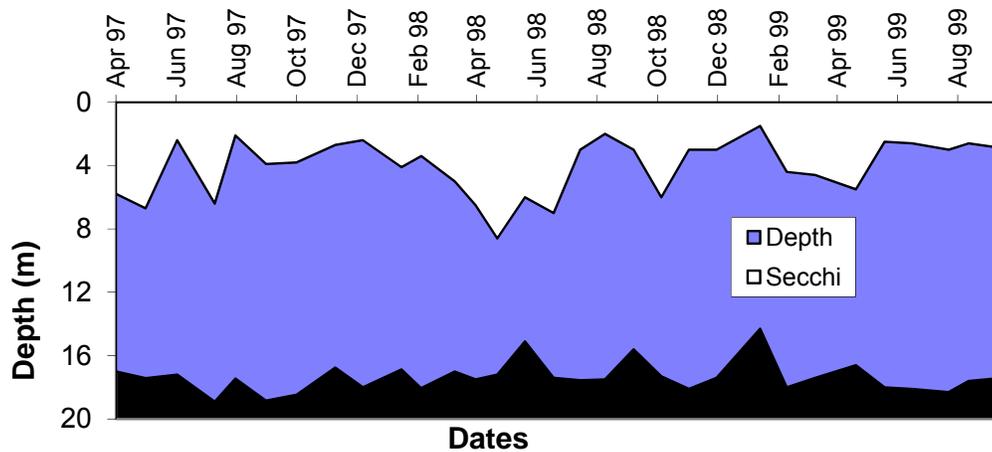


Figure 23. Changes in a) chlorophyll *a* (top and bottom of the water column) and b) Secchi depth (black = bottom, blue = water below Secchi depth).

There was no significant ( $P < 0.05$ ) trend of decreasing pH over time for Blue Waters, how (Figure 24a) ( $n = 83$ ,  $r^2 = 0.015$ ). There were a few high outlier points of up to pH 5.2; however these are likely to be from surface water accumulating rainfall during surveying in rain events. Equally, a single low outlier may be due to rainfall events with a location near over burden run-off. Nevertheless, all these data were strongly influenced by the intensive 1997–1999 surveying and large dataset from this time.

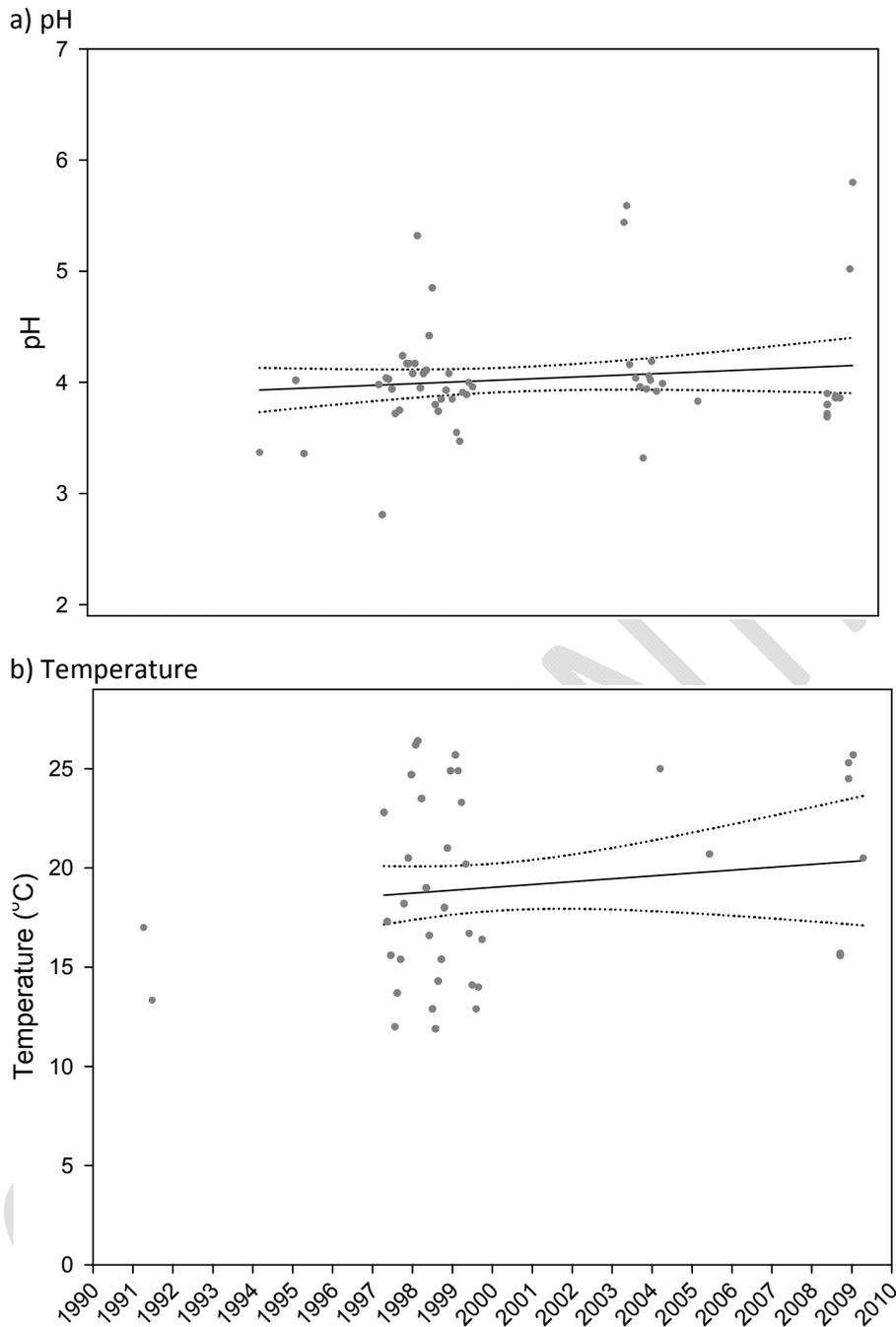
There was also no significant trend ( $P > 0.05$ ) of increasing temperature over time for Blue Waters (Figure 24b) ( $n = 78$ ,  $r^2 = 0.02$ ). This variation is likely to be due to the

great variety of intra- and inter-seasonal temperature fluctuation in the climate of the Collie region.

There was a slight significant ( $P < 0.05$ ) increase in electrical conductivity of Blue Waters' surface water (Figure 25a) ( $n = 50$ ,  $r^2 = 0.1$ ). Although the confidence intervals were relatively large, this trend is potentially real and could be accounted for by evapo-concentration of lake water in addition to continuing acidic surface water inflow from the over burden in the catchment of Blue Waters (Lund *et al.*, 2000b). These trends are however of minimal biological consequence.

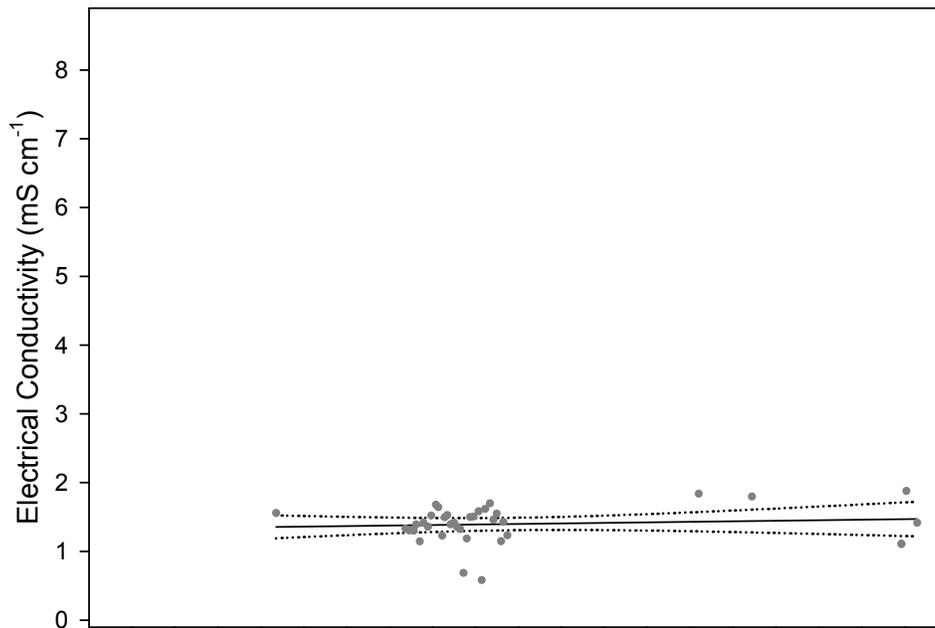
A plot of dissolved oxygen concentration ( $\text{mg L}^{-1}$ ) over time showed a slight increase over time (Figure 25b). However, however this trend was not significant ( $P > 0.05$ ;  $n = 64$ ,  $r^2 = 0.01$ ).

There are few and inconsistent data to suggest that there are significant water quality changes for either physico-chemistry or solutes in Blue waters (Table 8).

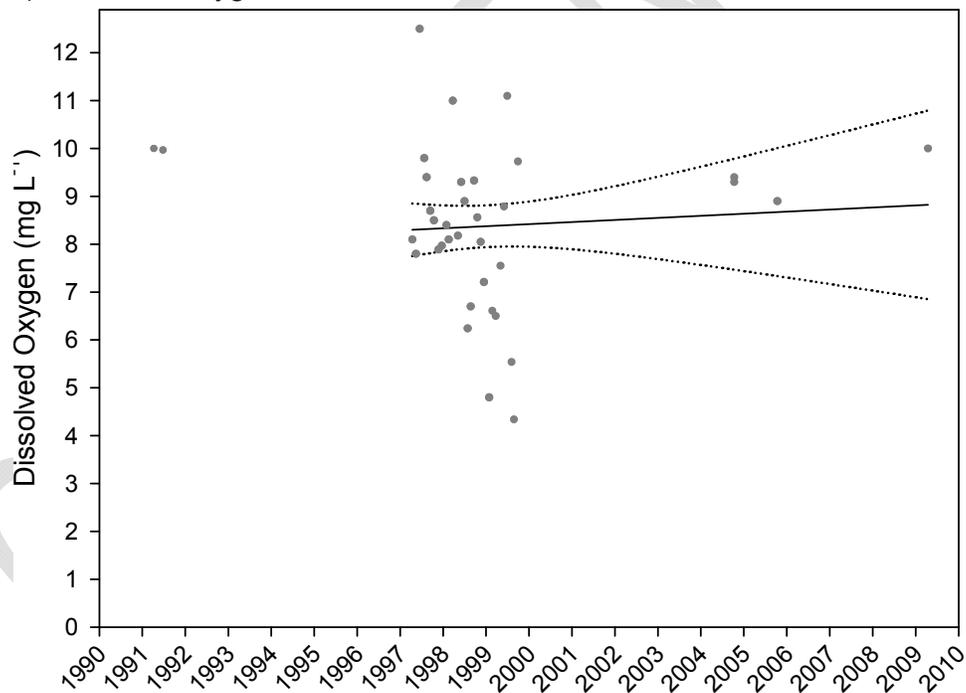


**Figure 24.** Long term changes in a) surface water pH and b) temperature in Blue Waters. Grey dots represent individual sample points, dashed black line represent smoothed data plot, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.

a) Electrical Conductivity



b) Dissolved oxygen



**Figure 25.** Long term changes in surface water electrical conductivity a) and dissolved oxygen b) in Blue Waters. Grey dots represent individual sample points, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.

**Table 8.** Mean surface (0 m) water ± standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Blue Waters. — = no data available for that year.

Parameter	1991	1994	1995	1997	1998	1999	2003	2004	2005	2008	2009
Temperature (°C)	15.2 ± 1.1 (4)	—	—	17.8 ± 1.0 (18)	19.2 ± 1.0 (24)	19.4 ± 1.6 (10)	19.0 ± 2.7 (5)	22.2 ± 2.5 (6)	20.7 (1)	18.7 ± 2.0 (6)	22.5 ± 1.6 (3)
pH	—	3.4 (1)	3.7 ± 0.2 (4)	3.8 ± 0.1 (16)	4.2 ± 0.1 (26)	3.9 ± 0.1 (10)	4.6 ± 0.4 (5)	3.9 ± 0.1 (6)	3.8 (1)	3.8 ± 0.0 (10)	4.9 ± 0.6 (3)
EC (mS cm <sup>-1</sup> )	—	1.560 (1)	—	1.348 ± 0.038 (8)	1.382 ± 0.070 (13)	(9)	1.825 ± 0.085 (5)	1.830 ± 0.104 (6)	1.800 (1)	1.110 (2)	1.599 ± 0.142 (3)
Salinity (ppt)	—	—	—	—	—	—	0.9 ± 0.0 (4)	1.1 ± 0.1 (5)	—	—	—
TDS (mg L <sup>-1</sup> )	—	—	—	—	—	—	817.4 ± 64.1 (5)	856.4 ± 63.0 (5)	—	785.0 ± 65.4 (6)	—
Dissolved oxygen (%)	—	—	—	—	—	—	88.9 ± 8.3 (5)	97.7 ± 6.6 (5)	—	—	103.6 (1)
Dissolved oxygen (mg L <sup>-1</sup> )	10.0 ± 0.0 (4)	—	—	9.0 ± 0.3 (18)	8.3 ± 0.3 (24)	7.0 ± 0.7 (10)	—	9.4 (2)	8.9 (2)	—	9.6 (2)
ORP (mV)	—	—	—	—	—	—	118 ± 6 (5)	243 ± 58 (5)	139 (1)	—	264 (1)
Turbidity (NTU)	—	—	—	—	—	—	0.0 ± 0.0 (5)	2.5 ± 1.7 (4)	—	—	0.0 (1)
TSS (mg L <sup>-1</sup> )	—	—	—	—	—	—	49.8 ± 4.8 (5)	51.0 (2)	—	—	13.5 (2)
Chlorophyll a (µg L <sup>-1</sup> )	—	—	<0.2 (0 2)	0.5 ± 0.1 (16)	0.6 ± 0.1 (22)	0.2 ± 0.0 (7)	0.1 ± 0.0 (5)	0.5 ± 0.4 (3)	—	—	0.0 (1)
Phaeophytin (µg L <sup>-1</sup> )	—	—	—	1.4 ± 0.2 (16)	1.6 ± 0.3 (22)	1.2 ± 0.2 (7)	—	—	—	—	—
KdPAR	—	—	—	—	—	—	—	0.13 (2)	—	—	—
Acidity	—	—	49.1 ± 2 (4)	—	—	—	33.3 ± 1 (5)	28.8 (2)	—	—	—
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	—	92 (2)	90 ± 5 (14)	—	—	83 ± 4 (5)	79 (2)	—	73 ± 9 (15)	98 (2)
Cl (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	456 ± 28 (15)	365 (2)
TP (µg L <sup>-1</sup> )	—	—	—	—	—	—	1 (2)	8 ± 8 (4)	—	—	102 (1)
FRP (µg L <sup>-1</sup> )	—	—	5 (1)	3 ± 1 (9)	1 ± 0 (13)	1 ± 0 (9)	5 ± 1 (5)	3 ± 1 (4)	—	—	5 (1)
TN (µg L <sup>-1</sup> )	—	—	—	—	—	—	745 ± 201 (5)	1013 (2)	—	—	237 (1)
NO <sub>x</sub> (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	181 (1)

Parameter	1991	1994	1995	1997	1998	1999	2003	2004	2005	2008	2009
NH <sub>4</sub> (µg L <sup>-1</sup> )	—	—	46 (2)	20 ± 2 (17)	37 ± 8 (13)	18 ± 1 (9)	103 ± 20 (5)	128 ± 22 (4)	—	—	37 (1)
NO <sub>3</sub> (µg L <sup>-1</sup> )	—	—	—	4 ± 1 (9)	2 ± 0 (13)	2 ± 0 (9)	62 ± 16 (4)	39 (2)	—	—	—
DOC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	5 (1)
As (µg L <sup>-1</sup> )	—	—	<10 (0 1)	—	—	—	—	<50 (0 1)	1.0 (2)	1.0 ± 0.0 (3 8)	<1 (0 1)
Al (mg L <sup>-1</sup> )	—	—	5.0 (2)	2.1 ± 0.4 (6)	1.8 ± 0.2 (8)	2.0 (1)	—	2.3 (1)	0.1 (2)	2.2 ± 0.1 (16)	2.0 ± 0.7 (3)
Ag (µg L <sup>-1</sup> )	—	—	<2 (0 2)	0.04 ± 0.02 (7)	0.07 ± 0.05 (13)	0.08 (1)	—	—	—	<1 (0 5)	—
B (µg L <sup>-1</sup> )	—	—	—	27.5 ± 4.3 (6)	21.3 ± 2.4 (8)	24.3 (1)	—	—	—	33.8 ± 4.0 (16)	<50 (0 1)
Ba (µg L <sup>-1</sup> )	—	—	—	38.8 ± 9.0 (7)	4051.8 ± 4028.2 (13)	41.7 (1)	—	—	—	—	—
Be (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	<10 (0 16)	—
Ca (mg L <sup>-1</sup> )	—	—	10.5 (2)	6.7 ± 0.9 (6)	5.0 ± 0.5 (8)	6.0 (1)	—	—	—	7.9 ± 1.1 (15 1)	12.3 (2)
Cd (µg L <sup>-1</sup> )	—	—	<2 (0 2)	0.1 ± 0.0 (7)	0.1 ± 0.0 (13)	0.1 (1)	—	<8 (0 1)	1.0 (1)	0.2 ± 0.0 (10 6)	<10 (0 1)
Co (µg L <sup>-1</sup> )	—	—	—	33.0 ± 6.8 (6)	27.8 ± 3.5 (8)	32.1 (1)	—	—	—	40.0 ± 0.0 (9 7)	45.0 (1)
Cr (µg L <sup>-1</sup> )	—	—	<100 (0 2)	9.7 ± 1.5 (6)	8.8 ± 0.9 (8)	9.7 (1)	—	—	1.0 (2)	1.0 (2 14)	<10 (0 1)
Cs (µg L <sup>-1</sup> )	—	—	—	0.2 ± 0.0 (5)	0.2 ± 0.0 (8)	0.2 (1)	—	—	—	—	—
Cu (µg L <sup>-1</sup> )	—	—	<50 (0 2)	65.6 ± 38.6 (6)	4.7 ± 0.8 (8)	32.6 (1)	—	—	10.0 (2)	<10 (0 16)	<10 (0 2)
Fe (mg L <sup>-1</sup> )	—	—	<100 (0 2)	0.2 ± 0.1 (6)	0.4 ± 0.1 (8)	0.3 (1)	—	0.2 ± 0.0 (3)	0.6 (2)	0.4 ± 0.0 (16)	0.5 ± 0.2 (3)
Hg (µg L <sup>-1</sup> )	—	—	<0.5 (0 2)	—	—	—	—	—	—	—	<100 (0 1)
K (mg L <sup>-1</sup> )	—	—	—	2.1 ± 0.2 (6)	1.4 ± 0.2 (8)	1.6 (1)	—	—	—	—	4.8 (1)
Mg (mg L <sup>-1</sup> )	—	—	32 (2)	17 ± 4 (7)	11 ± 3 (13)	20 (1)	—	41 (1)	—	30 ± 3 (15 1)	38 (2)
Mn (µg L <sup>-1</sup> )	—	—	<100 (0 2)	67 ± 5 (6)	49 ± 6 (8)	55 (1)	—	62 ± 21 (3)	30 (2)	54 ± 8 (16)	199 (2)
Mo (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	<10 (0 16)	—
Na (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	224 (2)

Parameter	1991	1994	1995	1997	1998	1999	2003	2004	2005	2008	2009
Ni ( $\mu\text{g L}^{-1}$ )	—	—	<100 (0 2)	40.9 $\pm$ 4.0 (5)	29.4 $\pm$ 3.7 (8)	33.8 (1)	—	20.0 (1)	30.0 (2)	50.0 $\pm$ 0.0 (9 7)	55.0 (1)
Pb ( $\mu\text{g L}^{-1}$ )	6.0 (2)	100.0 (1)	5.0 (1)	4.3 $\pm$ 0.8 (10)	10.0 $\pm$ 4.3 (15 2)	10.8 $\pm$ 4.4 (10)	—	51.3 (2)	10.0 (1)	2.4 $\pm$ 0.3 (3)	4.2 (1)
S ( $\text{mg L}^{-1}$ )	98 (1)	10 (1)	—	—	—	—	—	33 (1)	19 (1)	—	—
Sb ( $\mu\text{g L}^{-1}$ )	<1 (0 1)	—	—	—	—	—	—	—	—	—	—
Se ( $\mu\text{g L}^{-1}$ )	<1 (0 1)	200.0 (1)	—	—	—	—	—	200.0 (1)	20.0 (1)	—	—
SiO <sub>2</sub> ( $\text{mg L}^{-1}$ )	—	—	—	9 (1)	26 $\pm$ 10 (4)	9 $\pm$ 3 (4)	—	—	—	—	—
Sn ( $\mu\text{g L}^{-1}$ )	<1 (0 1)	—	—	—	—	—	—	—	—	—	—
Sr ( $\mu\text{g L}^{-1}$ )	860.0 (1)	—	—	—	74.5 $\pm$ 30.3 (3)	147.4 $\pm$ 37.7 (3)	—	—	—	60.2 (2)	67.6 (1)
Ti ( $\mu\text{g L}^{-1}$ )	<5 (0 1)	—	—	0.0 (1)	0.3 (2)	0.2 (1)	—	—	—	0.2 (1)	—
U ( $\mu\text{g L}^{-1}$ )	—	60.6 (1)	—	—	0.0 (2)	—	—	88.2 (1)	—	0.2 (2)	0.1 (1)
V ( $\mu\text{g L}^{-1}$ )	<1 (0 1)	—	—	—	28000.0 (2)	10.0 (2)	—	—	—	—	—
Zn ( $\mu\text{g L}^{-1}$ )	180.0 (2)	75.0 (1)	30.0 (1)	226.0 $\pm$ 102.5 (10)	298.2 $\pm$ 164.3 (15 1)	429.9 $\pm$ 248.6 (6)	—	42.5 (2)	51.0 (1)	73.0 $\pm$ 38.5 (3)	50.8 (1)

#### 4.2.4 Centaur

##### 4.2.4.1 History and development

Centaur was mined between 1966 and 1967 yielding 30,000 tonnes of coal (Stedman, 1988) by Griffin Coal Mining Company. No rehabilitation was undertaken at the location. An overburden dump lies alongside the lake to the east (Figure 26). The lake receives water from Chicken Creek during the wetter months (Figure 27). The lake does not appear to be a flow through system and as water levels rise, the Creek water bypasses the lake through a channel to east.



**Figure 26.** Lake Centaur looking north (09/2005).



**Figure 27.** Aerial photograph of Centaur pit lake (taken from Google Earth, imagery dated 2007) (top of picture is north).

Of all the historic lakes, there are the fewest data for Lake Centaur. The few data trends, however, suggest there may have been an increase in salinity as Na concentration (Table 9). This is also reflected in a slight increase in EC over the same period, and may be due to more saline water entering from the Chicken Creek catchment.

**Table 9.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Centaur. — = no data available for that year.

Parameter	2001	2006	2007	2008	2009
Temperature (°C)	—	—	—	19.9 (2)	20.9 (2)
pH	—	—	—	6.5 (2)	6.7 (2)
EC (mS cm <sup>-1</sup> )	—	—	—	2.305 (2)	2.970 (2)
Dissolved oxygen (%)	—	—	—	—	87.0 (1)
Dissolved oxygen (mg L <sup>-1</sup> )	7.2 (2)	7.6 $\pm$ 0.6 (5)	9.2 $\pm$ 0.3 (7)	7.2 (1)	7.3 (1)
ORP (mV)	—	—	—	—	191 (1)
Turbidity (NTU)	—	—	—	6.4 (1)	0.6 (1)
TSS (mg L <sup>-1</sup> )	—	—	—	36.0 (2)	—
Chlorophyll a ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	1.4 (1)
SO <sub>4</sub> (mg L <sup>-1</sup> )	61 (2)	—	—	47 $\pm$ 2 (13)	55 (1)
Cl (mg L <sup>-1</sup> )	—	—	—	726 $\pm$ 26 (13)	370 (1)
TP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	73 (1)
FRP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	10 (1)
TN ( $\mu$ g L <sup>-1</sup> )	—	—	—	400 (1)	651 (1)
NO <sub>x</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	30 (1)
NH <sub>4</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	115 (1)
DOC (mg L <sup>-1</sup> )	—	—	—	—	10 (1)
DIC (mg L <sup>-1</sup> )	—	—	—	—	1 (1)
As ( $\mu$ g L <sup>-1</sup> )	2.5 (2)	1.0 $\pm$ 0.0 (5)	<1 (0 6)	1.0 (2 11)	<5 (0 1)
Al (mg L <sup>-1</sup> )	1.2 (2)	0.3 $\pm$ 0.0 (4)	0.4 $\pm$ 0.1 (6)	0.2 $\pm$ 0.1 (13 3)	0.4 (1 1)
B ( $\mu$ g L <sup>-1</sup> )	—	—	—	<10 (0 12)	<50 (0 1)
Be ( $\mu$ g L <sup>-1</sup> )	—	—	—	<0.5 (0 13)	—
Ca (mg L <sup>-1</sup> )	24.0 (2)	—	—	23.5 $\pm$ 0.8 (13)	25.2 (1)
Cd ( $\mu$ g L <sup>-1</sup> )	5.0 (2)	1.0 $\pm$ 0.0 (5)	<1 (0 6)	<1 (0 15)	<10 (0 2)
Co ( $\mu$ g L <sup>-1</sup> )	—	—	—	<10 (0 13)	<10 (0 1)
Cr ( $\mu$ g L <sup>-1</sup> )	5.0 (2)	1.0 $\pm$ 0.0 (5)	<1 (0 6)	<1 (0 15)	<1 (0 2)
Cu ( $\mu$ g L <sup>-1</sup> )	15.0 (2)	10.0 $\pm$ 0.0 (5)	<10 (0 6)	10.0 (1 15)	<10 (0 1)
Fe (mg L <sup>-1</sup> )	0.5 (2)	0.8 $\pm$ 0.1 (5)	1.4 $\pm$ 1.1 (6)	0.1 $\pm$ 0.0 (15)	0.6 (1 1)
Hg ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	<100 (0 1)
K (mg L <sup>-1</sup> )	3.0 (2)	—	—	—	1.4 (1)
Mg (mg L <sup>-1</sup> )	70 (2)	—	—	66 $\pm$ 2 (13)	88 (1)
Mn ( $\mu$ g L <sup>-1</sup> )	20 (2)	58 $\pm$ 12 (5)	55 (2 4)	13 $\pm$ 3 (3 13)	81 (2)
Mo ( $\mu$ g L <sup>-1</sup> )	50.0 (2)	—	—	<5 (0 13)	—
Na (mg L <sup>-1</sup> )	329 (2)	—	—	358 (1)	406 (1)
Ni ( $\mu$ g L <sup>-1</sup> )	25.0 (2)	30.0 $\pm$ 0.0 (5)	<10 (0 6)	940.0 (1 15)	52.0 (1 1)
Pb ( $\mu$ g L <sup>-1</sup> )	81.0 (2)	25.0 (2 3)	100.0 (1)	—	<100 (0 1)
S (mg L <sup>-1</sup> )	—	76 (2)	2 (1)	—	102 (1)
Se ( $\mu$ g L <sup>-1</sup> )	—	<200 (0 2)	200.0 (1)	—	<200 (0 1)
SiO <sub>2</sub> (mg L <sup>-1</sup> )	19 (1)	—	—	—	—
U ( $\mu$ g L <sup>-1</sup> )	—	666.2 (2)	50.0 (1)	—	<50 (0 1)
V ( $\mu$ g L <sup>-1</sup> )	2.0 (1)	—	—	—	—
Zn ( $\mu$ g L <sup>-1</sup> )	605.0 (2)	426.2 $\pm$ 118.5 (5)	50.0 (1)	—	<50 (0 1)

#### 4.2.5 Ewington

##### 4.2.5.1 History and development

Ewington (also called Ewington No. 1 or Baby Blue) was mined during 1960 by Amalgamated Collieries and close the same year (Figure 28; Stedman, 1988). It only produced 27,174 tonnes and was difficult to mine due to the swampy area immediately to the north (Figure 29). Ewington is located on the same property as Blue Waters and was used for watering stock. Littoral rushes and sedges were sparsely distributed with a concentration on the eastern shallow wing (Lund *et al.*, 2000b). In 2009, the lake was drained and is currently being remined by Griffin Coal Mining Company. 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). Upon cessation of dewatering, the pit void formed a small lake around 5 m deep. The pit lake appears to receive little allochthonous or autochthonous input of organic matter as evidenced by the low organic matter content of sediments (Lund *et al.*, 2000b).

This lake has been the focus of considerable research effort, ranging from trial plantings around the edge, geological and hydrological investigations, to the installation of experimental ponds and a SAP (successively alkalinity producing) system, all of which is detailed in Phillips et al (2000).



**Figure 28.** Ewington (09/2006) looking south.

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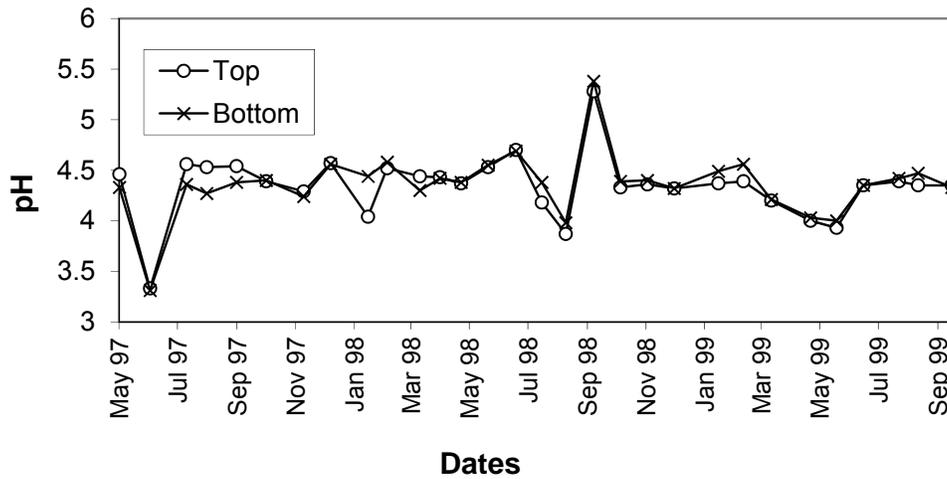


**Figure 29.** Aerial photograph of Ewington pit lake (taken from Google Earth, imagery dated 2007) (top of picture is north).

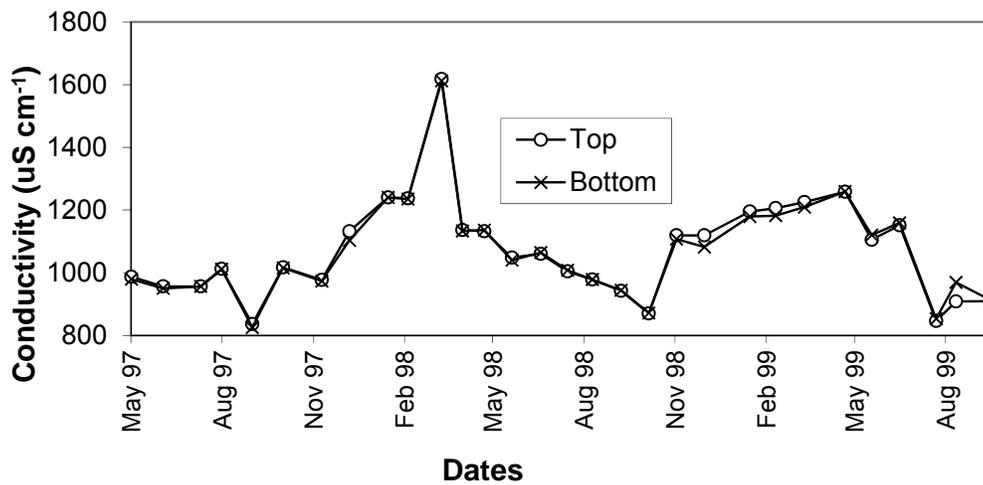
#### 4.2.5.2 Trends in water quality

Data from 1997–1999 shows that pH of Ewington pit lake (Figure 30a) varies little throughout the year. Electrical conductivity appears to vary on a seasonal basis probably due to evapo-concentration in summer and dilution from surface and shallow groundwater inflow in winter (Figure 30b). These changes in conductivity are small in magnitude and are unlikely to have any effects on pit lake biota. No difference was recorded between surface and bottom waters. Interestingly, no evapo-concentration effect can be seen for the pH.

a) pH

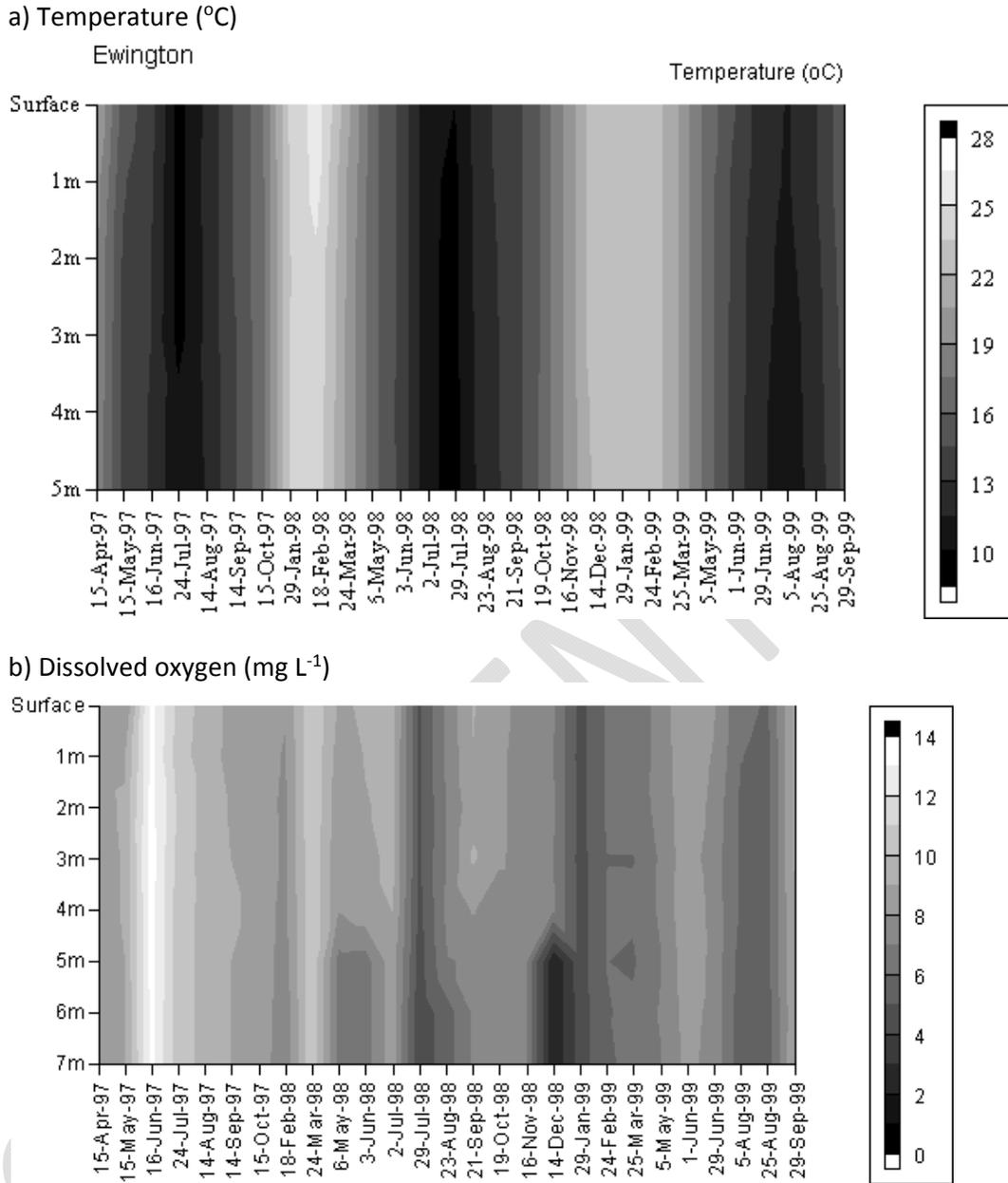


b) Electrical conductivity



**Figure 30.** Seasonal changes in a) pH and b) conductivity in Ewington between 1997 and 1999.

Ewington becomes thermally stratified in summer, although it appears to be only a temporary phenomenon with temperature differences rarely exceeding 2°C (Figure 31a). Slight declines in dissolved oxygen were noted during summer in the bottom waters, probably associated with the hypolimnion in the deepest section (Figure 31b).



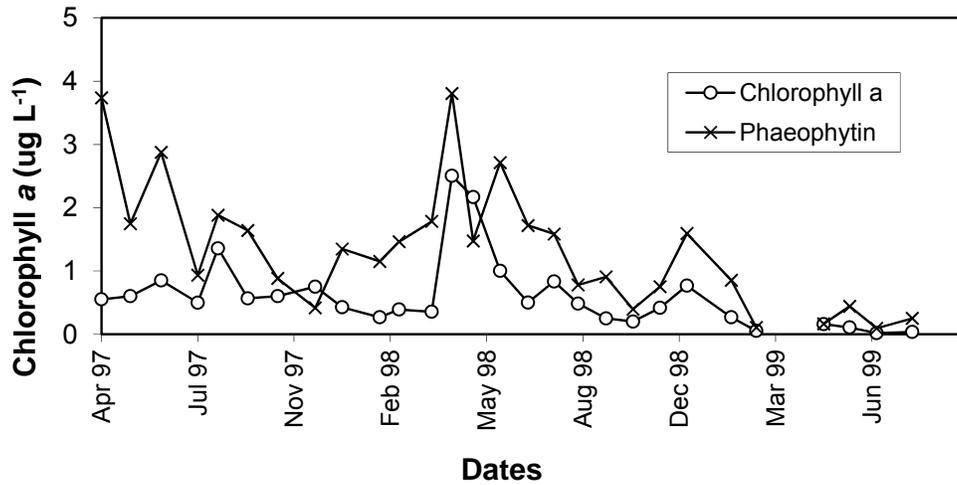
**Figure 31.** Changes in a) temperature and b) in Ewington (taken from Phillips *et al.*, 2000) over time and depth.

Water transparency was lower than would be expected given the low chlorophyll *a* values (Figure 32a) suggesting that turbidity (of clay particles) may be responsible for the low Secchi depths recorded (Figure 32b).

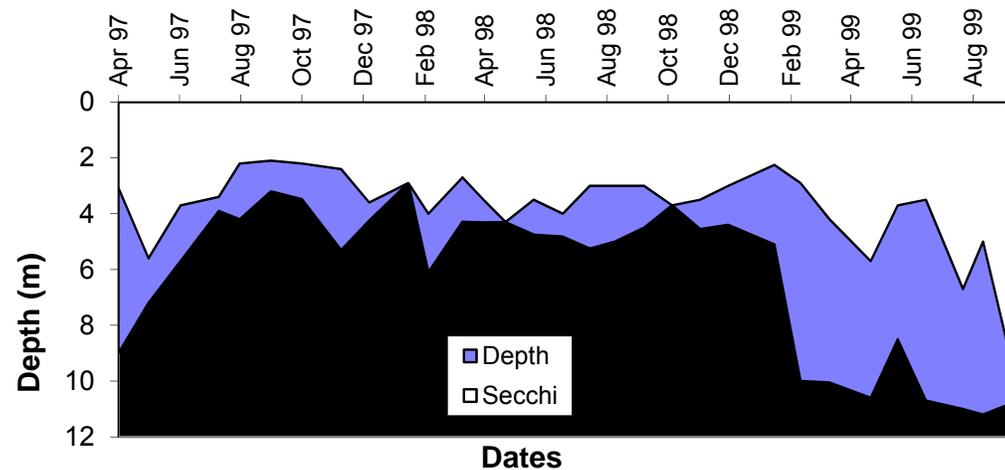
Chlorophyll *a* was probably low as a result of low FRP concentrations (Figure 32a) despite moderate levels of NO<sub>x</sub> and NH<sub>3</sub> (Figure 33). No strong seasonal trends are discernible in the pit lake for any of the nutrients, although there does appear to have

been a slight increase in algae in April 1998. The low organic matter concentrations in the sediment are likely to mean that ammonification of organic matter is unlikely to make a significant contribution to ammonia concentrations.

a) Chlorophyll *a*

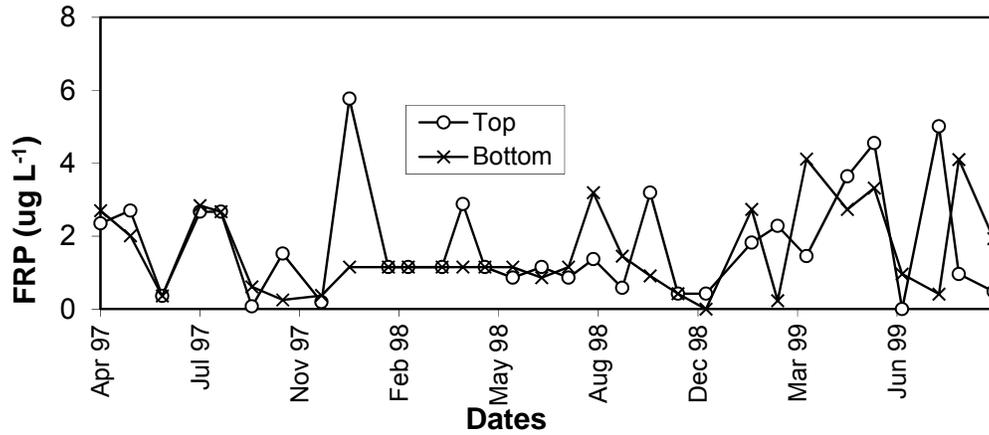


b) Secchi depth

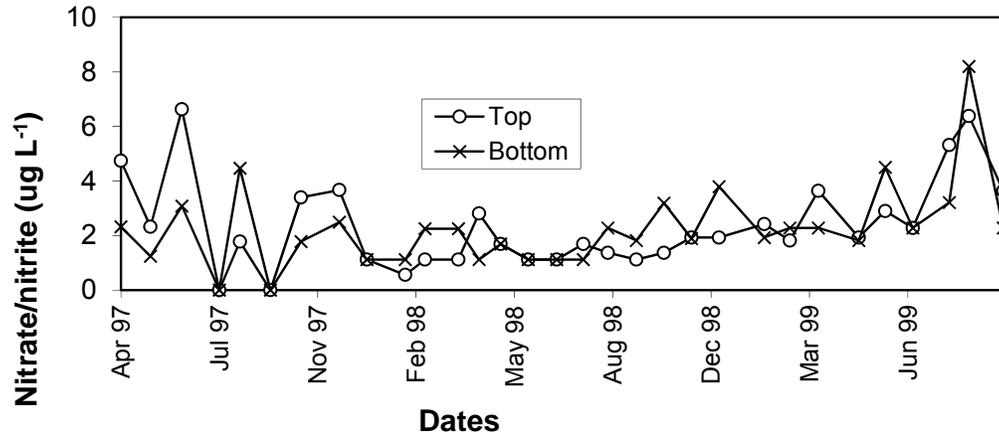


**Figure 32.** Changes in a) chlorophyll *a* (top and bottom of the water column) and b) Secchi depth (black = bottom, blue = water below Secchi depth) in Ewington.

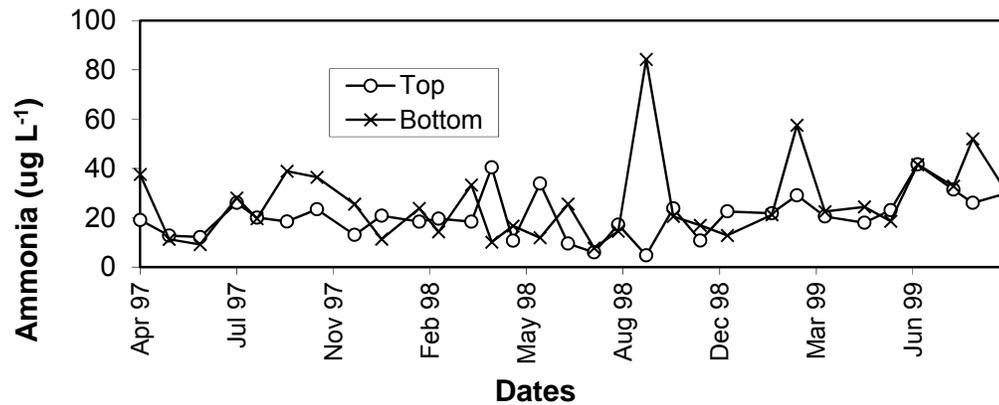
a) FRP



b) NOx



c) Ammonia

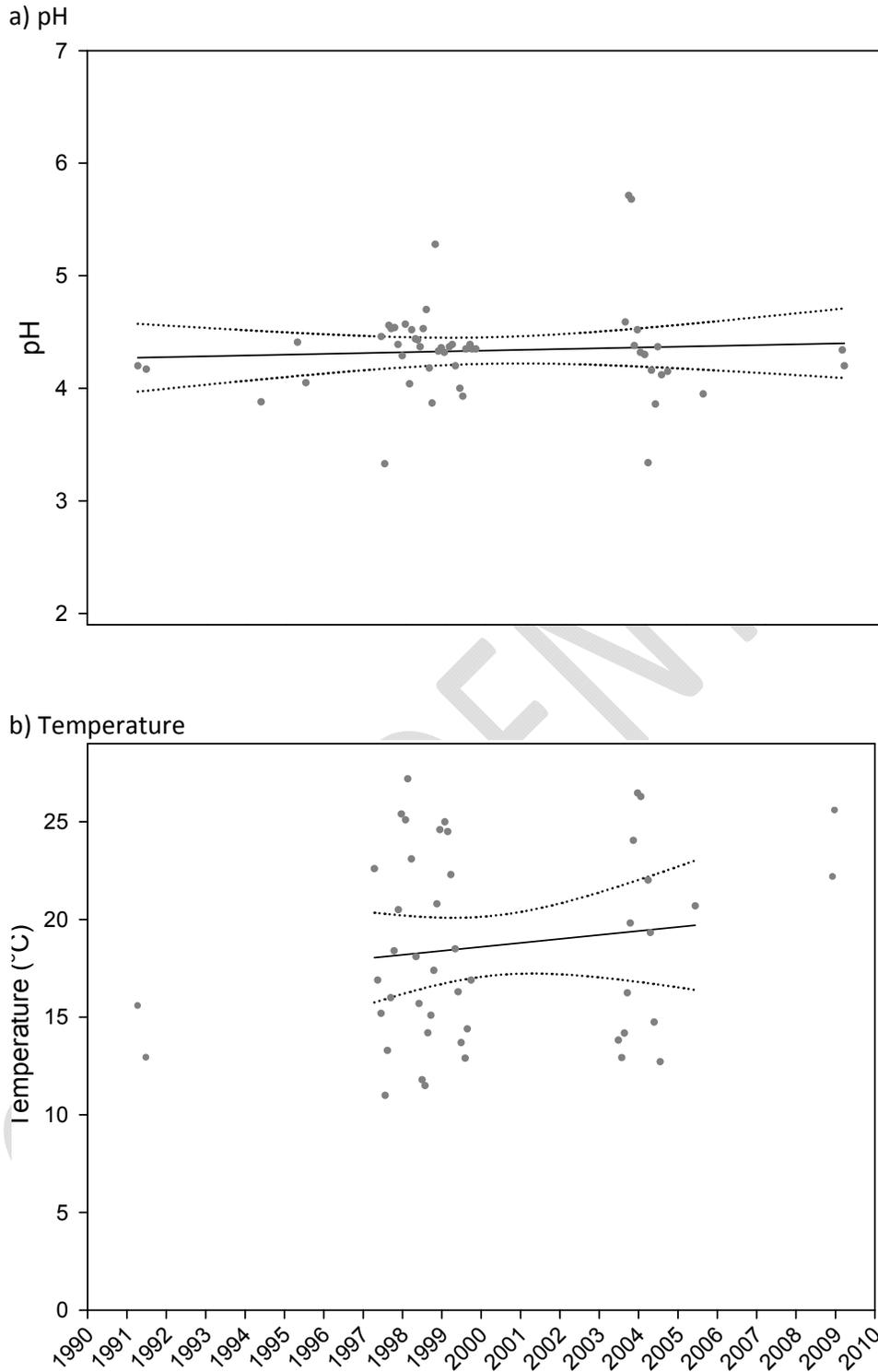


**Figure 33.** Seasonal changes in a) FRP, b) NOx and c) ammonia in Ewington between 1997 and 1999.

There was no significant ( $P > 0.05$ ) trend of increasing pH over time for Ewington (Figure 34a) ( $n = 51$ ,  $r^2 = 0.004$ ). Even when seasonally-biased outliers were removed, there was no significant ( $P > 0.05$ ) trend of increasing temperature over time for Ewington (Figure 34b) ( $n = 48$ ,  $r^2 = 0.01$ ). There was a weak but significant ( $P < 0.05$ ) increase in electrical conductivity in the surface water of Ewington (Figure 35a) ( $n = 49$ ,  $r^2 = 0.1$ ). This lake contains little overburden in its catchment, but this trend might be due to evapo-concentration of lake water or an increase in acidity or salinity of groundwater.

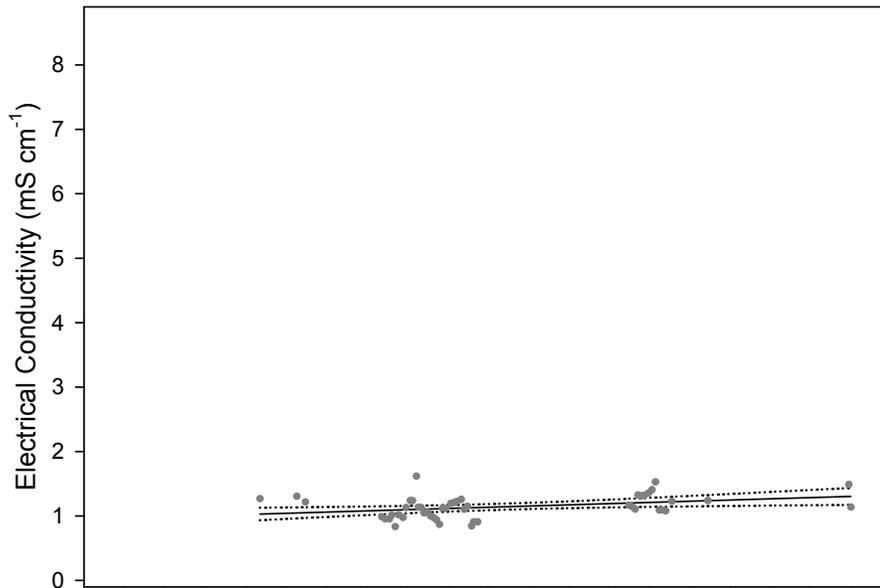
A plot of Ewington dissolved oxygen concentrations ( $\text{mg L}^{-1}$ ) over time showed no significant ( $P > 0.05$ ) change over time (Figure 35b) ( $n = 45$ ,  $r^2 = 0.002$ ).

The annual mean dataset for Ewington is the best of the lakes in the Collie Lake District. Phosphorus in particular, but also nitrogen total and fractions appear to have increased over the 18 years of data collection in Ewington Lake (Table 10). Aluminium and also some heavy metals such as nickel and lead may also have increased in concentration over this time.

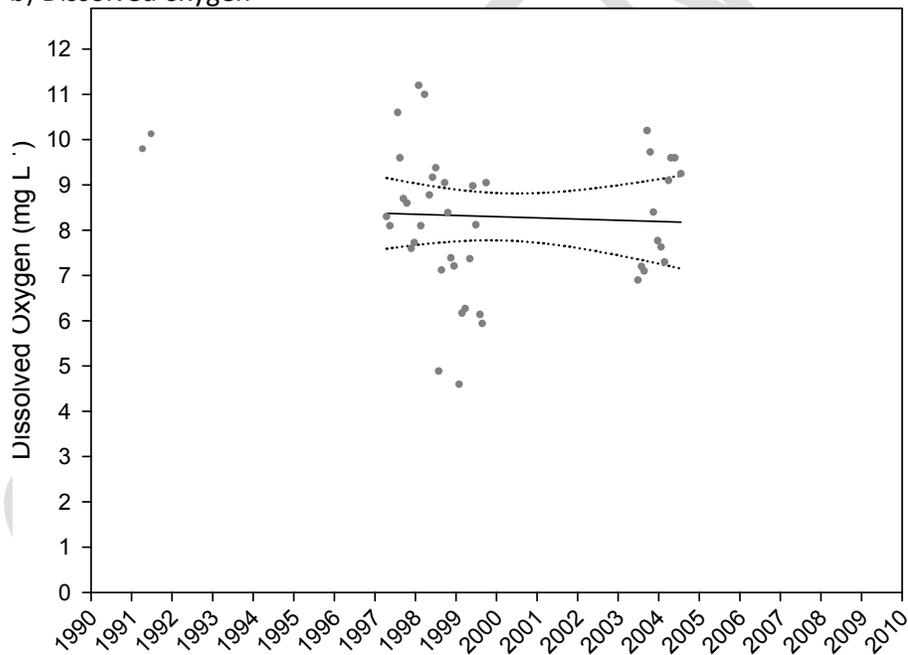


**Figure 34.** Long term changes in (a) surface water pH and (b) temperature in Ewington. Grey dots represent individual sample points, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in temperature regression line calculation.

a) Conductivity



b) Dissolved oxygen



**Figure 35.** Long term changes in (a) surface water electrical conductivity and (b) dissolved oxygen in Ewington Lake. Grey dots represent individual sample points, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.

**Table 10.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Ewington. — = no data available for that year.

Parameter	1991	1994	1995	1997	1998	1999	2003	2004	2005	2008
Temperature (°C)	14.3 (2)	—	—	17.7 $\pm$ 1.5 (9)	18.7 $\pm$ 1.5 (12)	18.3 $\pm$ 1.5 (9)	18.2 $\pm$ 2.0 (7)	21.0 $\pm$ 3.2 (5)	20.7 (1)	23.9 (2)
pH	4.2 (2)	3.9 (1)	4.2 (2)	4.3 $\pm$ 0.1 (8)	4.4 $\pm$ 0.1 (13)	4.3 $\pm$ 0.1 (9)	4.8 $\pm$ 0.2 (7)	3.9 $\pm$ 0.2 (5)	4.0 (1)	4.1 $\pm$ 0.1 (4)
EC (mS cm <sup>-1</sup> )	—	1.270 (1)	1.264 (2)	0.984 $\pm$ 0.029 (8)	1.116 $\pm$ 0.051 (13)	1.089 $\pm$ 0.053 (9)	1.248 $\pm$ 0.040 (7)	1.267 $\pm$ 0.088 (5)	1.240 (1)	1.213 $\pm$ 0.093 (4)
Salinity (ppt)	—	—	—	—	—	—	0.6 $\pm$ 0.0 (7)	0.7 $\pm$ 0.1 (5)	—	—
TDS (mg L <sup>-1</sup> )	—	780.0 (1)	—	—	—	—	—	—	—	580.0 (2)
Dissolved oxygen (%)	—	—	—	—	—	—	87.7 $\pm$ 7.0 (7)	95.8 $\pm$ 2.3 (5)	—	—
Dissolved oxygen (mg L <sup>-1</sup> )	10.0 (2)	—	—	9.2 $\pm$ 0.6 (9)	8.5 $\pm$ 0.5 (12)	7.0 $\pm$ 0.5 (9)	8.2 $\pm$ 0.5 (7)	8.6 $\pm$ 0.5 (5)	—	—
ORP (mV)	—	—	—	—	—	—	117 $\pm$ 20 (7)	269 $\pm$ 50 (5)	133 (1)	—
Turbidity (NTU)	—	—	—	—	—	—	0.0 $\pm$ 0.0 (7)	4.0 $\pm$ 2.3 (5)	—	—
TSS (mg L <sup>-1</sup> )	—	—	—	—	—	—	56.9 $\pm$ 13.0 (7)	51.6 (2)	—	11.0 (1 1)
Chlorophyll a ( $\mu$ g L <sup>-1</sup> )	—	—	0.9 (1)	0.7 $\pm$ 0.1 (9)	0.8 $\pm$ 0.2 (13)	0.1 $\pm$ 0.0 (6)	0.2 $\pm$ 0.1 (7)	0.3 $\pm$ 0.1 (3)	—	—
Phaeophytin ( $\mu$ g L <sup>-1</sup> )	—	—	—	1.7 $\pm$ 0.3 (9)	1.5 $\pm$ 0.2 (13)	0.3 $\pm$ 0.1 (6)	8.2 (1)	—	—	—
KdPAR	—	—	—	—	—	—	—	0.16 (1)	—	—
Acidity	—	—	15.9 (2)	—	—	—	23.4 $\pm$ 1 (7)	17.2 (2)	—	—
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	—	31 (1)	30 $\pm$ 1 (7)	—	—	34 $\pm$ 1 (7)	33 (2)	—	—
TP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	37 $\pm$ 8 (7)	47 $\pm$ 9 (4)	69 (1)	—
FRP ( $\mu$ g L <sup>-1</sup> )	—	—	6 (1)	2 $\pm$ 1 (9)	1 $\pm$ 0 (13)	2 $\pm$ 1 (9)	14 $\pm$ 3 (7)	36 $\pm$ 6 (4)	39 (1)	—
TN ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	1797 $\pm$ 489 (7)	954 (2)	—	—
NO <sub>x</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	71 $\pm$ 14 (7)	45 (2)	—	—
NH <sub>4</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	106 (1)	18 $\pm$ 2 (9)	18 $\pm$ 3 (13)	27 $\pm$ 2 (9)	82 $\pm$ 20 (6)	94 $\pm$ 12 (4)	62 (1)	—
NO <sub>3</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	3 $\pm$ 1 (9)	1 $\pm$ 0 (13)	3 $\pm$ 1 (9)	—	—	—	—
As ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	10.0 (1)	—	—
Al (mg L <sup>-1</sup> )	—	—	5.0 (1)	0.7 $\pm$ 0.0 (6)	0.6 $\pm$ 0.0 (9)	0.7 (1)	—	1.3 (1)	—	0.9 (1)
Ag ( $\mu$ g L <sup>-1</sup> )	—	—	<20 (0 1)	0.06 $\pm$ 0.02 (6)	0.02 $\pm$ 0.00 (13)	0.04 (1)	—	—	—	—

Parameter	1991	1994	1995	1997	1998	1999	2003	2004	2005	2008
B ( $\mu\text{g L}^{-1}$ )	—	—	—	34.4 ± 3.7 (6)	20.6 ± 1.2 (9)	26.1 (1)	—	40.0 (1)	—	—
Ba ( $\mu\text{g L}^{-1}$ )	—	—	—	97.6 ± 4.3 (6)	56.6 ± 11.9 (13)	88.1 (1)	—	—	—	—
Ca (mg L <sup>-1</sup> )	—	—	10.5 (1)	2.4 ± 0.2 (6)	1.7 ± 0.1 (9)	2.0 (1)	—	3.1 (1)	—	—
Cd ( $\mu\text{g L}^{-1}$ )	—	—	<20 (0 1)	0.1 ± 0.0 (5)	0.0 ± 0.0 (13)	0.0 (1)	—	0.6 (1)	—	<0.1 (0 1)
Co ( $\mu\text{g L}^{-1}$ )	—	—	—	2.8 ± 0.2 (6)	2.2 ± 0.2 (9)	2.4 (1)	—	4.0 (1)	—	—
Cr ( $\mu\text{g L}^{-1}$ )	—	—	<100 (0 1)	9.3 ± 1.1 (6)	9.5 ± 0.9 (9)	9.4 (1)	—	1.0 (1)	—	<1 (0 1)
Cs ( $\mu\text{g L}^{-1}$ )	—	—	—	0.3 ± 0.0 (6)	0.2 ± 0.0 (9)	0.2 (1)	—	—	—	—
Cu ( $\mu\text{g L}^{-1}$ )	—	—	<50 (0 1)	28.5 ± 10.0 (6)	4.7 ± 0.7 (9)	14.2 (1)	—	2.0 (1)	—	10.0 (1)
Fe (mg L <sup>-1</sup> )	—	—	<100 (0 1)	0.4 ± 0.0 (6)	0.3 ± 0.0 (9)	0.3 (1)	—	—	—	0.4 (1)
Hg ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	92.0 (1)	—	—
K (mg L <sup>-1</sup> )	—	—	—	2.8 ± 0.3 (6)	1.8 ± 0.1 (9)	2.2 (1)	—	0.01 (1)	—	—
Mg (mg L <sup>-1</sup> )	—	—	32 (1)	15 ± 1 (6)	9 ± 2 (13)	14 (1)	—	18 (1)	—	—
Mn ( $\mu\text{g L}^{-1}$ )	—	—	<100 (0 1)	21 ± 1 (6)	17 ± 1 (9)	19 (1)	—	20 (1)	—	20 (1)
Na (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	130 (1)	—	—
Ni ( $\mu\text{g L}^{-1}$ )	—	—	<100 (0 1)	5.4 ± 0.3 (6)	4.3 ± 0.3 (9)	4.7 (1)	—	6.0 (1)	—	20.0 (1)
P ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	—	—	—
Pb ( $\mu\text{g L}^{-1}$ )	35.5 (2)	5.0 (1)	5.0 (2)	5.0 ± 0.0 (9 1)	3.1 ± 0.4 (9)	3.0 ± 1.4 (9)	—	10.0 (1 1)	—	2.5 (1)
S (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	52 (2)	—	—
Se ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	<100 (0 1)	—	—
SiO <sub>2</sub> (mg L <sup>-1</sup> )	24 (1)	10 (1)	10 (1)	10 (2)	—	13 (1)	—	—	—	—
Sr ( $\mu\text{g L}^{-1}$ )	430.0 (1)	—	—	—	—	41.6 ± 1.5 (3)	—	—	—	—
Ti ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	0.1 (2)	—	—	—	—
U ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	0.0 ± 0.0 (3)	—	210.5 (1)	—	—
V ( $\mu\text{g L}^{-1}$ )	<2 (0 2)	—	—	—	—	0.0 (2)	—	—	—	—
Zn ( $\mu\text{g L}^{-1}$ )	1925.0 (2)	—	—	248.0 ± 45.9 (5)	302.5 ± 74.3 (8)	295.3 ± 146.3 (9)	—	489.0 (2)	—	20.0 (1)

#### 4.2.6 Lake Stockton

Stockton was originally an underground mine that commenced operations in 1927, in 1943 open cut operations started. Both types of mining ran concurrently for a few years with open cut operations providing easy access to underground operations (Stedman, 1988). Stockton was the first open-cut operation in Collie. Open cut operations finished in 1957, with underground operations closing in 1960 with the close of Amalgamated Collieries, a total of 1,519,910 tonnes of coal were abstracted (Stedman, 1988). The pit eventually filled with water creating a lake which is popularly used for recreational activities including waterskiing, camping, swimming and marron fishing (Figure 36). Lake Stockton is managed by the Western Australian Department of Environment and Conservation (DEC) who have rehabilitated much of the lake's surrounding land. Nonetheless, Large spoil dumps exist to the west, however spoil from the original underground operations was dispersed throughout the forest to the west, these spoil piles are small the size of 1-2 cartloads. The lake is still directly connected to underground workings through a shaft in the northwest quadrant of the lake. Steep cliffs on the northern side of the lake have been protected from erosion by the construction of a deep trench (2-3 m) 50 m back from the cliffs which intercepts overland flow. Lake Stockton may experience considerable pH change from the top of the lake (mean pH of 5.5) to the bottom (mean pH 4.8) which is thought to be due to groundwater ingress through the extensive historic underground workings that surround this lake (Lund et al, 1999).

In 1994, Lake Stockton (ironically a lake which post abandonment has had most of its surrounds rehabilitated), was temporarily closed by the Government Agency responsible when pH levels dropped below 4.5 which is the Australasian contact standard (ANZECC/ARMCANZ, 2000d). 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.

Circum-neutral water from dewatering operations at the new Ewington mine were discharged in a natural stream that enters Stockton Lake from the east to increase pH to acceptable levels. Interestingly, when this flow ceases (for operational reasons) pH rapidly drops back to around 4 (*pers. obs.*). An outlet in the southwest corner drains the lake ultimately into the Collie River south branch. Water from the outlet also

floods a small sump area to the south of the lake (Figure 37). This area has not been closely studied but was extremely acidic at pH 2 (*pers. obs.*), the source of the acidity is probably the large spoil pile located at the western end of the sump.



**Figure 36.** Lake Stockton (04/2009) looking west.



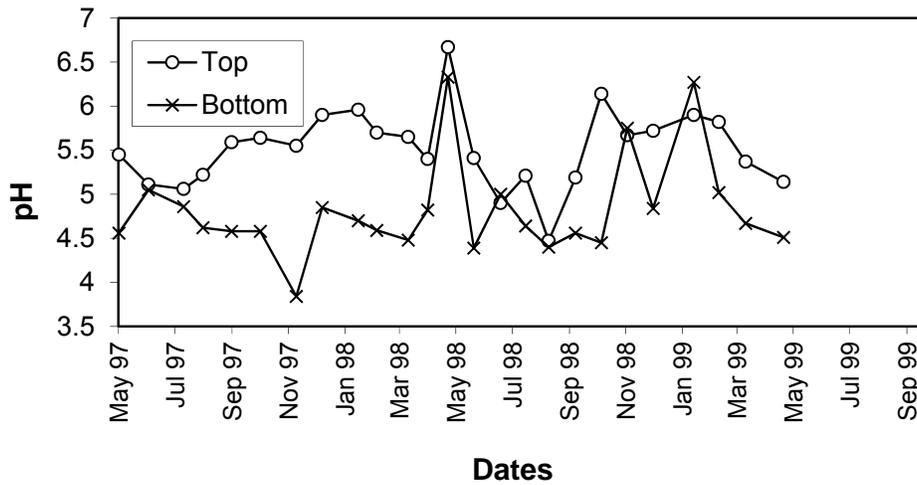
**Figure 37.** Aerial photograph of Stockton pit lake (taken from Google Earth, imagery dated 2009) (top of picture is north).

#### 4.2.6.1 Trends in water quality

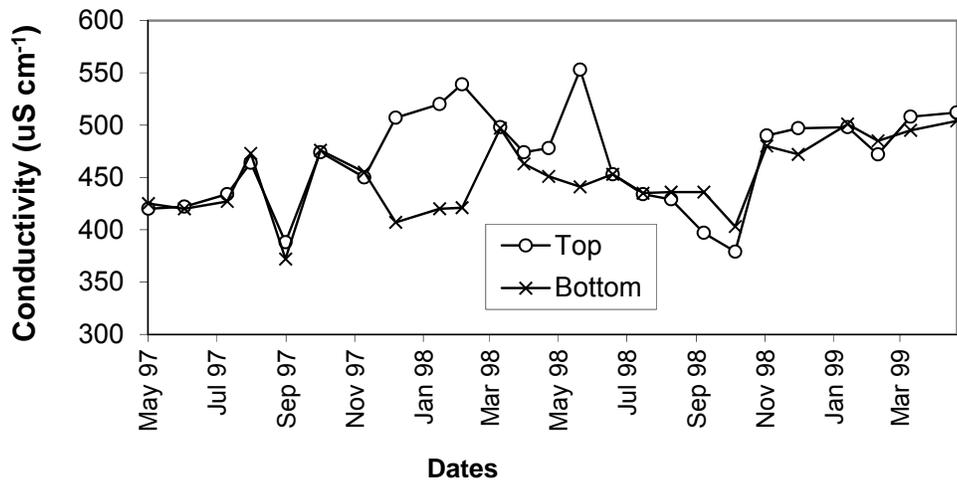
A stream has brought large quantities of dewatering water from Ewington mine into Stockton Lake since 1996. This stream of high pH water significantly increased the difference between surface and bottom waters during summer (Figure 38a). The inflow has maintained suitable pH for aquatic recreation during the summer. The difference became less pronounced when inflow has ceased on occasion.

Conductivity has been almost halved by the discharge; during stratification the surface water has a slightly higher conductivity than the bottom waters (Figure 38b). The conductivity remains the same top and bottom during stratification in summer 1998/99 without the discharge.

a) pH

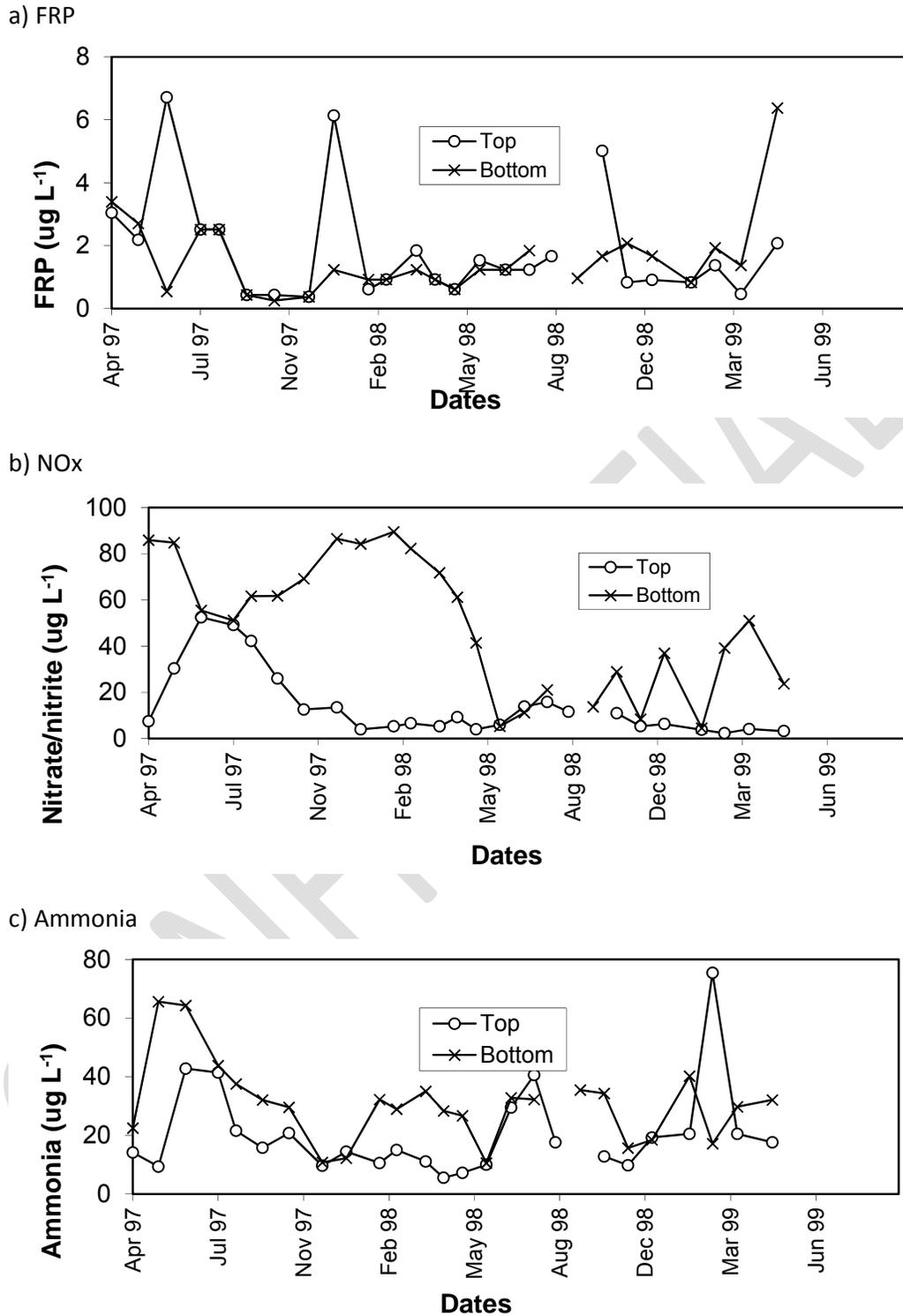


b) Electrical conductivity



**Figure 38.** Seasonal changes in a) pH and b) conductivity in Stockton Lake 1997 to 1999.

Stockton was stratified between October and May, and then thoroughly mixed for the rest of the year. The epilimnion extends to 3-4 m, the metalimnion from 3-4 to 7-8 m (Figure 39). Changes in a) temperature and b) in Stockton Lake (taken from Phillips et al, 2000) over time and depth.



**Figure 40.** Seasonal changes in a) FRP, b) NOx and c) ammonia in Stockton Lake between 1997 and 1999.

Interestingly Secchi depth was highest during summer months (Figure 41a). After the discharge commenced the bottom waters were noticeably turbid and it is suspected that in winter, mixing of the void makes the entire void turbid, reducing Secchi depths. The cause of the apparent increase in turbidity remains unclear. The changes could not be accounted for by algal biomass as productivity was very low (Figure 41b).

As a result of the many different agents (government, industry and university researchers) involved with the publicly accessible and highly utilised Lake Stockton, there is a very good dataset spanning back at least 18 years for this historic pit lake (Table 11).

At the end of summer, the stratification had resulted in anoxia (March to May) in the hypolimnion (Figure 39. Changes in a) temperature and b) in Stockton Lake (taken from Phillips et al, 2000) over time and depth.

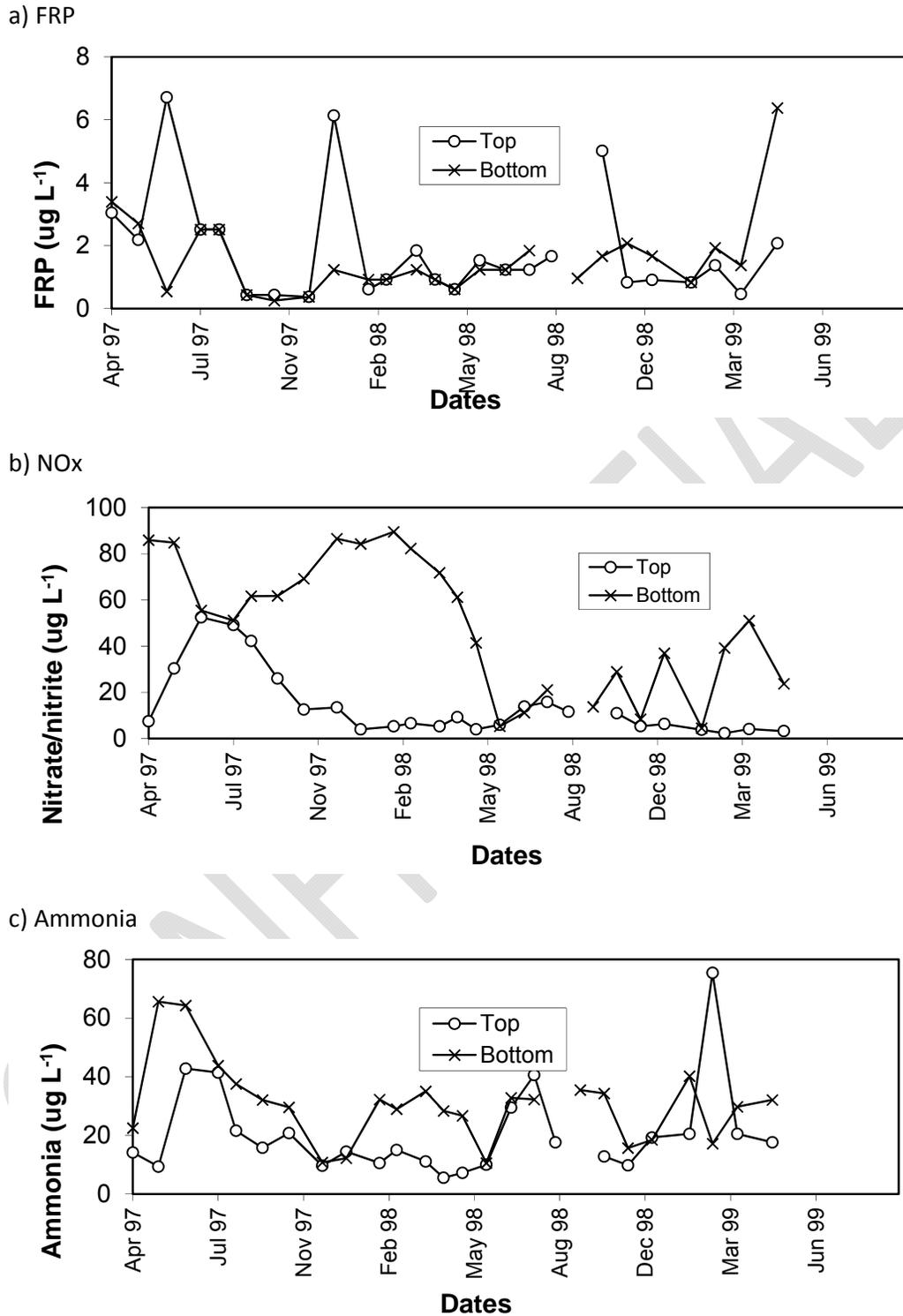
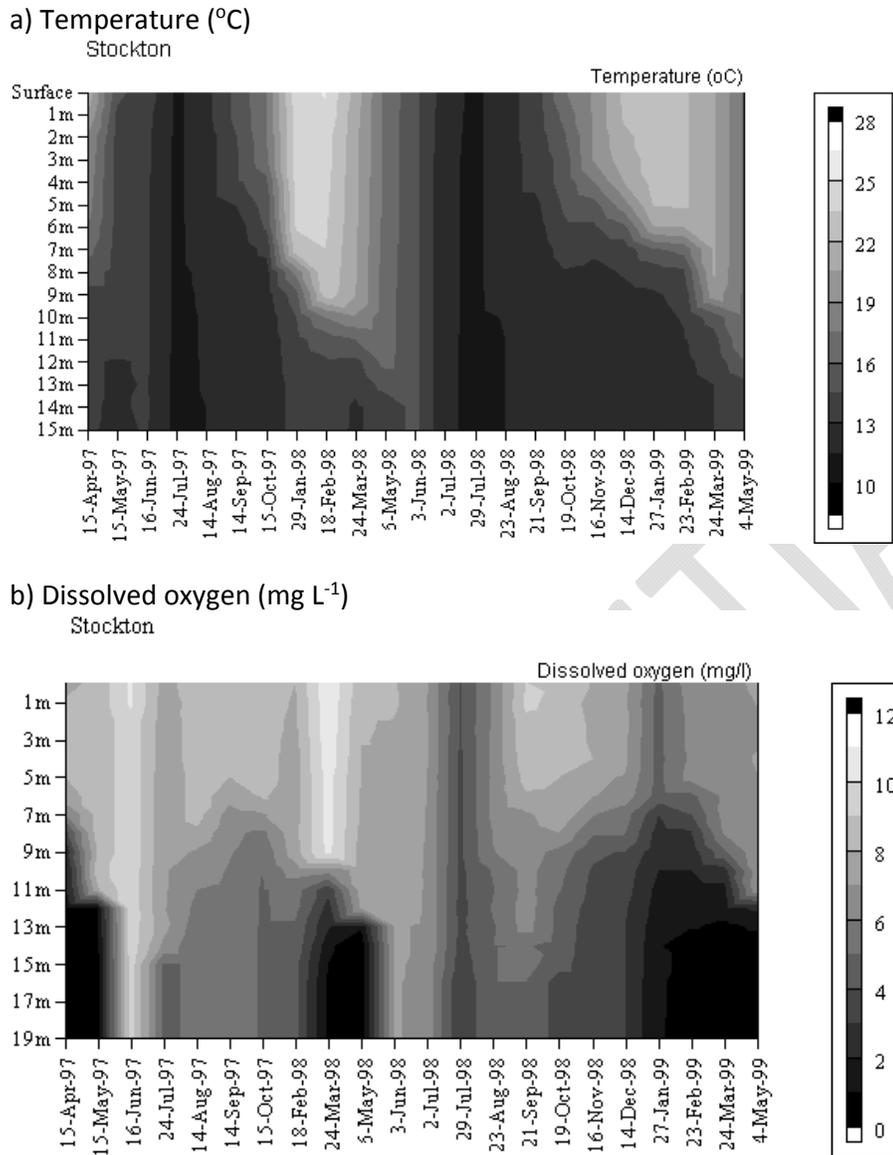


Figure 40. Seasonal changes in a) FRP, b) NOx and c) ammonia in Stockton Lake between 1997 and 1999.

Interestingly Secchi depth was highest during summer months (Figure 41a). After the discharge commenced the bottom waters were noticeably turbid and it is suspected that in winter, mixing of the void makes the entire void turbid, reducing Secchi depths. The cause of the apparent increase in turbidity remains unclear. The changes could not be accounted for by algal biomass as productivity was very low (Figure 41b).

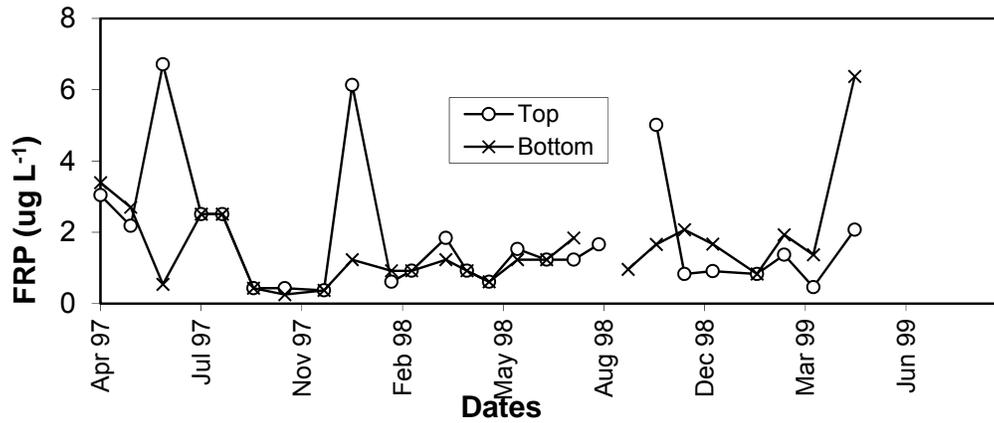
As a result of the many different agents (government, industry and university researchers) involved with the publicly accessible and highly utilised Lake Stockton, there is a very good dataset spanning back at least 18 years for this historic pit lake (Table 11).

The discharge was insufficient to mix the lake during periods of stratification and would flow over the stratified layer directly to the outflow. During stratification in the bottom waters, nitrate and ammonia concentrations were higher than at the surface of the lake (Figure 40). Levels of FRP were all low (Figure 40).

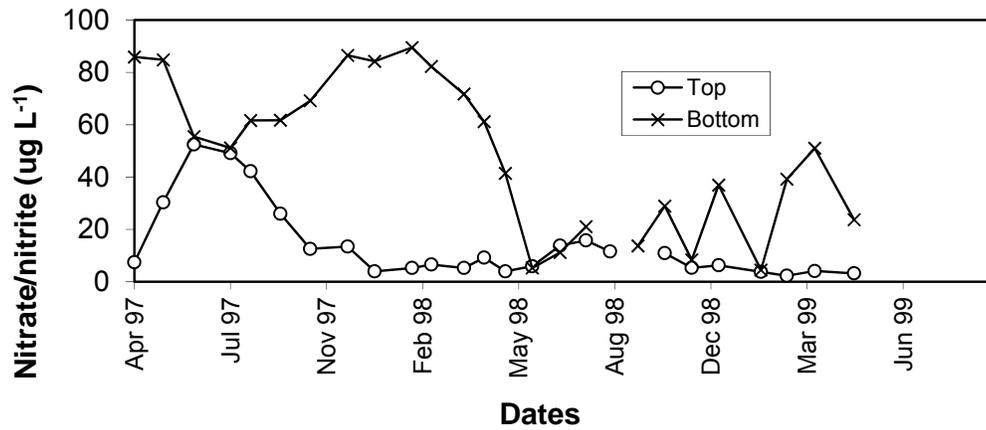


**Figure 39.** Changes in a) temperature and b) in Stockton Lake (taken from Phillips et al, 2000) over time and depth.

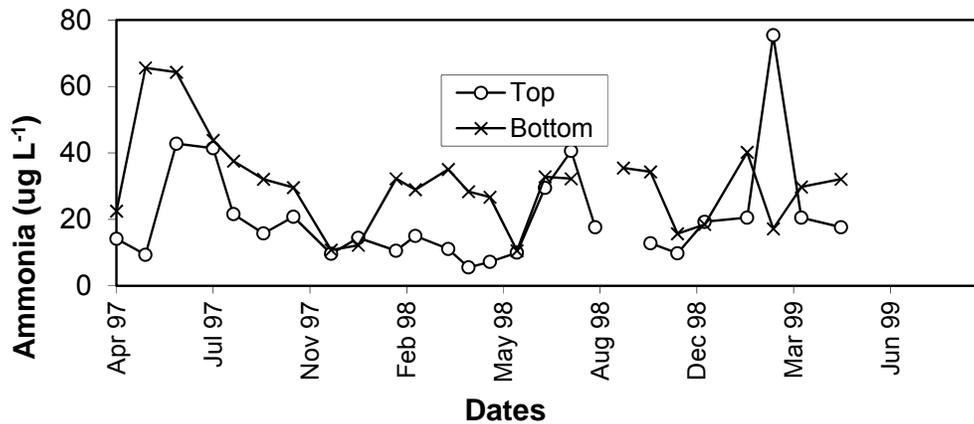
a) FRP



b) NOx



c) Ammonia



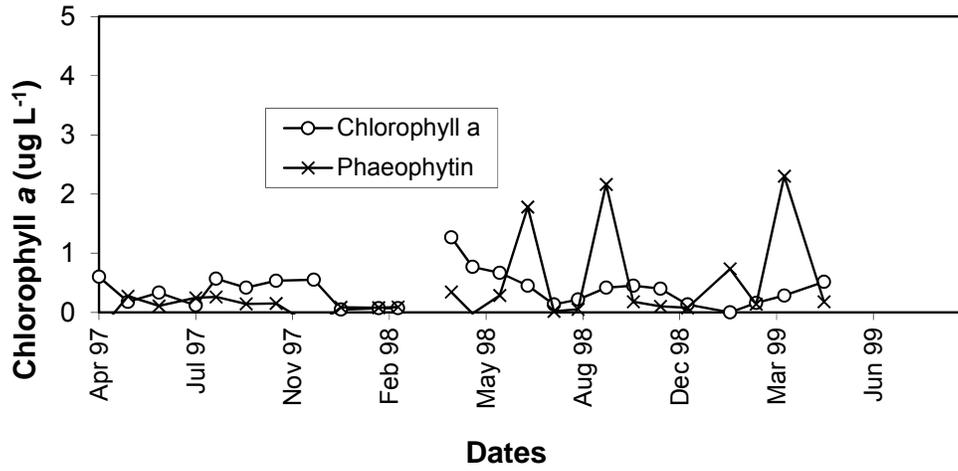
**Figure 40.** Seasonal changes in a) FRP, b) NOx and c) ammonia in Stockton Lake between 1997 and 1999.

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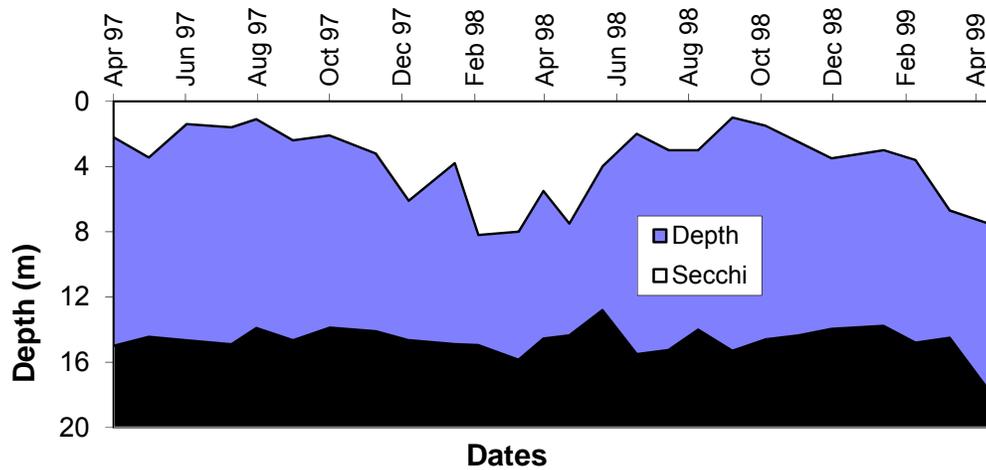
As a result of the many different agents (government, industry and university researchers) involved with the publicly accessible and highly utilised Lake Stockton, there is a very good dataset spanning back at least 18 years for this historic pit lake (Table 11).

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a) Chlorophyll *a*



b) Secchi depth



**Figure 41.** Changes in a) chlorophyll *a* (top and bottom of the water column) and b) Secchi depth (black = bottom, blue = water below Secchi depth) in Stockton Lake

**Table 11.** Mean surface (0 m) water ± standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Stockton. — = no data available for that year.

Parameter	1991	1994	1995	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Temperature (°C)	15.4 (2)	—	—	18.0 ± 1.4 (9)	19.1 ± 1.4 (12)	22.3 ± 1.2 (4)	—	—	—	—	22.9 (2)	20.7 (1)	—	—	20.6 ± 1.3 (12)	24.4 ± 1.8 (6)
pH	4.3 (2)	3.8 ± 0.1 (5)	4.2 (2)	5.4 ± 0.1 (8)	5.5 ± 0.2 (13)	5.6 ± 0.2 (4)	—	—	—	—	4.3 (2)	4.1 (1)	—	—	4.5 ± 0.2 (12)	5.4 ± 0.2 (8)
EC (mS cm <sup>-1</sup> )	0.696 (2)	0.678 ± (5)	0.696 (2)	0.445 ± (8)	0.472 ± (13)	0.498 ± (4)	—	—	—	—	0.475 (2)	0.490 (1)	—	—	0.772 ± (12)	0.469 ± (6)
TDS (mg L <sup>-1</sup> )	—	378.5 (2)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Dissolved oxygen (%)	—	—	—	—	—	—	—	—	—	—	101.7 (1)	—	—	—	—	91.1 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	9.9 (2)	—	—	8.2 ± 0.2 (18)	7.6 ± 0.3 (25)	8.1 ± 0.4 (16)	8.4 ± 0.3 (12)	8.5 ± 0.3 (9)	8.7 ± 0.2 (7)	8.7 ± (4)	8.5 ± (8)	8.5 ± 0.5 (12)	8.6 ± 0.3 (11)	8.3 ± 0.2 (11)	9.0 ± 0.5 (10)	9.1 ± 0.4 (6)
ORP (mV)	—	—	—	—	—	—	—	—	—	—	166 (1)	128 (1)	—	—	—	329 ± 13 (3)
Turbidity (NTU)	—	—	—	—	—	—	—	—	—	—	1.6 (1)	—	—	0.6 (1)	2.1 ± 0.6 (3)	0.3 ± 0.3 (4)
TSS (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	—	—	—	—	9.7 ± 1.9 (3 3)	8.3 ± 1.2 (3)
Chlorophyll a (µg L <sup>-1</sup> )	—	—	<0.1 (0 1)	0.4 ± 0.1 (9)	0.4 ± 0.1 (12)	0.2 ± 0.1 (4)	—	—	—	—	0.3 (1)	—	—	—	—	0.0 (2)
Phaeophytin (µg L <sup>-1</sup> )	—	—	—	0.2 ± 0.0 (7)	0.5 ± 0.2 (11)	0.8 ± 0.5 (4)	—	—	—	—	0.1 (1)	—	—	—	—	—
KdPAR	—	—	—	—	—	—	—	—	—	—	0.17 (2)	—	—	—	—	—
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	54 ± 1 (4)	54 (1)	31 ± 2 (7)	—	—	—	—	—	—	—	—	—	15 (1)	228 ± 51 (9 1)	64 ± 20 (4)
Cl (mg L <sup>-1</sup> )	—	153 (1)	—	—	—	—	—	—	—	—	—	—	—	116 (1)	69 ± 14 (10)	89 ± 12 (4)
TP (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	75 (1)	—	—	—	—	46 ± 3 (3)
FRP (µg L <sup>-1</sup> )	—	—	13 (1)	3 ± 1 (9)	1 ± 0 (12)	1 ± 0 (4)	—	—	—	—	—	—	—	—	—	4 (1 2)
TN (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	—	—	—	100 (1)	250 (2 1)	125 ± 44 (3)

Parameter	1991	1994	1995	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
NO <sub>x</sub> (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	44 ± 3 (3)
NH <sub>4</sub> (µg L <sup>-1</sup> )	—	—	113 (1)	21 ± 4 (9)	16 ± 3 (12)	34 ± 14 (4)	—	—	—	—	—	—	—	—	—	69 ± 43 (3)
NO <sub>3</sub> (µg L <sup>-1</sup> )	—	1 (2)	—	26 ± 6 (9)	8 ± 1 (12)	3 ± 0 (4)	—	—	—	—	—	—	—	—	—	—
DOC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4 ± 2 (3)
DIC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0 (1)
As (µg L <sup>-1</sup> )	—	<100 (0 1)	(0 1)	—	—	—	—	2.5 (1)	—	—	—	0.0 (2 1)	0.5 ± 0.2 (11)	1.0 (1 9)	1.0 (2 8)	64.0 (1 1)
Al (mg L <sup>-1</sup> )	—	0.4 (2)	(0 1)	(5)	(9)	0.0 (1)	—	0.1 (1)	—	—	—	0.2 (1 1)	0.3 ± 0.1 (5)	0.2 ± 0.0 (7 3)	1.4 ± 0.2 (8 4)	0.5 ± 0.2 (5)
Ag (µg L <sup>-1</sup> )	—	—	(0 1)	(6)	(8)	0.01 (1)	—	—	—	—	—	—	—	—	—	—
B (µg L <sup>-1</sup> )	—	20.0 (2)	—	16.3 ± 2.7 (5)	17.5 ± 2.5 (9)	16.1 (1)	—	—	—	—	—	—	—	—	16.7 ± 2.1 (6)	<50 (0 2)
Ba (µg L <sup>-1</sup> )	—	50.0 (2)	—	45.1 ± 10.0 (6)	48.6 ± 3.2 (9)	47.6 (1)	—	—	—	—	—	—	—	—	—	—
Be (µg L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	—	—	—	<0.5 (0 1)	<10 (0 10)	—
Ca (mg L <sup>-1</sup> )	—	6.0 ± 0.0 (4)	7.7 (1)	2.5 ± 0.3 (5)	2.2 ± 0.3 (9)	2.1 (1)	—	—	—	—	—	—	—	2.0 (1)	2.6 ± 0.2 (10)	2.1 (2)
Cd (µg L <sup>-1</sup> )	—	<2 (0 2)	(0 1)	<3 (6)	0.0 ± 0.0 (8)	0.0 (1)	—	5.0 (1)	—	—	—	<1 (0 1)	1.0 ± 0.0 (6)	2.0 (2 7)	0.2 ± 0.0 (3 6)	0.1 (1 2)
Co (µg L <sup>-1</sup> )	—	<50 (0 2)	—	2.7 ± 0.3 (5)	2.7 ± 0.4 (9)	2.6 (1)	—	—	—	—	—	—	—	<10 (0 1)	<10 (0 10)	33.0 (1 1)
Cr (µg L <sup>-1</sup> )	—	<20 (0 2)	(0 1)	<2 (5)	4.5 ± 0.5 (5)	5.3 ± 0.5 (9)	5.2 (1)	—	5.0 (1)	—	—	<1 (0 1)	1.0 ± 0.0 (6)	1.0 (1 8)	<1 (0 9)	<1 (0 3)
Cs (µg L <sup>-1</sup> )	—	—	—	(5)	0.2 ± 0.0 (9)	0.2 (1)	—	—	—	—	—	—	—	—	—	—
Cu (µg L <sup>-1</sup> )	—	<20 (0 2)	(0 1)	<100 (5)	11.8 ± 7.5 (5)	2.2 ± 0.3 (9)	2.4 (1)	—	5.0 (1)	—	—	0.01 (2 1)	6.4 ± 2.0 (11)	15.0 (2 8)	<1 (0 12)	<10 (0 3)
Fe (mg L <sup>-1</sup> )	—	0.7 ± 0.4 (4)	<1 (0 1)	<1 (14)	0.2 ± 0.1 (22)	0.1 ± 0.0 (13)	0.2 ± 0.0 (12)	0.1 ± 0.0 (9)	0.1 ± 0.0 (7)	0.2 ± 0.1 (4)	0.3 ± 0.1 (7)	0.1 ± 0.0 (13)	0.2 ± 0.1 (11)	0.1 ± 0.0 (6 3)	0.3 ± 0.0 (8 1)	0.1 ± 0.0 (3 2)

Parameter	1991	1994	1995	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Hg ( $\mu\text{g L}^{-1}$ )	—	<0.5 (0 1)	<0.5 (0 1)	—	—	—	—	—	—	—	—	—	—	—	—	<100 (0 2)
K (mg L <sup>-1</sup> )	—	5.5 ± 0.3 (4)	—	2.1 ± 0.3 (5)	2.0 ± 0.3 (9)	1.9 (1)	—	—	—	—	—	—	—	4.8 (1)	5.2 ± 0.1 (3)	3.0 (1 1)
Li ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Mg (mg L <sup>-1</sup> )	—	15 ± 0 (4)	14 (1)	6 ± 1 (6)	8 ± 1 (9)	8 (1)	—	—	—	—	—	10 (1)	—	7 (1)	14 ± 2 (10)	6 (2)
Mn ( $\mu\text{g L}^{-1}$ )	—	330 ± 0 (4)	300 (1)	58 ± 7 (14)	66 ± 7 (22)	56 ± 6 (13)	84 ± 7 (12)	110 ± 19 (9)	86 ± 15 (7)	133 ± 9 (4)	123 ± 5 (7)	87 ± 10 (9)	155 ± 88 (11)	60 ± 5 (9 1)	35 ± 8 (11 1)	113 ± 15 (3 1)
Mo ( $\mu\text{g L}^{-1}$ )	—	<100 (0 1)	—	—	—	—	—	—	—	—	—	—	—	<5 (0 1)	<10 (0 10)	—
Na (mg L <sup>-1</sup> )	—	85 ± 1 (4)	—	43 ± 12 (5)	40 ± 10 (7)	—	—	—	—	—	—	—	—	60 (1)	64 ± 1 (4)	25 (2)
Ni ( $\mu\text{g L}^{-1}$ )	—	<20 (0 2)	<20 (0 1)	2.8 ± 0.2 (5)	2.7 ± 0.4 (9)	2.7 (1)	—	10.0 (1)	—	—	—	<30 (0 1)	30.0 ± 0.0 (6)	30.0 (1 9)	20.0 (1 11)	47.7 ± 17.8 (3)
P ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Pb ( $\mu\text{g L}^{-1}$ )	—	—	—	9.8 ± 7.0 (7 3)	17.7 ± 14.1 (7 6)	12.3 (2 1)	71.7 ± 24.7 (6 6)	<10 (0 8)	<10 (0 7)	<100 (0 2)	—	100.0 (1)	—	—	23.7 ± 0.7 (3 1)	<100 (0 1)
S (mg L <sup>-1</sup> )	—	—	—	—	21 (2)	153 (2)	76 (2)	—	—	—	—	5 (1)	—	—	95 ± 14 (4)	45 (1)
Sb ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	1.00 (1)	—	—	—	—	—	—	—	—	<1 (0 3)	—
Se ( $\mu\text{g L}^{-1}$ )	—	—	—	—	<200 (0 2)	1.0 (1 1)	200.0 (2)	—	—	—	—	200.0 (1)	—	—	200.0 (1 3)	<200 (0 1)
Si (mg L <sup>-1</sup> )	—	—	—	—	—	4.9 (1)	—	—	—	—	—	—	—	—	4.9 ± 0.0 (3)	—
SiO <sub>2</sub> (mg L <sup>-1</sup> )	—	—	—	9 (1)	11 (1)	6 (1)	5 (2)	3 (1)	—	—	—	—	—	—	7 ± 1 (4)	—
Sn ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	1.00 (1)	—	—	—	—	—	—	—	—	<1 (0 3)	—
Sr ( $\mu\text{g L}^{-1}$ )	—	—	—	50.5 ± 5.0 (6)	72.9 ± 16.9 (8)	245.7 (2)	—	165.0 ± 8.5 (6)	171.7 ± 6.0 (6)	—	—	—	—	—	436.7 ± 3.3 (3)	—
Ti ( $\mu\text{g L}^{-1}$ )	—	—	—	—	0.2 (1)	<5 (0 1)	—	—	—	—	—	—	—	—	<5 (0 3)	—
U ( $\mu\text{g L}^{-1}$ )	—	—	—	0.0 ± 0.0 (3)	58.2 ± 46.4 (4)	176.0 (2)	666.2 (2)	—	—	—	—	101.0 (1)	—	—	1156.6 (1)	<5 (0 1)
V ( $\mu\text{g L}^{-1}$ )	—	—	—	—	5.5 ± 2.6 (4 4)	1.0 (1)	—	<2 (0 7)	<10 (0 6)	—	—	—	—	—	1.5 (2 2)	—

Parameter	1991	1994	1995	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Zn ( $\mu\text{g L}^{-1}$ )	—	—	—	70.0 ± 11.7 (10)	71.0 ± 17.1 (14 1)	767.9 ± 460.2 (3)	395.2 ± 92.3 (6)	32.9 ± 11.3 (7)	28.6 ± 8.6 (7)	10.0 (1 1)	—	50.0 (1)	—	—	373.3 ± 74.4 (9)	117.0 (1)

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### 4.3 New Premier Sub-Basin Lakes

Chicken Creek was mined from 1981 by Griffin Coal Mining Company until 1996 (Nguyen 2004). Backfilling left two voids that became pit lakes; Chicken Creek 4 and Chicken Creek 5. Neither lake has been rehabilitated, although in 2002, a constructed wetland was built adjacent to Chicken Creek 4. This aimed to treat water pumped from the lake, by passing through fluidized limestone treatment system before discharging to the constructed wetland for polishing. Issues associated with the fluidized limestone treatment system ensured the system never ran properly. It was later abandoned when the Collie River Diversion Project commenced in 2005 and finished in 2007. Water was pumped from the Collie River and stored in Chicken Creek 4. Pumping was timed to collect the most saline water in the river, and thereby reduce the salt load entering Wellington Dam. Chicken Creek 5 will be dewatered in 2010 to permit Wesfarmers Premier to mine on their lease nearby. It is likely that Chicken Creek 4 will also be dewatered, however the Department of Water will need to deal with the acidic and now salty water.

**Table 12.** Physical features of the new Premier sub-basin pit lakes.

Lake	Area (Ha)	Perimeter (m)	Maximum Depth (m)
Chicken Creek 4	21.6	2690	41
Chicken Creek 5	15.5	2000	NA

#### Chicken Creek 4

Chicken Creek 4 has a surface area of approximately 40 ha and a maximum depth of 41 m (Figure 42). The steep walls and adjacent large piles of over/inter-burden shelter the lake from wind, but also likely contribute to high loads of acidity in surface runoff waters. No remediation attempts have been made on the overburden around the lake, hence the barren visage. There are plans to re-mine this lake in the future. It is currently managed by the Griffin Coal Mining Company Ltd. A wetland was constructed next to the lake in 2002, to treat water from the lake firstly by fluidized limestone and then through an aerobic processes. This wetland formed a research location for the Centre for Sustainable Mine Lakes. In 2007, the wetland was abandoned (Figure 43).



**Figure 42.** Chicken Creek 4 (02/2006) looking west.



**Figure 43.** Aerial photograph of Chicken Creek 4 pit lake (taken from Google Earth, imagery dated 2009) (top of picture is north).

4.3.1.1 *Trends in water quality*

Although Chicken Creek 4 has not been monitored for long (only since 2004), this monitoring period represents a large part of this pit lake's existence (Table 13). The monitoring dataset is also reasonably robust with numerous sampling occasions. This good dataset is largely the result of extensive government data collections as part of the saline diversion strategy for the Collie River.

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**Table 13.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Chicken Creek 4. — = no data available for that year.

Parameter	2004	2005	2006	2007	2008	2009
Temperature (°C)	20.1 (2)	16.5 $\pm$ 1.5 (4)	16.9 $\pm$ 0.0 (17)	15.8 $\pm$ 0.3 (20)	21.1 (2)	21.1 $\pm$ 1.1 (3)
pH	3.1 (2)	2.6 $\pm$ 0.0 (4)	2.8 $\pm$ 0.0 (17)	5.7 $\pm$ 0.2 (20)	4.0 (2)	4.0 $\pm$ 0.3 (3)
EC (mS cm <sup>-1</sup> )	2.535 (2)	—	—	—	6.800 (2)	7.447 $\pm$ 0.075 (3)
Salinity (ppt)	1.4 (2)	—	—	—	—	—
TDS (mg L <sup>-1</sup> )	1,620	—	—	—	4,350	4,760
Dissolved oxygen (%)	96.2 (1)	—	—	—	—	101.7 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	9.3 (1)	—	8.5 $\pm$ 0.2 (27)	8.2 $\pm$ 0.2 (28)	7.9 $\pm$ 0.4 (3)	8.7 (2)
ORP (mV)	372 (2)	—	—	—	—	423 (2)
Turbidity (NTU)	11.4 (1)	8.3 $\pm$ 1.7 (3)	3.7 $\pm$ 0.3 (6)	5.9 $\pm$ 2.0 (4)	1.3 $\pm$ 0.2 (3)	1.2 (2)
TSS (mg L <sup>-1</sup> )	—	4.7 $\pm$ 0.7 (3)	1.3 $\pm$ 0.2 (6)	3.3 $\pm$ 1.9 (3)	11.0 (2)	10.0 (1)
Chlorophyll a ( $\mu$ g L <sup>-1</sup> )	—	0.0 $\pm$ 0.0 (3)	0.001 $\pm$ 0.0 (5 1)	0.001 (1 2)	—	0.0 (2)
Chlorophyll b ( $\mu$ g L <sup>-1</sup> )	—	<0.001 (0 3)	<0.001 (0 6)	<0.001 (0 3)	—	—
Chlorophyll c ( $\mu$ g L <sup>-1</sup> )	—	<0.001 (0 3)	0.001 (1 5)	0.001 (1 2)	—	—
Phaeophytin ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—
KdPAR	0.40 (2)	—	—	—	—	—
Alkalinity	—	—	—	—	—	—
Acidity	—	—	—	—	—	—
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	287 $\pm$ 7 (3)	288 $\pm$ 9 (7)	223 $\pm$ 30 (5)	210 $\pm$ 5 (4)	221 (2)
Cl (mg L <sup>-1</sup> )	—	980 $\pm$ 0 (3)	1691 $\pm$ 335 (7)	2541 $\pm$ 180 (4)	2338 $\pm$ 8 (4)	1410 (2)
TP ( $\mu$ g L <sup>-1</sup> )	—	237 $\pm$ 77 (3)	6 $\pm$ 0 (3 3)	6 $\pm$ 1 (3)	—	67 (2)
FRP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	16 (2)
TN ( $\mu$ g L <sup>-1</sup> )	—	380 $\pm$ 40 (3)	368 $\pm$ 35 (6)	595 $\pm$ 32 (4)	433 $\pm$ 176 (3)	477 (2)
NO <sub>x</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	61 (2)
NH <sub>4</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	336 (2)

Parameter	2004	2005	2006	2007	2008	2009
NO <sub>3</sub> (µg L <sup>-1</sup> )	—	—	—	—	—	—
DOC (mg L <sup>-1</sup> )	—	—	—	—	—	2 (2)
DIC (mg L <sup>-1</sup> )	—	—	—	—	—	0 (1)
As (µg L <sup>-1</sup> )	10.0 (1)	<1 (0 3)	1.1 ± 0.5 (18 6)	4.0 ± 3.0 (3 14)	<1 (0 4)	80.0 (1 1)
Al (mg L <sup>-1</sup> )	18.0 (1)	14.0 ± 0.6 (3)	10.3 ± 0.8 (17)	7.9 ± 0.9 (29)	2.8 ± 0.5 (7)	4.9 ± 0.8 (3)
Ag (µg L <sup>-1</sup> )	—	<1 (0 3)	2.00 (1 5)	<1 (0 3)	—	—
B (µg L <sup>-1</sup> )	49.0 (1)	23.0 ± 0.6 (3)	33.0 ± 0.8 (6)	9.0 (1 2)	—	<5 (0 2)
Ba (µg L <sup>-1</sup> )	—	64.7 ± 0.3 (3)	82.0 ± 5.1 (6)	94.3 ± 5.2 (3)	—	—
Be (µg L <sup>-1</sup> )	—	—	—	660.0 (1 1)	1.0 ± 0.1 (4)	—
Ca (mg L <sup>-1</sup> )	—	32.7 ± 0.3 (3)	63.1 ± 11.3 (7)	81.9 ± 21.9 (5)	84.3 ± 5.6 (4)	79.6 (2)
Cd (µg L <sup>-1</sup> )	1.6 (1)	1.2 ± 0.0 (3)	3.7 ± 2.3 (17)	1.2 ± 0.3 (8 7)	<1 (0 4)	<10 (0 3)
Co (µg L <sup>-1</sup> )	170.0 (1)	110.0 ± 0.0 (3)	91.8 ± 12.9 (6)	35.5 ± 12.7 (4 1)	62.5 ± 7.5 (4)	63.5 (2)
Cr (µg L <sup>-1</sup> )	—	4.0 ± 0.0 (3)	5.2 ± 2.5 (16 1)	2.3 ± 0.8 (6 9)	<1 (0 4)	<10 (0 3)
Cs (µg L <sup>-1</sup> )	—	—	—	—	—	—
Cu (µg L <sup>-1</sup> )	19.0 (1)	11.7 ± 0.3 (3)	8.6 ± 1.7 (25)	18.7 ± 3.7 (12 5)	16.7 ± 6.7 (3 4)	<10 (0 2)
Fe (mg L <sup>-1</sup> )	11.0 (1)	5.7 ± 0.1 (3)	2.5 ± 0.4 (34)	2.7 ± 0.4 (30)	1.1 ± 0.2 (4)	2.9 ± 0.8 (3)
Hg (µg L <sup>-1</sup> )	—	—	—	<1 (0 3)	—	<100 (0 2)
K (mg L <sup>-1</sup> )	—	4.7 ± 0.1 (3)	4.9 ± 0.7 (7)	2.6 ± 0.7 (5)	3.7 ± 0.0 (3)	3.4 (2)
Li (µg L <sup>-1</sup> )	—	—	—	—	—	—
Mg (mg L <sup>-1</sup> )	63 (1)	120 ± 0 (3)	218 ± 25 (7)	233 ± 61 (5)	267 ± 3 (4)	247 (2)
Mn (µg L <sup>-1</sup> )	770 (1)	450 ± 6 (3)	354 ± 20 (34)	298 ± 20 (30 1)	141 ± 5 (7)	239 ± 31 (3)
Mo (µg L <sup>-1</sup> )	—	<1 (0 3)	5.0 (1 6)	271.0 (1 4)	<5 (0 4)	—
Na (mg L <sup>-1</sup> )	—	460 ± 6 (3)	703 ± 111 (7)	1046 ± 64 (5)	1000 ± 9 (4)	878 (2)
Ni (µg L <sup>-1</sup> )	200.0 (1)	123.3 ± 3.3 (3)	106.4 ± 8.5 (17)	111.9 ± 13.0 (15 2)	64.3 ± 5.7 (7)	80.7 ± 17.8 (3)
P (µg L <sup>-1</sup> )	—	—	—	—	—	—
Pb (µg L <sup>-1</sup> )	2.5 (1)	1.0 (1)	5.3 ± 3.7 (27 11)	5210.8 ± 5200.0 (18 23)	—	1.0 (1 1)

Parameter	2004	2005	2006	2007	2008	2009
S (mg L <sup>-1</sup> )	—	—	98 ± 1 (3)	100 ± 9 (7)	—	236 (1)
Sb (µg L <sup>-1</sup> )	—	—	1.00 (2 1)	1.00 (2 2)	—	—
Se (µg L <sup>-1</sup> )	—	—	67.3 ± 66.3 (3 1)	51.0 ± 49.7 (4 3)	—	<200 (0 1)
Si (mg L <sup>-1</sup> )	—	—	4.6 ± 0.1 (3)	3.9 ± 0.7 (3)	—	—
SiO <sub>2</sub> (mg L <sup>-1</sup> )	—	—	10 ± 0 (3)	9 ± 1 (20)	—	10 (1)
Sn (µg L <sup>-1</sup> )	—	—	1.00 (2 1)	1.00 (2 2)	—	—
Sr (µg L <sup>-1</sup> )	—	—	678.1 ± 191.9 (4)	621.5 ± 137.9 (5)	—	—
Ti (µg L <sup>-1</sup> )	—	—	3.4 ± 1.6 (3 1)	3.5 ± 1.5 (3 2)	—	—
U (µg L <sup>-1</sup> )	—	—	727.3 (1)	682.2 ± 287.9 (3)	—	123.4 (1)
V (µg L <sup>-1</sup> )	—	—	1.2 ± 0.4 (5 1)	1.6 ± 0.2 (5 16)	—	2.0 (1)
Zn (µg L <sup>-1</sup> )	20.0 (1)	33.3 ± 3.3 (3)	184.6 ± 44.2 (37)	227.6 ± 44.1 (40)	—	210.5 (2)

#### **4.3.2 Chicken Creek 5**

Chicken Creek 5 is a new Griffin Coal Mining Company Pty. Ltd. pit lake in the Muja sub-basin that is not rehabilitated (Figure 44). As a result, it has a very limited catchment which contains a large amount of waste rock. It will be dewatered in around 2010 to facilitate mining in Wesfarmers' Premier pit operation adjacent to the north (Figure 45).



**Figure 44.** Chicken Creek 5 (11/2009) looking south-west.



**Figure 45.** Aerial photograph of Chicken Creek 5 pit lake (taken from Google Earth, imagery dated 2009) (top of picture is north).

4.3.2.1 *Long term changes in surface water quality*

The pH of Chicken Creek 5 Lake was initially about pH 3.0 in data from 2008–2009 (Table 14). The EC and Cl concentration from 2007 to 2009 were high compared to other lakes. The concentration of uranium is reasonably high (Table 14).

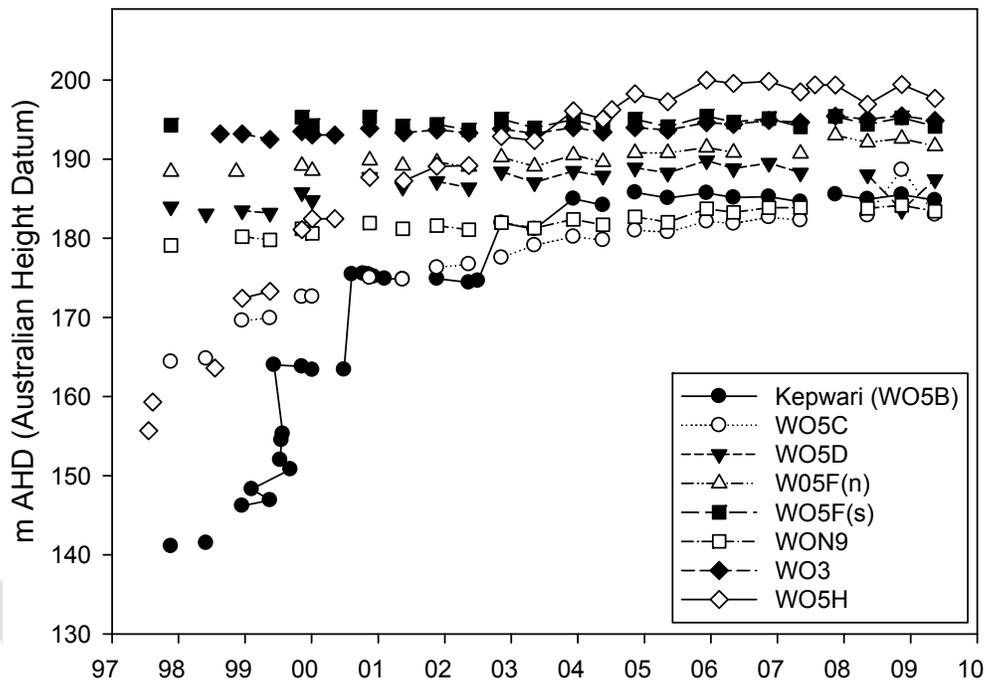
**Table 14.** Mean surface (0 m) water ± standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Chicken Creek 5. — = no data available for that year.

Parameter	1997	2006	2007	2008	2009
Temperature(°C)	—	—	—	22.8 (2)	21.8 (2)
pH	—	—	—	2.9 (2)	2.9 (2)
EC (mS cm <sup>-1</sup> )	—	—	—	2.060 (2)	2.860 (2)
Dissolved oxygen (%)	—	—	—	—	119.3 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	—	8.3 ± 0.2 (4)	8.7 ± 0.3 (8)	7.9 (1)	10.3 (2)
ORP (mV)	—	—	—	—	490 (2)
Turbidity (NTU)	—	—	1.5 (1)	1.0 (1)	0.0 (2)
TSS (mg L <sup>-1</sup> )	—	—	—	9.5 (2)	—
Chlorophyll a (µg L <sup>-1</sup> )	—	—	—	—	0.0 (2)
SO <sub>4</sub> (mg L <sup>-1</sup> )	79 (2)	—	336 (1)	349 ± 3 (8)	506 (2)
Cl (mg L <sup>-1</sup> )	—	—	555 (1)	564 ± 5 (8)	403 (2)
TP (µg L <sup>-1</sup> )	—	—	—	—	50 (2)
FRP (µg L <sup>-1</sup> )	—	—	—	—	19 (2)
TN (µg L <sup>-1</sup> )	—	—	1100 (1)	1800 (2)	1389 (2)
NO <sub>x</sub> (µg L <sup>-1</sup> )	—	—	—	—	76 (2)
NH <sub>4</sub> (µg L <sup>-1</sup> )	—	—	—	—	1085 (2)
DOC (mg L <sup>-1</sup> )	—	—	—	—	7 (2)
DIC (mg L <sup>-1</sup> )	—	—	—	—	0 (1)
As (µg L <sup>-1</sup> )	—	1.0 ± 0.0 (4)	1.5 (2 6)	<1 (0 8)	<50 (0 2)
Al (mg L <sup>-1</sup> )	1.1 (2)	10.0 ± 0.3 (4)	10.1 ± 0.2 (8)	9.9 ± 0.3 (11)	8.6 (2)
B (µg L <sup>-1</sup> )	—	—	—	138.6 ± 24.3 (7)	<50 (0 2)
Be (µg L <sup>-1</sup> )	—	—	6.1 (1)	5.9 (1)	—
Ca (mg L <sup>-1</sup> )	11.5 (2)	—	17.1 (1)	17.8 ± 0.1 (8)	64.8 (2)
Cd (µg L <sup>-1</sup> )	—	3.3 ± 0.3 (4)	3.0 ± 0.4 (7)	4.9 ± 0.8 (9 1)	<10 (0 2)

Parameter	1997	2006	2007	2008	2009
Co ( $\mu\text{g L}^{-1}$ )	—	—	110.0 (1)	120.0 (1)	94.0 (2)
Cr ( $\mu\text{g L}^{-1}$ )	—	3.3 $\pm$ 0.3 (4)	3.0 $\pm$ 0.4 (7)	4.9 $\pm$ 0.8 (9 1)	<10 (0 2)
Cs ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—
Cu ( $\mu\text{g L}^{-1}$ )	—	17.5 $\pm$ 4.8 (4)	23.3 $\pm$ 3.3 (3 5)	35.7 $\pm$ 8.1 (7 4)	<50 (0 1)
Fe (mg L <sup>-1</sup> )	14.5 (2)	11.4 $\pm$ 0.1 (4)	10.1 $\pm$ 1.7 (7)	10.5 $\pm$ 0.5 (10)	9.7 (2)
Hg ( $\mu\text{g L}^{-1}$ )	—	—	—	—	<100 (0 2)
K (mg L <sup>-1</sup> )	5.0 (2)	—	—	7.2 (1)	4.6 (2)
Mg (mg L <sup>-1</sup> )	16 (2)	—	68 (1)	73 $\pm$ 1 (8)	217 (2)
Mn ( $\mu\text{g L}^{-1}$ )	495 (2)	710 $\pm$ 6 (4)	748 $\pm$ 7 (8)	704 $\pm$ 13 (11)	668 (2)
Mo ( $\mu\text{g L}^{-1}$ )	1100.0 (2)	—	<5 (0 1)	<5 (0 1)	—
Na (mg L <sup>-1</sup> )	200 (2)	—	300 (1)	317 (1)	606 (2)
Ni ( $\mu\text{g L}^{-1}$ )	—	135.0 $\pm$ 2.9 (4)	136.3 $\pm$ 7.1 (8)	155.5 $\pm$ 9.6 (11)	166.5 (2)
Pb ( $\mu\text{g L}^{-1}$ )	—	—	10.0 $\pm$ 4.2 (4 1)	44.1 $\pm$ 15.5 (10 1)	<100 (0 1)
S (mg L <sup>-1</sup> )	—	—	—	—	354 (1)
Se ( $\mu\text{g L}^{-1}$ )	—	—	—	—	<200 (0 1)
SiO <sub>2</sub> (mg L <sup>-1</sup> )	—	13 (1)	12 $\pm$ 1 (3)	19 $\pm$ 0 (3)	—
U ( $\mu\text{g L}^{-1}$ )	—	—	—	—	<50 (0 1)
V ( $\mu\text{g L}^{-1}$ )	—	—	—	2.0 (1 2)	—
Zn ( $\mu\text{g L}^{-1}$ )	—	1035.0 (2)	720.0 $\pm$ 130.7 (5)	560.0 $\pm$ 9.6 (11)	388.5 (2)

#### 4.4 Cardiff sub-basin Lakes

All Cardiff sub-basin pit lakes have filled reasonably rapidly after decommissioning (Figure 46). Not surprisingly, rapid-filled lakes such as Lake Kepwari filled by a river diversion have filled within only a few years. Observations before and after the 2009 winter of at least one of these lakes, WO5D, suggest that surface run-off may super-charge lake heights, at least for short periods of time. However, there is also opportunity for lake height increases above those currently considered stable even if not responding directly to groundwater levels changes, if prevailing rainfall patterns change in lakes where there is significant catchment for lake surface area (Table 15).



**Figure 46.** Water levels at completed open cut Cardiff sub-basin mines (Wesfarmers)

**Table 15.** Physical features of the Cardiff sub-basin Collie pit lakes, current area and perimeter estimated from Google Earth, other data provided by Wesfarmers Premier Ltd.

Lake	Area (Ha)	Perimeter (m)	Maximum Depth (m)	Volume (m <sup>3</sup> )
Kepwari	98.5 (includes Island of 0.7 Ha)	5470	65	24,000,000
Lake WON9	7.8 (max. 13.7)	1140	33	1,076,134 (2007), 2,079,030 (max.)
Lake WO3	4.7	1200		-
WO5C	14.2 (max. 35)	2340	49	1,931,905 (2007), 6,165,576 (max.)
WO5D	5.5 (max. 8.6)	1480	22	189,863 (2007), 1,907,358 (max.)
WO5F	-	-	-	-
WO5H	43.5 (max. 43.7)	2840	80.8	10,199,076 (2008), 11,099,500 (max.)

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**Figure 47.** WO5D Lake in April (a) and November (b) showing increase in water level following heavy 2009 winter rains (looking west).

Although a single smaller pit lake, WO3, is older than the main historic lakes, pit lakes formed by Premier Coal mining activities in the Cardiff sub-basin are otherwise all less than 20 years old (Table 16). Most lakes have been groundwater filled as per the historic lakes. However, both WO5B (Kepwari) and WO5H have been rapid filled to at least some extent, in addition to significant groundwater contributions.

**Table 16.** Cardiff sub-basin pit decommissioning dates.

Pit Lake	Mining ceased	Rapid fill?	High water level reached?	Final Water Level (m AHD)	Water Level June 2009 (m AHD)	Mechanism for Rapid Fill
WON9	1991	No	No	200	183.4	Not applicable
WO3	1954–1959	No	Yes	ass195	195	Not applicable
WO5B (Kepwari)	June 1996	1999–2004	Yes	190	185	Collie River South Branch diversion
WO5C	1996	No	No	196	183	Not applicable
WO5D	1996	No	Yes	186	187.4	Not applicable
WO5F	1994	No	Yes	193	192	Not applicable
WO5H	1986–1997	1997–2004	Yes	199	198	Sump A / Pit 4 surface runoff

#### 4.4.1 WO5B (Lake Kepwari)

Mining ceased in WO5B in 1997, the mine is situated in the Cardiff sub-basin and is larger than Chicken Creek 4 and 5 Lakes. The overburden around the edges has been extensively revegetated with native plants and the lake has been flagged as a recreation resource (SWDC 2001). It is owned and managed by Wesfarmers Premier Coal. The pit lake was renamed Lake Kepwari to facilitate its acceptance by the community (Figure 48).

The volume of Lake Kepwari is now  $3.2 \times 10^7 \text{ m}^3$ , with a maximum depth of 65 m and surface area of  $1.03 \text{ km}^2$ . During research into the geochemistry of lake filling, a lake diagnostic system (LDS) was installed in the lake in October 2003 to investigate physical processes and validate predictive geochemical models (Salmon *et al.*, 2008). Lake Kepwari typically had a pH of between 4.3 and 5 during this time.

Prior to filling with water, reactive overburden dumps and exposed coal seams were covered with waste rock, battered and revegetated with endemic flora by direct seeding (Figure 49). In order to further reduce wall exposure and rates of resulting acid production, the lake was rapid-filled by a diversion from the South Branch of the Collie River over three winters until 2005 (Oldham *et al.*, in press). The proposed end use for this pit lake was contact recreation such as water skiing (Evans & Ashton, 2000). Although the river water initially raised water pH, it has now returned to 4.8 with elevated metal concentrations (Salmon *et al.*, 2008). Although the relatively high water quality of the pit lake potentially lends itself to a range of end uses, low pH and high Al concentrations still remain a challenge to remediate (Lund & McCullough, 2009; Neil *et al.*, 2009, submitted). Increasing pressure from the Collie community continues to pressure state government to encourage and support development of recreational activity infrastructure in spite of a current failure to meet Australian bathing guidelines (ANZECC/ARMCANZ, 2000d). This pit lake is a good example of community supported rehabilitation, but a lack of understanding of below-water processes (in this case suspected intrusion of ferrous iron) has resulted in water quality unsuited to the currently proposed end-use.



**Figure 48.** Lake Kepwari looking south (09/2009).



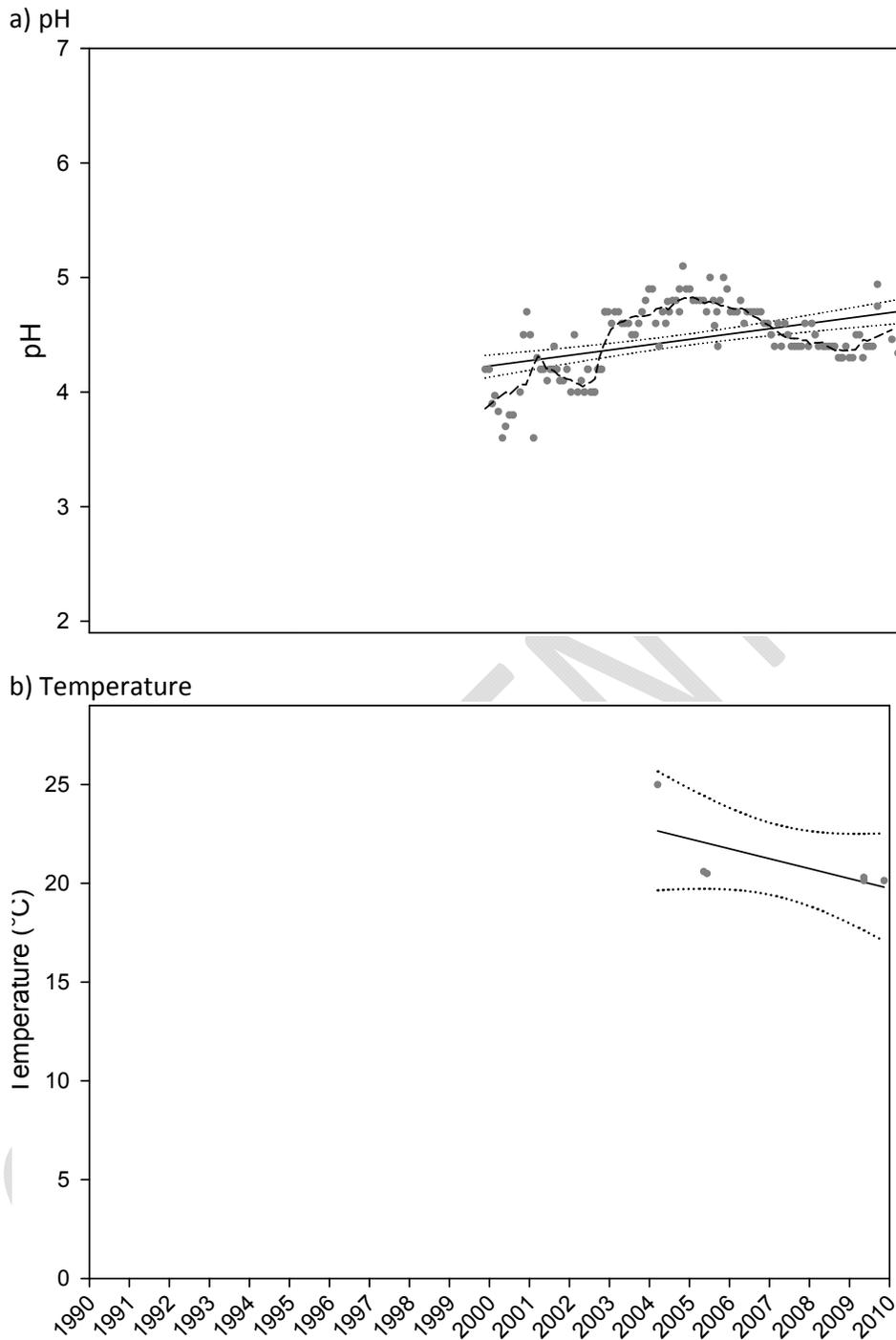
**Figure 49.** Aerial photograph of Lake Kepwari (taken from Google Earth, imagery dated 2009) (top of picture is north).

4.4.1.1 *Long term changes in surface water quality*

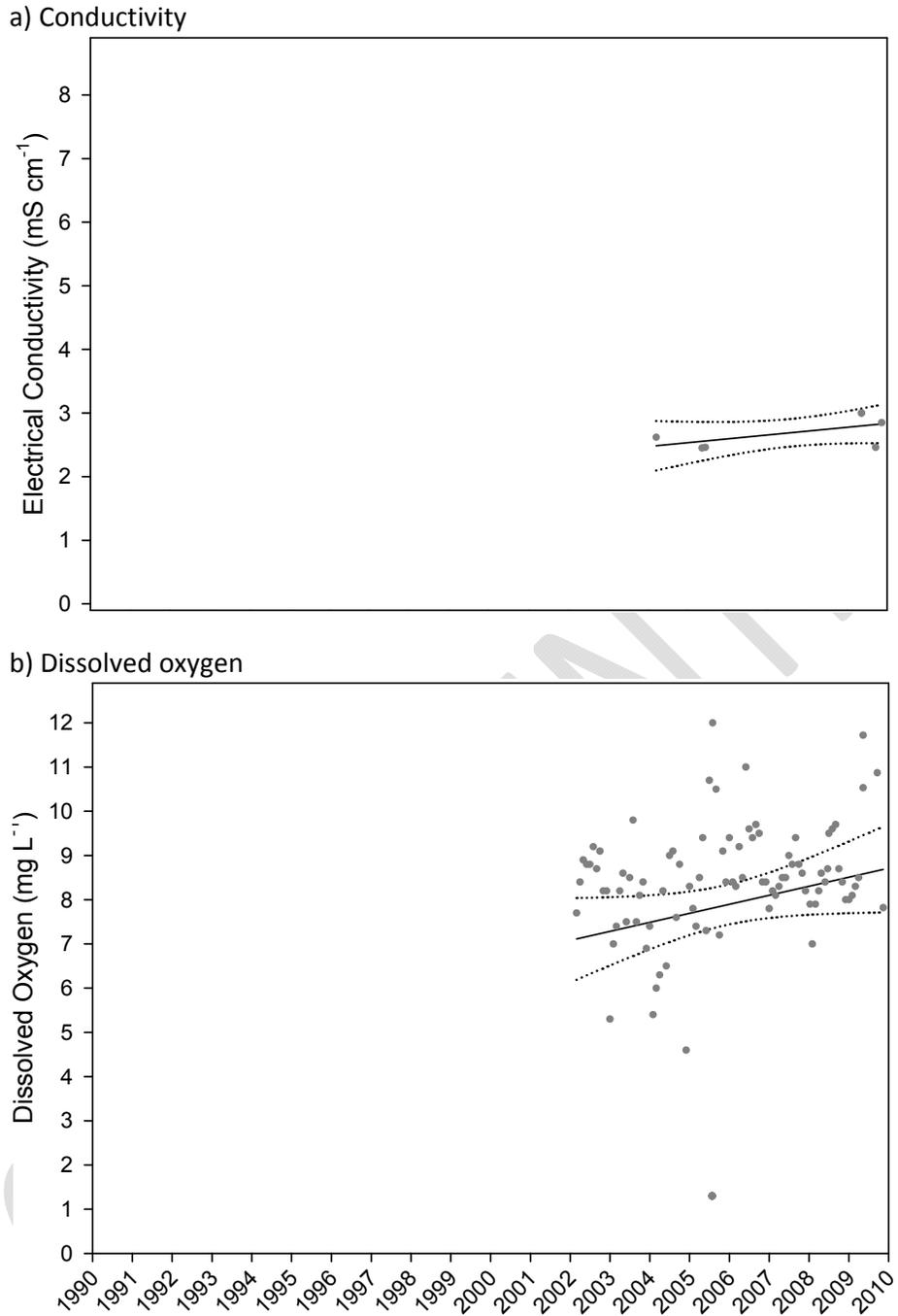
The pH of Lake Kepwari has remained steady between 4.0 and 5.0 for the last ten years. However, although pH in Lake Kepwari since initial groundwater filling began in 2000 has shown an increase, this trend is much more complex than the simple linear regression would suggest (Figure 50a) ( $n = 130$ ,  $r^2 = 0.20$ ). A smoothed trendline more accurately shows the pattern of pH increase as Collie River water was diverted in to fast fill the pit; with a decrease in pH after 2007 when river water diversion ceased. It is thought that groundwater inflows, dominant in ferrous iron, began to dominate pit lake inflow hydrology at this time, leading to a consumption of alkalinity introduced with river water and a consequent decrease in pH.

The Lake Kepwari temperature shows no significant ( $P > 0.05$ ) trend, but is based upon a very small dataset ( $n = 5$ ,  $r^2 = 0.42$ ) as the emphasis on lake Kepwari data collection has been for pH data alone (Figure 50b). Electrical conductivity in Lake Kepwari is also based on a very small dataset ( $n = 6$ ,  $r^2 = 0.30$ ) but shows no significant trends ( $P > 0.05$ ) (Figure 51a). Dissolved oxygen showed a weak but significant ( $P < 0.05$ ) increase over time ( $n = 99$ ,  $r^2 = 0.20$ ) (Figure 51b).

Lake Kepwari has one of the longest and most contiguous data sets of all the pit lakes, however on close inspection it is still relatively poor in terms of sufficient detail to adequately understand the impact of rapid fill and ultimately its suitability for human recreation (Table 17).



**Figure 50.** Long term changes in (a) surface water pH and (b) temperature in Lake Kepwari. Grey dots represent individual sample points, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.



**Figure 51.** Long term changes in surface water electrical conductivity (a) and dissolved oxygen (b) in Lake Kepwari. Grey dots represent individual sample points, solid line represents linear regression and dotted line represents 95% confidence interval. 1991 sampling events not included in regression line calculation.

**Table 17.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in Lake Kepwari. — = no data available for that year.

Parameter	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Temperature (°C)	—	—	—	—	—	25.0 (1)	20.6 (2)	—	—	—	20.1 (2)
pH	4.1 $\pm$ 0.1 (4)	4.0 $\pm$ 0.1 (11)	4.2 $\pm$ 0.0 (13)	4.3 $\pm$ 0.1 (19)	4.6 $\pm$ 0.0 (12)	4.8 $\pm$ 0.0 (14)	4.8 $\pm$ 0.0 (14)	4.6 $\pm$ 0.0 (12)	4.5 $\pm$ 0.0 (11)	4.4 $\pm$ 0.0 (13)	4.5 $\pm$ 0.1 (7)
EC (mS cm <sup>-1</sup> )	—	—	—	—	—	2.620 (1)	2.455 (2)	—	—	—	2.770 $\pm$ 0.161 (3)
TDS (mg L <sup>-1</sup> )	1185 $\pm$ 56 (4)	1249 $\pm$ 65 (11)	1245 $\pm$ 14 (12)	1326 $\pm$ 32 (19)	1549 $\pm$ 31 (12)	1620 $\pm$ 27 (12)	1595 $\pm$ 33 (12)	1532 $\pm$ 38 (12)	1502 $\pm$ 26 (11)	1551 $\pm$ 19 (13)	1611 $\pm$ 67 (4)
Dissolved oxygen (%)	—	—	—	—	—	—	—	—	—	—	99.3 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	—	—	—	8.3 $\pm$ 0.3 (11)	7.9 $\pm$ 0.2 (12)	7.3 $\pm$ 0.5 (11)	5.9 $\pm$ 0.9 (20 2)	9.0 $\pm$ 0.3 (12)	8.6 $\pm$ 0.1 (11)	8.5 $\pm$ 0.2 (13)	8.8 $\pm$ 0.4 (7)
ORP (mV)	—	—	—	—	—	—	106 (2)	—	—	—	370 $\pm$ 14 (3)
Turbidity (NTU)	—	—	—	—	—	—	—	—	—	—	0.0 (2)
Chlorophyll a ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	0.0 (2)
Acidity	—	—	0.5 (1)	—	—	0.1 (1)	—	—	—	—	—
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	—	120 (1)	—	—	107 (1)	101 $\pm$ 1 (10)	—	—	—	195 (2)
Cl (mg L <sup>-1</sup> )	439 $\pm$ 88 (4)	500 $\pm$ 38 (10)	563 $\pm$ 5 (13)	621 $\pm$ 12 (19)	727 $\pm$ 4 (12)	762 $\pm$ 4 (12)	793 $\pm$ 11 (22)	781 $\pm$ 3 (12)	798 $\pm$ 5 (11)	810 $\pm$ 2 (13)	737 $\pm$ 79 (6)
TP ( $\mu$ g L <sup>-1</sup> )	—	—	6 (1)	—	—	7 (1)	—	—	—	—	44 (2)
FRP ( $\mu$ g L <sup>-1</sup> )	—	—	6 (1)	—	—	<2 (0 1)	—	—	—	—	5 (1 1)
TN ( $\mu$ g L <sup>-1</sup> )	—	—	1900 (1)	—	—	1370 (1)	1200 $\pm$ 0 (10)	—	—	—	1083 (2)
NO <sub>x</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	—	—	—	610 (2)
NH <sub>4</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	500 (1)	—	—	239 (1)	—	—	—	—	64 (2)
NO <sub>3</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	2 (1)	—	—	1 (1)	—	—	—	—	—
DOC (mg L <sup>-1</sup> )	—	—	1 (1)	—	—	2 (1)	1 $\pm$ 0 (8 2)	—	—	—	2 (2)
DIC (mg L <sup>-1</sup> )	—	—	—	—	—	<0.5 (0 1)	—	—	—	—	0 (1)

Parameter	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
As ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	<0.8 (0 3)	<0.8 (0 2)	—	—	—	<50 (0 2)
Al ( $\text{mg L}^{-1}$ )	—	—	4.0 (1)	—	—	1.1 $\pm$ 0.0 (4)	1.2 $\pm$ 0.0 (12)	—	—	—	3.6 (2)
Ag ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	<1 (0 1)	—	—	—	—	—
B ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	14.7 $\pm$ 4.7 (3)	12.5 (2)	—	—	—	<50 (0 2)
Ba ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	57.0 (1)	—	—	—	—	—
Be ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	60.6 (2)	68.5 (2)	—	—	—	—
Ca ( $\text{mg L}^{-1}$ )	22.3 $\pm$ 0.3 (3)	23.1 $\pm$ 0.5 (10)	21.3 $\pm$ 1.8 (12)	23.4 $\pm$ 1.4 (8)	—	28.2 (1)	30.0 $\pm$ 0.0 (10)	—	—	31.7 $\pm$ 0.2 (6)	32.2 $\pm$ 2.3 (6)
Cd ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	0.5 (2 1)	0.5 (2)	—	—	—	<10 (0 2)
Co ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	58.1 $\pm$ 1.6 (3)	60.9 (2)	—	—	—	86.0 (2)
Cr ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	<4 (0 3)	<10 (0 2)	—	—	—	<10 (0 2)
Cu ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	<4 (0 3)	<10 (0 2)	—	—	—	<50 (0 1)
Fe ( $\text{mg L}^{-1}$ )	0.9 $\pm$ 0.1 (4)	1.1 $\pm$ 0.2 (11)	0.6 $\pm$ 0.1 (13)	0.5 $\pm$ 0.1 (19)	0.2 $\pm$ 0.0 (12)	0.2 $\pm$ 0.0 (14)	0.2 $\pm$ 0.0 (22)	0.2 $\pm$ 0.0 (12)	0.3 $\pm$ 0.0 (11)	0.3 $\pm$ 0.0 (12 1)	1.4 $\pm$ 1.1 (6)
Hg ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	<0.6 (0 3)	<0.6 (0 2)	—	—	—	<100 (0 2)
K ( $\text{mg L}^{-1}$ )	—	—	5.3 (1)	—	—	4.9 (1)	4.8 $\pm$ 0.0 (10)	—	—	—	4.0 (2)
Mg ( $\text{mg L}^{-1}$ )	—	—	59 (1)	—	—	77 (2)	79 $\pm$ 0 (10)	—	—	—	89 (2)
Mn ( $\mu\text{g L}^{-1}$ )	335 $\pm$ 9 (4)	315 $\pm$ 25 (11)	239 $\pm$ 5 (13)	256 $\pm$ 7 (19)	223 $\pm$ 4 (12)	222 $\pm$ 2 (16)	231 $\pm$ 3 (24)	227 $\pm$ 3 (12)	244 $\pm$ 5 (11)	248 $\pm$ 3 (13)	335 $\pm$ 58 (6)
Mo ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	<0.05 (0 3)	<0.05 (0 2)	—	—	—	—
Na ( $\text{mg L}^{-1}$ )	244 (1)	156 $\pm$ 68 (4)	273 $\pm$ 7 (11)	308 $\pm$ 13 (19)	328 $\pm$ 11 (12)	327 $\pm$ 26 (13)	353 $\pm$ 3 (22)	370 $\pm$ 7 (12)	369 $\pm$ 5 (11)	389 $\pm$ 8 (13)	385 $\pm$ 24 (6)
Ni ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	61.7 $\pm$ 4.4 (3)	62.5 (2)	—	—	—	89.5 (2)
Pb ( $\mu\text{g L}^{-1}$ )	2.8 (1)	2.5 $\pm$ 0.0 (3)	2.3 $\pm$ 0.2 (3)	9.3 $\pm$ 3.9 (7)	2.5 $\pm$ 0.0 (3)	14.0 (2)	5.6 $\pm$ 2.3 (3 1)	9.5 $\pm$ 4.3 (5 2)	2.5 (1)	20.0 (2)	<100 (0 2)

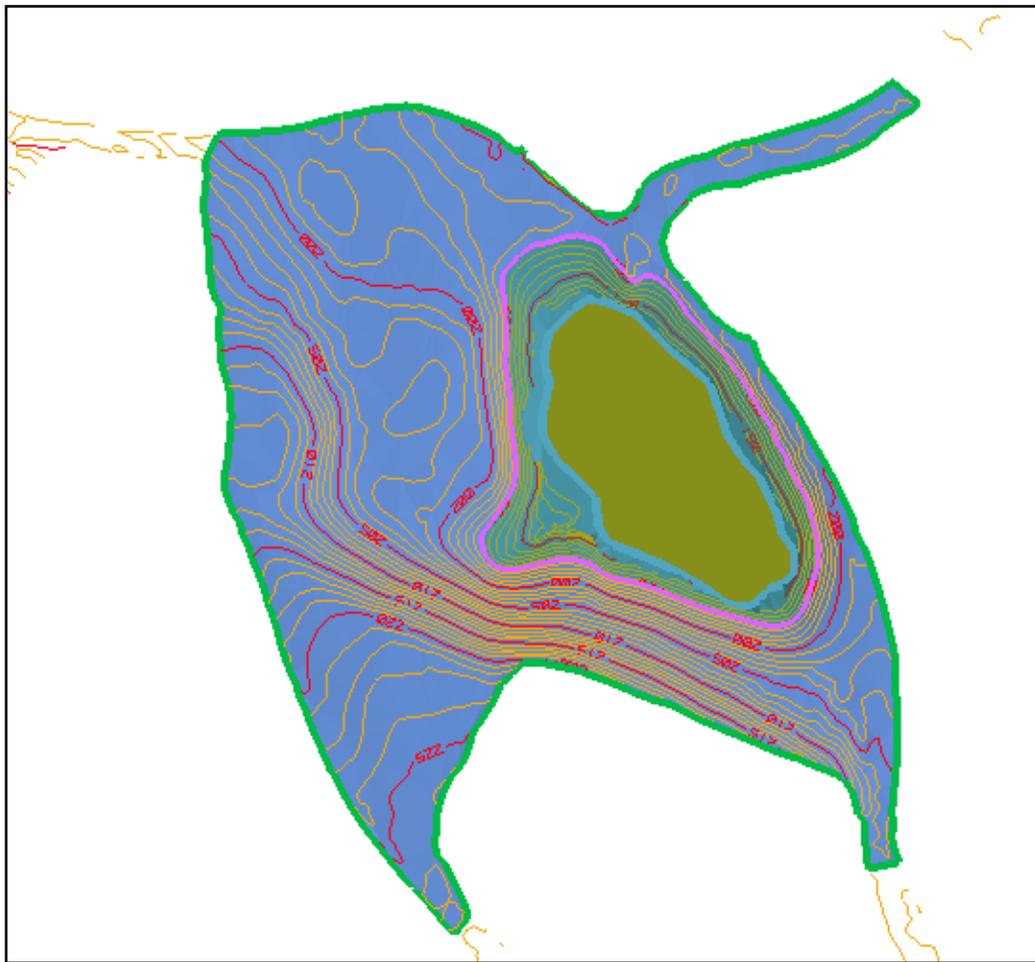
Parameter	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
S (mg L <sup>-1</sup> )	—	—	—	80 ± 8 (4)	—	82 (1)	—	—	—	—	63 (2)
Sb (µg L <sup>-1</sup> )	—	—	—	1.00 ± 0.00 (4)	—	1.00 (1)	<5 (0 1)	—	—	5.00 (1)	—
Se (µg L <sup>-1</sup> )	—	—	—	1.3 ± 0.3 (4)	—	1.0 (1)	<5 (0 1)	—	—	—	<200 (0 2)
SiO <sub>2</sub> (mg L <sup>-1</sup> )	—	—	—	6 (2)	—	6 (1)	—	—	—	—	—
Sn (µg L <sup>-1</sup> )	—	—	—	1.00 ± 0.00 (4)	—	1.00 (1)	<10 (0 1)	—	—	—	—
Sr (µg L <sup>-1</sup> )	64.6 (1)	—	51.9 (1)	421.6 ± 135.9 (6)	—	440.0 (1)	107.5 ± 50.7 (3)	209.0 (1)	—	210.0 (2)	—
Ti (µg L <sup>-1</sup> )	0.1 (1)	—	—	4.0 ± 1.0 (5)	—	5.0 (1)	0.1 (1)	—	—	—	—
U (µg L <sup>-1</sup> )	0.2 (1)	—	0.1 (1)	0.2 (2)	—	—	0.1 (2)	—	—	—	56.6 (2)
V (µg L <sup>-1</sup> )	—	—	—	0.8 ± 0.2 (5)	—	1.0 (1)	<20 (0 1)	<20 (0 1)	—	20.0 (1)	—
Zn (µg L <sup>-1</sup> )	23.8 (1)	33.3 ± 8.8 (3)	51.1 ± 35.1 (3)	253.0 ± 109.9 (7)	30.0 ± 0.0 (3)	330.0 (2)	344.6 ± 254.7 (4)	81.4 ± 30.7 (7)	20.0 (1)	200.0 (2)	323.0 (2)

**4.4.2 Lake WO5-N9**

Lake WO5-N9 is a large new lake (Figure 52) located close to Lake Kepwari. Like most other Premier Coal lakes, Lake WON9 steep bank was reshaped into a reposed slope and exposed coal seams were covered with waste rock, battered and revegetated with endemic flora by direct seeding (Figure 53). Near the water level where vegetation has not been seeded, there is extensive lake edge erosion which has been largely covered now by the ca. 2 m lake water level rises due to the high rainfall of the 2009 winter season (Figure 54).



**Figure 52.** Lake WON9 (04/2009) looking south-west.



**Figure 53.** Bathymetry of WON9 as provided by Wesfarmers (top of picture is north).

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**Figure 54.** Aerial photograph of WON9 (taken from Google Earth, imagery dated 2007) (top of picture is north).

**Table 18.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in WON9.

Parameter	2009
Temperature ( $^{\circ}$ C)	21.0 (2)
pH	3.7 (2)
EC ( $\text{mS cm}^{-1}$ )	1.277 (2)
Dissolved oxygen (%)	91.4 (2)
Dissolved oxygen ( $\text{mg L}^{-1}$ )	8.1 (2)
ORP (mV)	412 (2)
Turbidity (NTU)	0.0 (2)
Chlorophyll a ( $\mu\text{g L}^{-1}$ )	0.0 (2)
$\text{SO}_4$ ( $\text{mg L}^{-1}$ )	670 (2)
Cl ( $\text{mg L}^{-1}$ )	122 (2)
TP ( $\mu\text{g L}^{-1}$ )	97 (2)
FRP ( $\mu\text{g L}^{-1}$ )	27 (2)
TN ( $\mu\text{g L}^{-1}$ )	412 (2)
$\text{NO}_x$ ( $\mu\text{g L}^{-1}$ )	31 (2)
$\text{NH}_4$ ( $\mu\text{g L}^{-1}$ )	53 (2)
DOC ( $\text{mg L}^{-1}$ )	1 (2)
DIC ( $\text{mg L}^{-1}$ )	0 (1)
As ( $\mu\text{g L}^{-1}$ )	<50 (0 2)
Al ( $\text{mg L}^{-1}$ )	38.0 (2)
B ( $\mu\text{g L}^{-1}$ )	<50 (0 2)
Ca ( $\text{mg L}^{-1}$ )	18.6 (2)
Cd ( $\mu\text{g L}^{-1}$ )	<10 (0 2)
Co ( $\mu\text{g L}^{-1}$ )	489.0 (2)
Cr ( $\mu\text{g L}^{-1}$ )	<0.01 (0 2)
Cu ( $\mu\text{g L}^{-1}$ )	<50 (0 1)
Fe ( $\text{mg L}^{-1}$ )	2.1 (2)
Hg ( $\mu\text{g L}^{-1}$ )	<100 (0 2)
K ( $\text{mg L}^{-1}$ )	3.6 (2)
Mg ( $\text{mg L}^{-1}$ )	49 (2)
Mn ( $\mu\text{g L}^{-1}$ )	449 (2)
Na ( $\text{mg L}^{-1}$ )	93 (2)
Ni ( $\mu\text{g L}^{-1}$ )	469.0 (2)
Pb ( $\mu\text{g L}^{-1}$ )	5.0 (1 1)
S ( $\text{mg L}^{-1}$ )	392 (1)
Se ( $\mu\text{g L}^{-1}$ )	<200
U ( $\mu\text{g L}^{-1}$ )	<50 (0 1)
Zn ( $\mu\text{g L}^{-1}$ )	2118.0 (2)

**4.4.3 WO3**

Lake WO3 is in the middle of Collie Basin (Figure 55) and is the oldest of the Cardiff sub-Basin lakes (Figure 56). It is maximum 8 m depth and the water is blue coloured. pH was low at 4.2, with high aluminium concentrations, NO<sub>x</sub> levels were also very high (

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Table 19).



**Figure 55.** Lake WO3 (04/2009) looking north.

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**Figure 56.** Aerial photograph of WO3 (taken from Google Earth, imagery dated 2007) (top of picture is north).

**Table 19.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in WO3.

<b>Parameter</b>	<b>2009</b>
Temperature ( $^{\circ}$ C)	21.7 (2)
pH	3.9 (2)
EC ( $\text{mS cm}^{-1}$ )	1.920 (2)
Dissolved oxygen (%)	89.3 (2)
Dissolved oxygen ( $\text{mg L}^{-1}$ )	7.8 (2)
ORP (mV)	405 (2)
Turbidity (NTU)	0.0 (2)
Chlorophyll a ( $\mu\text{g L}^{-1}$ )	6.0 (2)
$\text{SO}_4$ ( $\text{mg L}^{-1}$ )	542 (2)
Cl ( $\text{mg L}^{-1}$ )	217 (2)
TP ( $\mu\text{g L}^{-1}$ )	112 (2)
FRP ( $\mu\text{g L}^{-1}$ )	11 (2)
TN ( $\mu\text{g L}^{-1}$ )	22717 (2)
$\text{NO}_x$ ( $\mu\text{g L}^{-1}$ )	2428 (2)
$\text{NH}_4$ ( $\mu\text{g L}^{-1}$ )	18145 (2)
DOC ( $\text{mg L}^{-1}$ )	3 (2)
DIC ( $\text{mg L}^{-1}$ )	0 (1)
As ( $\mu\text{g L}^{-1}$ )	<50 (0 2)
Al ( $\text{mg L}^{-1}$ )	18.3 (2)
B ( $\mu\text{g L}^{-1}$ )	<50 (0 2)
Ca ( $\text{mg L}^{-1}$ )	27.8 (2)
Cd ( $\mu\text{g L}^{-1}$ )	<10 (0 2)
Co ( $\mu\text{g L}^{-1}$ )	283.0 (2)
Cr ( $\mu\text{g L}^{-1}$ )	<10 (0 2)
Cu ( $\mu\text{g L}^{-1}$ )	<50 (0 1)
Fe ( $\text{mg L}^{-1}$ )	1.2 (2)
Hg ( $\mu\text{g L}^{-1}$ )	<100 (0 2)
K ( $\text{mg L}^{-1}$ )	7.2 (2)
Mg ( $\text{mg L}^{-1}$ )	60 (2)
Mn ( $\mu\text{g L}^{-1}$ )	1514 (2)
Na ( $\text{mg L}^{-1}$ )	183 (2)
Ni ( $\mu\text{g L}^{-1}$ )	239.5 (2)
Pb ( $\mu\text{g L}^{-1}$ )	<100 (0 1)
S ( $\text{mg L}^{-1}$ )	370 (1)
Se ( $\mu\text{g L}^{-1}$ )	<200 (0 1)
U ( $\mu\text{g L}^{-1}$ )	<50 (0 1)
Zn ( $\mu\text{g L}^{-1}$ )	1329.0 (1)

**4.4.4 WO5C**

Lake WO5C is a narrow shaped lake with blue coloured water and steep lake bank (Figure 57, Figure 58, Figure 59), a small lake southeast of Lake Kepwari. pH was 3.4 and EC was relatively high at 1.4 mS cm<sup>-1</sup> (

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Table 20).



Figure 57. Lake WO5C (04/2009) looking south.

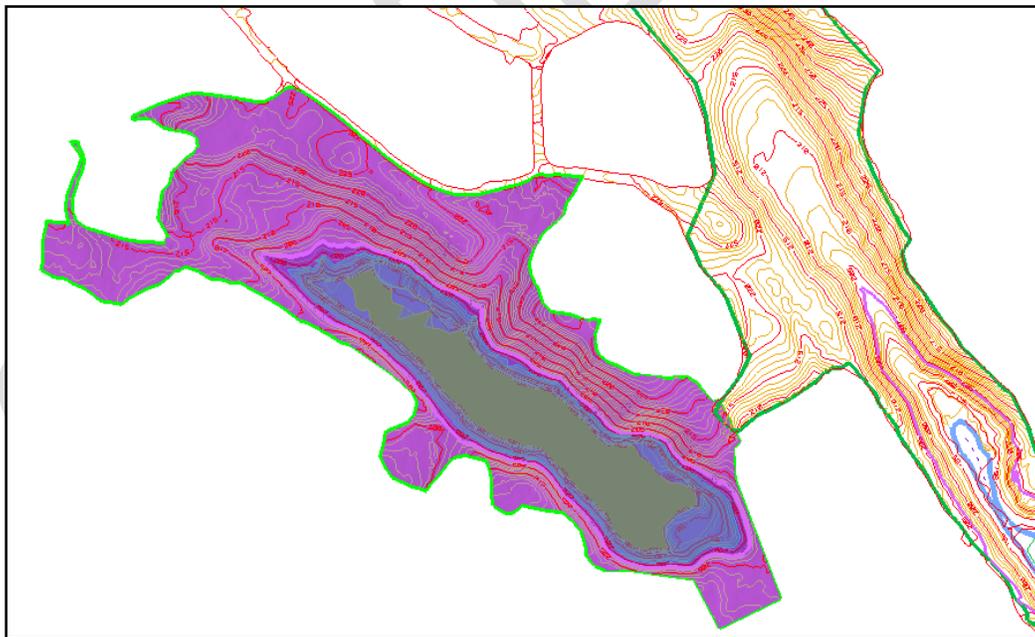


Figure 58. Bathymetry of WO5C as provided by Wesfarmers (top of picture is north).



**Figure 59.** Aerial photograph of W05C (taken from Google Earth, imagery dated 2007) (top of picture is north).

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**Table 20.** Mean surface (0 m) water ± standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in WO5C.

<b>Parameter</b>	<b>2009</b>
Temperature (°C)	23.5 (1)
pH	3.2 (1)
EC (mS cm <sup>-1</sup> )	1.670 (1)
Dissolved oxygen (%)	86.0 (1)
Dissolved oxygen (mg L <sup>-1</sup> )	7.3 (1)
ORP (mV)	461 (1)
Turbidity (NTU)	0.0 (1)
Chlorophyll a (µg L <sup>-1</sup> )	0.0 (1)
SO <sub>4</sub> (mg L <sup>-1</sup> )	906 (2)
Cl (mg L <sup>-1</sup> )	155 (2)
TP (µg L <sup>-1</sup> )	44 (2)
FRP (µg L <sup>-1</sup> )	17 (2)
TN (µg L <sup>-1</sup> )	2592 (2)
NO <sub>x</sub> (µg L <sup>-1</sup> )	113 (2)
NH <sub>4</sub> (µg L <sup>-1</sup> )	1979 (2)
DOC (mg L <sup>-1</sup> )	1 (2)
DIC (mg L <sup>-1</sup> )	0.1 (1)
As (µg L <sup>-1</sup> )	<50 (0 2)
Al (mg L <sup>-1</sup> )	41.1 (2)
B (µg L <sup>-1</sup> )	<50 (0 2)
Ca (mg L <sup>-1</sup> )	8.0 (2)
Cd (µg L <sup>-1</sup> )	<10 (0 2)
Co (µg L <sup>-1</sup> )	385.5 (2)
Cr (µg L <sup>-1</sup> )	<10 (0 2)
Cu (µg L <sup>-1</sup> )	<50 (0 1)
Fe (mg L <sup>-1</sup> )	3.3 (2)
Hg (µg L <sup>-1</sup> )	<100 (0 2)
K (mg L <sup>-1</sup> )	1.2 (1 1)
Mg (mg L <sup>-1</sup> )	21 (2)
Mn (µg L <sup>-1</sup> )	109 (1 1)
Na (mg L <sup>-1</sup> )	55 (2)
Ni (µg L <sup>-1</sup> )	358.0 (2)
Pb (µg L <sup>-1</sup> )	<100 (0 1)
S (mg L <sup>-1</sup> )	570 (1)
Se (µg L <sup>-1</sup> )	<200 (0 1)
U (µg L <sup>-1</sup> )	<50 (0 1)
Zn (µg L <sup>-1</sup> )	4093.0 (1)

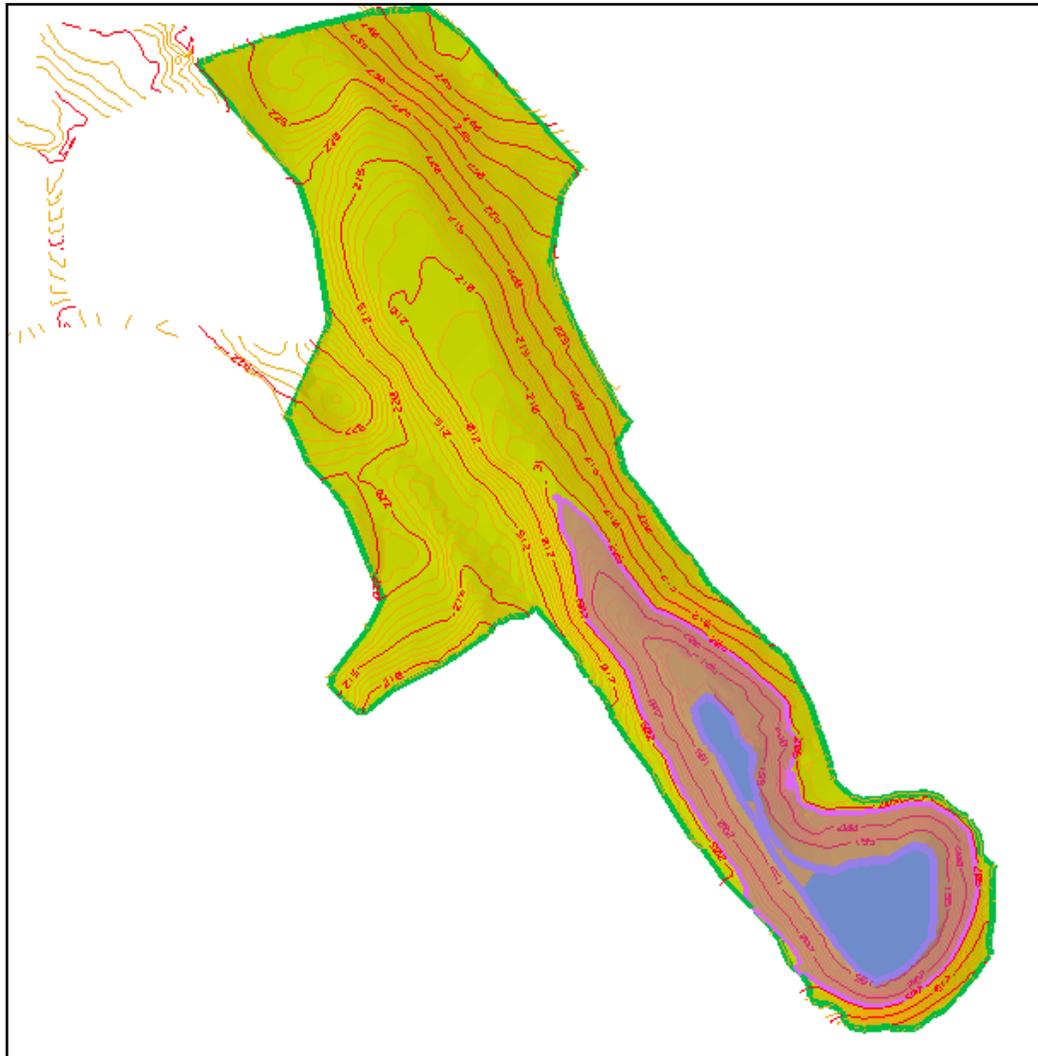
**4.4.5 Lake WO5D**

Lake WO5D is a much smaller lake near Lake WO5C, in a near round shape and the lake bank with gentle slope (Figure 60, Figure 61, Figure 62). This lake was acidic (pH 4.2), and showing signs of acidity generation in the catchment with high sulphate and aluminium concentrations (Table 21).



**Figure 60.** Lake WO5D (04/2009) looking west.

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**Figure 61.** Bathymetry of WO5D as provided by Wesfarmers (top of picture is north).



**Figure 62.** Aerial photograph of WO5C (taken from Google Earth, imagery dated 2007) (top of picture is north).

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**Table 21.** Mean surface (0 m) water ± standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in WO5D.

Parameter	2009
Temperature (°C)	23.8 (2)
pH	4.0 (2)
EC (mS cm <sup>-1</sup> )	0.733 (2)
Dissolved oxygen (%)	83.9 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	7.1 (2)
ORP (mV)	414 (2)
Turbidity (NTU)	0.0 (2)
TSS (mg L <sup>-1</sup> )	—
Chlorophyll a (µg L <sup>-1</sup> )	0.0 (2)
SO <sub>4</sub> (mg L <sup>-1</sup> )	361 (2)
Cl (mg L <sup>-1</sup> )	90 (2)
TP (µg L <sup>-1</sup> )	38 (2)
FRP (µg L <sup>-1</sup> )	4 (2)
TN (µg L <sup>-1</sup> )	650 (2)
NO <sub>x</sub> (µg L <sup>-1</sup> )	12 (2)
NH <sub>4</sub> (µg L <sup>-1</sup> )	18 (2)
DOC (mg L <sup>-1</sup> )	2 (2)
DIC (mg L <sup>-1</sup> )	0 (1)
As (µg L <sup>-1</sup> )	<50 (0 1)
Al (mg L <sup>-1</sup> )	6.9 (1)
B (µg L <sup>-1</sup> )	<50 (0 1)
Ca (mg L <sup>-1</sup> )	7.7 (1)
Cd (µg L <sup>-1</sup> )	<10 (0 1)
Co (µg L <sup>-1</sup> )	169.0 (1)
Cr (µg L <sup>-1</sup> )	<10 (0 1)
Fe (mg L <sup>-1</sup> )	0.1 (1)
Hg (µg L <sup>-1</sup> )	<100 (0 1)
K (mg L <sup>-1</sup> )	0.4 (1)
Mg (mg L <sup>-1</sup> )	21 (1)
Mn (µg L <sup>-1</sup> )	60 (1)
Na (mg L <sup>-1</sup> )	41 (1)
Ni (µg L <sup>-1</sup> )	118.0 (1)
Pb (µg L <sup>-1</sup> )	<100 (0 1)
S (mg L <sup>-1</sup> )	137 (1)
Se (µg L <sup>-1</sup> )	<20 (0 1)
Zn (µg L <sup>-1</sup> )	675.0 (1)

**4.4.6 WO5F**

Lake WO5F is a small lake near Lake Kepwari, with a nearly round shape, it is currently filling. The lake bank also has a gentle slope (Figure 63, Figure 64), but with less vegetation than that of Lake WO5F. The pH in Lake WO5F was near neutral, 6.5 in 2009 (

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Table 22), suggesting that it was filled primarily with rainwater and that there was little acid generation in the catchment.



**Figure 63.** Lake WO5F (04/2009) looking north.



**Figure 64.** Aerial photograph of WO5F (taken from Google Earth, imagery dated 2007) (top of picture is north).

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**Table 22.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in WO5F.

Parameter	2009
Temperature ( $^{\circ}$ C)	21.7 (2)
pH	5.8 (2)
EC ( $\text{mS cm}^{-1}$ )	0.325 (2)
Dissolved oxygen (%)	90.7 (2)
Dissolved oxygen ( $\text{mg L}^{-1}$ )	8.0 (2)
ORP (mV)	300 (2)
Turbidity (NTU)	0.0 (2)
Chlorophyll a ( $\mu\text{g L}^{-1}$ )	0.0 (2)
$\text{SO}_4$ ( $\text{mg L}^{-1}$ )	60 (2)
Cl ( $\text{mg L}^{-1}$ )	67 (2)
TP ( $\mu\text{g L}^{-1}$ )	35 (2)
FRP ( $\mu\text{g L}^{-1}$ )	2 (1 1)
TN ( $\mu\text{g L}^{-1}$ )	864 (2)
$\text{NO}_x$ ( $\mu\text{g L}^{-1}$ )	482 (2)
$\text{NH}_4$ ( $\mu\text{g L}^{-1}$ )	155 (2)
DOC ( $\text{mg L}^{-1}$ )	38 (2)
DIC ( $\text{mg L}^{-1}$ )	0 (1)
As ( $\mu\text{g L}^{-1}$ )	<50 (0 2)
Al ( $\text{mg L}^{-1}$ )	0.2 (2)
B ( $\mu\text{g L}^{-1}$ )	<50 (0 2)
Ca ( $\text{mg L}^{-1}$ )	4.5 (2)
Cd ( $\mu\text{g L}^{-1}$ )	<10 (0 2)
Co ( $\mu\text{g L}^{-1}$ )	<10 (0 2)
Cr ( $\mu\text{g L}^{-1}$ )	<10 (0 2)
Cu ( $\mu\text{g L}^{-1}$ )	<50 (0 1)
Fe ( $\text{mg L}^{-1}$ )	0.04 (2)
Hg ( $\mu\text{g L}^{-1}$ )	<100 (0 2)
K ( $\text{mg L}^{-1}$ )	1.3 (2)
Mg ( $\text{mg L}^{-1}$ )	6 (2)
Mn ( $\mu\text{g L}^{-1}$ )	50 (2)
Na ( $\text{mg L}^{-1}$ )	35 (2)
Ni ( $\mu\text{g L}^{-1}$ )	45.0 (2)
Pb ( $\mu\text{g L}^{-1}$ )	<100 (0 1)
S ( $\text{mg L}^{-1}$ )	16 (1)
Se ( $\mu\text{g L}^{-1}$ )	<200 (0 1)
U ( $\mu\text{g L}^{-1}$ )	<50 (0 1)
Zn ( $\mu\text{g L}^{-1}$ )	<50 (0 1)

#### 4.4.7 WO5H

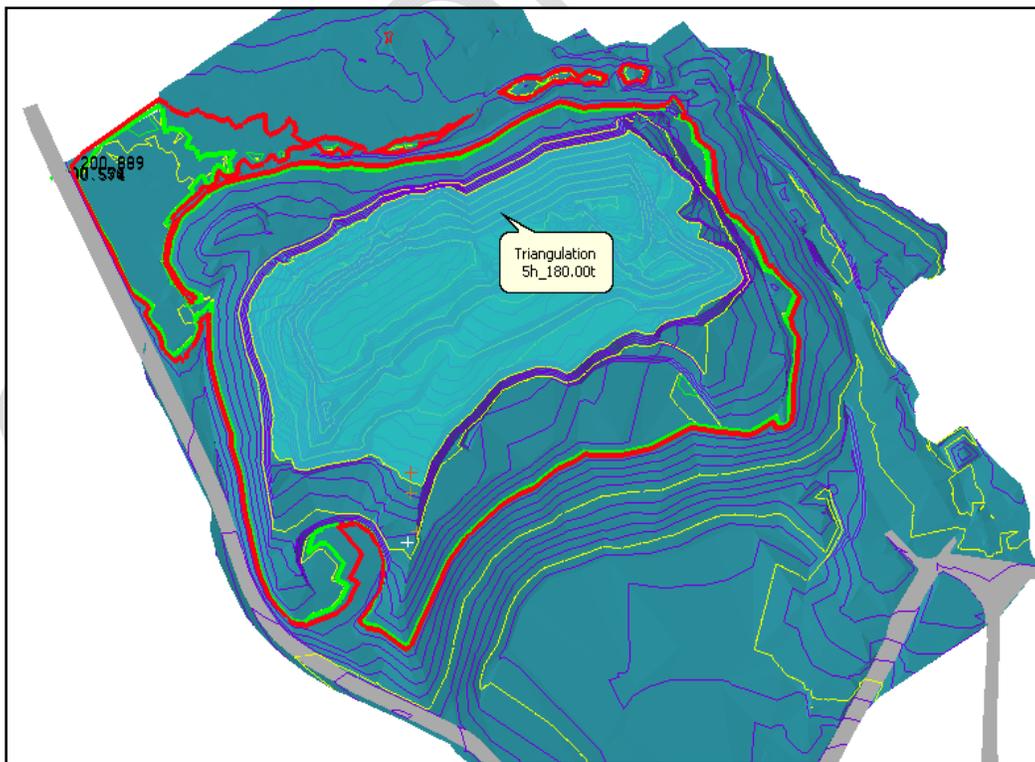
WO5H had a finfish and marron aquaculture research facility established next to it as part of the activities of the Centre for Sustainable Mine Lakes (Figure 65). Water was pumped from the lake and through a fluidised liming system to remediate pH prior to then gravity-feeding down through the ponds and then back to the lake again (Evans *et al.*, 2007). However, this aquaculture facility only consisted of some 5 ponds and the associated water consumption and discharge was relatively low. A seasonal stream also flows into the north-eastern side of the lake and this stream can have very high salinities (Digby Short, Wesfarmer Premier, pers. comm.; Figure 66, Figure 67, Figure 68). However, in May 2009 this stream had a pH of 4.9 and an electrical conductivity of only  $2.01 \text{ mS cm}^{-1}$ . The pH in lake WO5H was low, about 3.0 to 3.5 in year 2002 to 2009 (Table 23).



**Figure 65.** Lake WO5H (05/2009) looking north-west.



**Figure 66.** Stream flowing into WO5H (05/2009).



**Figure 67.** Bathymetry of WO5H as provided by Wesfarmers (top of picture is north).



**Figure 68.** Aerial photograph of WO5H (taken from Google Earth, imagery dated 2007) (top of picture is north).

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**Table 23.** Mean surface (0 m) water  $\pm$  standard error (sample size|number below detection limit) for physico-chemical water quality parameters and solute concentrations in WO5H. — = no data available for that year.

Parameter	2002	2003	2004	2005	2006	2007	2008	2009
Temperature (°C)	—	—	—	20.4 (1)	—	—	—	20.6 (2)
pH	3.5 $\pm$ 0.0 (11)	3.3 $\pm$ 0.0 (12)	3.2 $\pm$ 0.0 (12)	3.2 $\pm$ 0.0 (13)	3.2 $\pm$ 0.0 (12)	3.2 $\pm$ 0.0 (11)	3.2 $\pm$ 0.0 (13)	3.1 $\pm$ 0.0 (6)
EC (mS cm <sup>-1</sup> )	—	—	—	1.170 (1)	—	—	—	1.425 (2)
TDS (mg L <sup>-1</sup> )	549.9 $\pm$ 16.6 (11)	658.3 $\pm$ 60.0 (12)	637.9 $\pm$ 17.3 (12)	672.0 $\pm$ 12.4 (12)	681.3 $\pm$ 12.4 (12)	727.7 $\pm$ 20.2 (11)	712.3 $\pm$ 23.4 (13)	787.5 $\pm$ 15.1 (4)
Dissolved oxygen (%)	—	—	—	—	—	—	—	90.9 (2)
Dissolved oxygen (mg L <sup>-1</sup> )	8.2 $\pm$ 0.3 (11)	8.0 $\pm$ 0.2 (11)	7.4 $\pm$ 0.5 (11)	9.0 $\pm$ 0.4 (12)	8.9 $\pm$ 0.2 (12)	8.4 $\pm$ 0.1 (11)	8.4 $\pm$ 0.2 (13)	8.2 $\pm$ 0.2 (6)
ORP (mV)	—	—	—	172 (1)	—	—	—	478 (2)
Turbidity (NTU)	—	—	—	—	—	—	—	0.0 (2)
Chlorophyll a ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	0.0 (2)
SO <sub>4</sub> (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	572 (2)
Cl (mg L <sup>-1</sup> )	177 $\pm$ 4 (11)	174 $\pm$ 5 (12)	175 $\pm$ 4 (10)	177 $\pm$ 2 (12)	177 $\pm$ 2 (12)	181 $\pm$ 7 (11)	177 $\pm$ 2 (13)	170 $\pm$ 10 (6)
TP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	44 (2)
FRP ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	16 (2)
TN ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	689 (2)
NO <sub>x</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	141 (2)
NH <sub>4</sub> ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	471 (2)
DOC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	3 (2)
DIC (mg L <sup>-1</sup> )	—	—	—	—	—	—	—	0 (1)
As ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	62.0 (1 1)
Al (mg L <sup>-1</sup> )	—	—	—	16.0 (1)	—	—	—	17.5 (2)
B ( $\mu$ g L <sup>-1</sup> )	—	—	—	—	—	—	—	<50 (0 2)
Ca (mg L <sup>-1</sup> )	15.3 $\pm$ 0.7 (11)	20.3 $\pm$ 2.6 (12)	18.0 $\pm$ 0.2 (11)	17.3 $\pm$ 1.4 (12)	20.2 $\pm$ 0.4 (12)	21.4 $\pm$ 0.5 (11)	22.1 $\pm$ 0.2 (13)	22.3 $\pm$ 1.6 (6)
Cd ( $\mu$ g L <sup>-1</sup> )	—	—	—	1.7 (1)	—	—	—	<10 (0 2)

Parameter	2002	2003	2004	2005	2006	2007	2008	2009
Co ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	226.5 (2)
Cr ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	<10 (0 2)
Cu ( $\mu\text{g L}^{-1}$ )	—	—	—	200.0 (1)	—	—	—	<10 (0 1)
Fe (mg $\text{L}^{-1}$ )	2.2 ± 0.1 (11)	2.9 ± 0.1 (12)	2.7 ± 0.1 (12)	2.3 ± 0.3 (13)	3.7 ± 0.1 (12)	3.8 ± 0.2 (11)	4.8 ± 0.2 (13)	4.7 ± 0.7 (6)
Hg ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	<100 (0 2)
K (mg $\text{L}^{-1}$ )	—	—	—	—	—	—	—	3.9 (2)
Mg (mg $\text{L}^{-1}$ )	—	—	—	31 (1)	—	—	—	34 (2)
Mn ( $\mu\text{g L}^{-1}$ )	1229 ± 71 (11)	1334 ± 86 (12)	1360 ± 14 (12)	1425 ± 27 (13)	1496 ± 11 (12)	1522 ± 43 (11)	1622 ± 19 (13)	1807 ± 162 (6)
Na (mg $\text{L}^{-1}$ )	93 ± 1 (11)	90 ± 2 (12)	89 ± 1 (12)	92 ± 1 (12)	91 ± 1 (12)	119 ± 26 (11)	96 ± 1 (13)	104 ± 10 (6)
Ni ( $\mu\text{g L}^{-1}$ )	—	—	—	—	—	—	—	299.0 (2)
Pb ( $\mu\text{g L}^{-1}$ )	10.0 (1 2)	—	4.4 ± 0.6 (4)	6.5 ± 1.5 (4)	12.0 (1)	6.3 (2)	2.5 ± 0.0 (3)	10.0 (2 1)
S (mg $\text{L}^{-1}$ )	19 ± 8 (3)	—	—	98 (1)	99 (1)	24 (1)	—	189 ± 84 (3)
Sb ( $\mu\text{g L}^{-1}$ )	—	—	—	1.00 (1)	1.00 (1)	—	—	1.00 (2)
Se ( $\mu\text{g L}^{-1}$ )	20.0 (1 2)	—	—	1.0 (1)	1.0 (1)	20.0 (1)	—	1.0 (2 1)
Sn ( $\mu\text{g L}^{-1}$ )	—	—	—	1.00 (1)	1.00 (1)	—	—	1.00 (2)
Sr ( $\mu\text{g L}^{-1}$ )	—	—	—	860.0 (1)	900.0 (1)	—	—	875.0 (2)
Ti ( $\mu\text{g L}^{-1}$ )	—	—	—	5.0 (1)	5.0 (1)	—	—	5.0 (2)
U ( $\mu\text{g L}^{-1}$ )	94.6 (2)	—	—	—	—	—	—	<50 (0 1)
V ( $\mu\text{g L}^{-1}$ )	—	—	—	1.0 (1)	1.0 (1)	—	—	1.0 (2)
Zn ( $\mu\text{g L}^{-1}$ )	48.0 (2 1)	—	245.0 ± 124.0 (4)	312.5 ± 79.3 (4)	290.0 (1)	75.0 (2)	13.3 ± 8.3 (3)	866.3 ± 576.3 (3)

## 5 Aquatic Biota

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### 5.1 Macroinvertebrates

Aquatic macroinvertebrates are typically the most popular biological community chosen to assess aquatic impacts. Internationally, analysis of macroinvertebrate communities has been the foremost tool for biological assessment of aquatic ecosystems due to the availability of good taxonomy, a species diverse community and an extensive literature of response to pollutant effects (Norris *et al.*, 1995). Although historically biological methods have been slow to be accepted in Australia, water managers now rely heavily upon aquatic macroinvertebrate communities for day-to-day assessment of water quality across the country (ANZECC/ARMCANZ, 2000d).

#### 5.1.1.1 1997 data

An unpublished ECU report in 1997 surveyed Lakes Blue Waters and Stockton for aquatic macroinvertebrates (Lyons, 1997). This study used a 500 µm mesh kicknet to sample 1 m<sup>3</sup> of water in Spring 1997. At each of the lakes being studied, 5 emergent macrophyte sites and 5 open water sites were selected along the banks. The contents of these sweeps was placed in a plastic lock-seal bag, preserved with alcohol, labelled with location, date and habitat type, and sealed for later identification in the laboratory using Davis & Chrisidis (1997).

This study found that Blue Waters Lake had no Oligochaeta, Cladocera, Copepoda Harpacticoida, Amphipoda, Empididae, Leptoceridae, Limnephilidae or Ephemeroptera species present (Table 24). Conversely, Lake Stockton had no Oxidae, Collembola, Odonata, Ecnomidae, Ptiliidae, Noteridae, Hemiptera or Neuroptera species present.

**Table 24.** Macroinvertebrate survey data for Blue Waters and Lake Stockton after Lyons (1997). Values mean of 10 replicates (5 in open littoral, 5 in vegetation) taken with a 500 µm mesh sweep net over 1 m<sup>3</sup> in Spring 1997. A = adult, L = larvae and P = pupae stages.

Order	Family	Species	Abundance (m <sup>-3</sup> )	
			Blue Waters	Stockton
Amphipoda	Ceinidae	<i>Perthia acutitelson</i>	0.0	2.1
Coeloptera	Dytiscidae	<i>Necterosoma darwini</i> (A)	2.3	0.1
Coleoptera	Dytiscidae	<i>Necterosoma darwini</i> (L)	16.3	7.5
Coleoptera	Dytiscidae	<i>Sternopriscus browni</i>	0.4	1.0
Diptera	Ceratopogonidae	sp. (P)	0.1	0.2
Diptera	Culicidae	<i>Culex</i> sp.	0.0	0.5
Diptera	Tanypodinae	<i>Ablabesmyia notabilis</i>	5.5	2.6
Emphemeroptera	Caenidae	<i>Tasmanocoenis</i> sp.	0.0	1.4
Hemiptera	Corixidae	<i>Micronecta robusta</i>	1.5	2.1
Hemiptera	Notonectidae	<i>Anisops</i> sp.	0.1	0.0
Odonata	Libellulidae	<i>Orthetrum caledonicum</i>	0.0	0.2
Odonata	Lestidae	<i>Austrolestes psyche</i>	0.2	0.0
Ostracoda	Cyprididae	<i>Mytilocypris ambigua</i>	0.0	13.5
Total abundance			26	31
Total taxa richness			8	11

#### 5.1.1.2 1997–1998 data

Macroinvertebrate communities were also studied in monthly surveys of some historic pit lake littoral margins over 1997–1999. This study by Lund *et al* (2000) surveyed four lakes monthly (Black Diamond - 1 year, Stockton - 2 years and Blue Waters and Ewington - 2.5 years) for macroinvertebrates using a 500 µm mesh dip net.

Despite the higher pH and the extensive growth of charophytes across the lake bottom, this did not seem to have increased the diversity or abundance of macroinvertebrates within Lake Black Diamond (Table 25). Macroinvertebrate abundance was also low, but diversity was reasonable in Blue Waters Lake.

Lake Ewington macroinvertebrate abundance was extremely low (<15 individuals caught on each occasion), no doubt reflecting the low productivity of the system. However, Lake Ewington macroinvertebrate diversity was more reasonable, with a large range of higher trophic level taxa, including Odonata and Coleoptera. Macroinvertebrate diversity and abundances were very low in Lake Stockton compared to the other historic pit lakes studied.

**Table 25.** Seasonal changes in the presence of macroinvertebrate taxa in some historic pit lakes. Greyed box = taxa present.

		Black Diamond													
		1997							1998						
Species		A	M	J	J	S	O	D	J	F	M	A	M	J	A
Crustacea	Amphipoda	Perthia acutitelson													
	Decapoda	Cherax quinquecarinatus													
	Ostracoda	Mytilocypris ambiguosa													
Insecta	Coleoptera	Hydraenidae sp.													
		Necterosoma darwini adult													
		Gyrinidae sp.													
		Megaporus Larval sp.													
		Megaporus solidus													
		Necterosoma darwini Larval													
		Coleoptera Sp. 1													
		Sternopriscus browni													
	Diptera	Ceratopogonidae larval sp.													
		Ceratopogonidae pupa sp.													
		Culex sp.													
		Ablabesmyia notabilis													
	Emphemeroptera	Tasmanocoenis sp.													
	Hemiptera	Micronecta robusta													
		Anisops sp.													
	Lepidoptera	Lepidoptera sp1													
	Odonata	Aeshna brevistyla													
		Austrogomphus sp.													
		Orthetrum caledonicum													
		Austrolestes psyche													
		Zygoptera Juv.													
		Procordulia affinis													
	Trichoptera	Trichoptera sp.													
		Triplectides australis													

		Ewington																			
		1997							1998							1999					
Species		A	M	J	J	S	O	D	J	F	M	A	M	J	J	A	S	O	N	D	J
		Perthia acutitelson																			
		Cherax quinquecarinatus																			
		Mytilocypris ambiguosa																			
		Hydraenidae sp.																			
		Necterosoma darwini adult																			
		Gyrinidae sp.																			
		Megaporus Larval sp.																			
		Megaporus solidus																			
		Necterosoma darwini Larval																			
		Coleoptera Sp. 1																			
		Sternopriscus browni																			
		Ceratopogonidae larval sp.																			
		Ceratopogonidae pupa sp.																			
		Culex sp.																			
		Ablabesmyia notabilis																			
		Tasmanocoenis sp.																			
		Micronecta robusta																			
		Anisops sp.																			
		Lepidoptera sp1																			
		Aeshna brevistyla																			
		Austrogomphus sp.																			
		Orthetrum caledonicum																			
		Austrolestes psyche																			
		Zygoptera Juv.																			
		Procordulia affinis																			
		Trichoptera sp.																			
		Triplectides australis																			

		Blue Waters																			
		1997							1998							1999					
Species		A	M	J	J	O	D	F	M	A	M	J	J	J	A	S	O	N	D	J	
		Perthia acutitelson																			
		Cherax quinquecarinatus																			
		Mytilocypris ambiguosa																			
		Hydraenidae sp.																			
		Necterosoma darwini adult																			
		Gyrinidae sp.																			
		Megaporus Larval sp.																			
		Megaporus solidus																			
		Necterosoma darwini Larval																			
		Coleoptera Sp. 1																			
		Sternopriscus browni																			
		Ceratopogonidae larval sp.																			
		Ceratopogonidae pupa sp.																			
		Culex sp.																			
		Ablabesmyia notabilis																			
		Tasmanocoenis sp.																			
		Micronecta robusta																			
		Anisops sp.																			
		Lepidoptera sp1																			
		Aeshna brevistyla																			
		Austrogomphus sp.																			
		Orthetrum caledonicum																			
		Austrolestes psyche																			
		Zygoptera Juv.																			
		Procordulia affinis																			
		Trichoptera sp.																			
		Triplectides australis																			

		Stockton																			
		1997							1998							1999					
Species		A	M	J	J	O	D	J	F	M	A	M	J	J	A	S	O	N	D	J	
		Perthia acutitelson																			
		Cherax quinquecarinatus																			
		Mytilocypris ambiguosa																			
		Hydraenidae sp.																			
		Necterosoma darwini adult																			
		Gyrinidae sp.																			
		Megaporus Larval sp.																			
		Megaporus solidus																			
		Necterosoma darwini Larval																			
		Coleoptera Sp. 1																			
		Sternopriscus browni																			
		Ceratopogonidae larval sp.																			
		Ceratopogonidae pupa sp.																			
		Culex sp.																			
		Ablabesmyia notabilis																			
		Tasmanocoenis sp.																			
		Micronecta robusta																			
		Anisops sp.																			
		Lepidoptera sp1																			
		Aeshna brevistyla																			
		Austrogomphus sp.																			
		Orthetrum caledonicum																			
		Austrolestes psyche																			
		Zygoptera Juv.																			
		Procordulia affinis																			
		Trichoptera sp.																			
		Triplectides australis																			

5.1.1.3 2000 data

Kumar *et al.* (in press) analysed the dataset of Lund *et al.* (2000) and found that the Collie pit lake aquatic fauna was low in diversity with few macroinvertebrate families present. Many families, common in natural regional water bodies, were entirely absent. Only a few families of aquatic macroinvertebrates were found in surveys of Collie pit lakes, relative to other mining lake areas that had higher pH (Table 26).

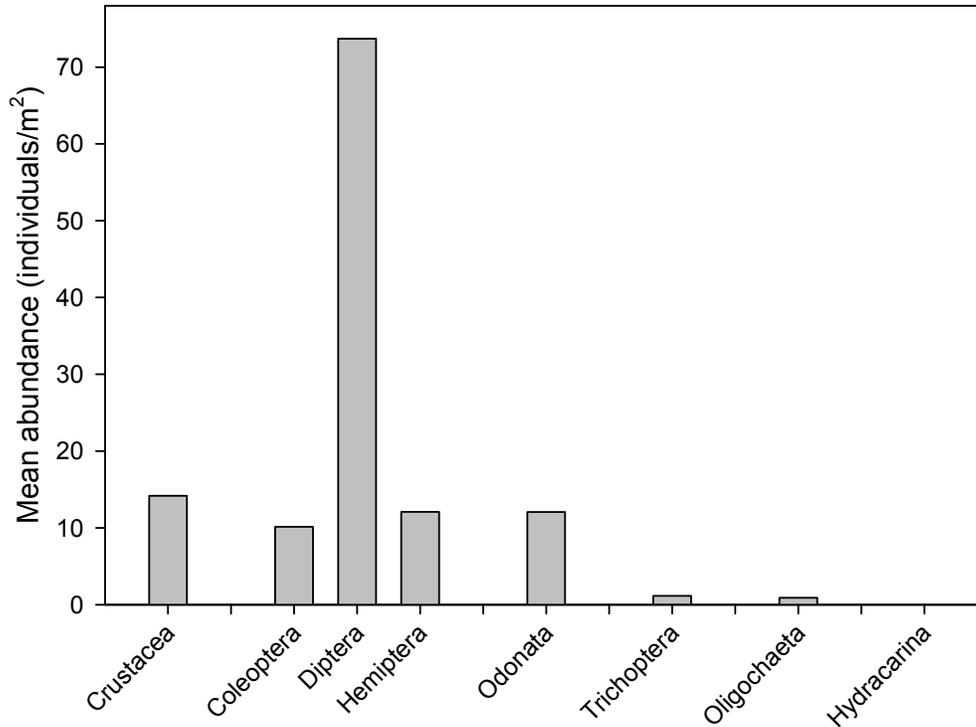
**Table 26.** Macroinvertebrate families occurring in Collie pit lakes (after Lund *et al.*, 2000). 1 = rare (0-1 individuals) , 2 = occasional (2-10), 3 = common (11-100), 4 = abundant (100+).

Taxon	Collie Basin, Western Australia (N = 4)
Amphipoda	2
Ceratopogonidae	2
Chironomidae	2
Corduliidae	1
Culicidae	1
Dytiscidae	2
Leptoceridae	1
Libellulidae	1
Notonectidae	1

5.1.1.4 2003–2009 data

The data collected in 2009 by the authors used the same methods and sites as that collected back to 2003 by the authors, as such the datasets have been combined to provide an inter-annual view of the communities. Benthic macroinvertebrate assemblages in Collie pit lakes were dominated by aquatic insects (Figure 69). The most common insect group was the order Diptera (two-winged flies) with a mixture of primarily detritus feeders and some predators. The next most common order was the crustacea which were a mixture of swimming copepod (zooplankton) and ostracod (seed shrimps) and also bottom dwelling amphipods (sand hoppers). The next most common insect groups were the Coleoptera (beetles), Hemiptera (bugs) and Odonata (dragonflies). Of these, the beetles and dragonflies are all predators that would have probably preyed mainly upon the Dipteran larvae. The bugs were a mixture of predators such as backswimmer predators (Notonectidae) and boatmen (Corixidae) omnivores. There was also a small component of leptocerid Trichoptera (caddis flies)

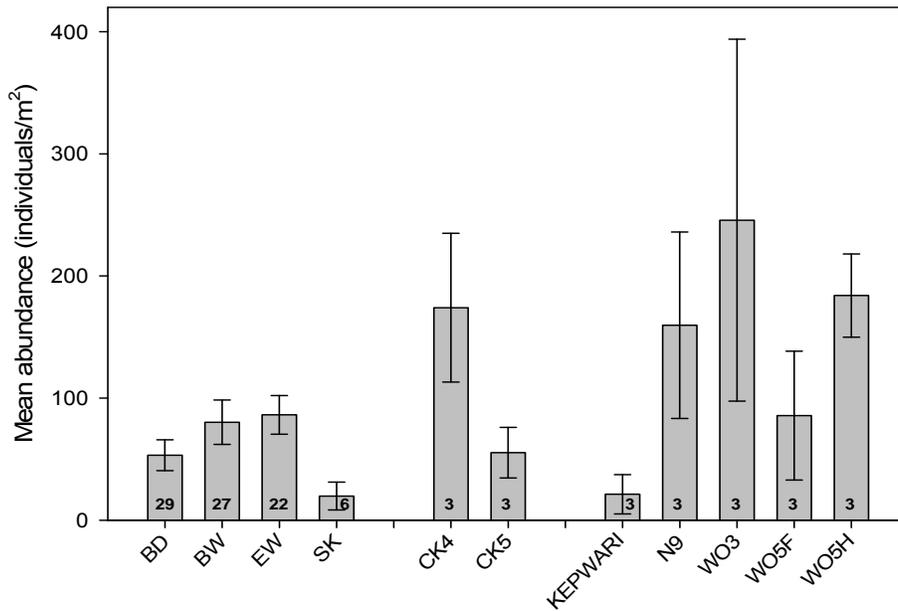
and oligochaetes (worms) in the pit lakes these are detritivores feeding on fallen decaying vegetation such as leaves.



**Figure 69.** Mean abundance of aquatic macroinvertebrate orders in historic, new Premier and Cardiff pit lakes (2003-2009).

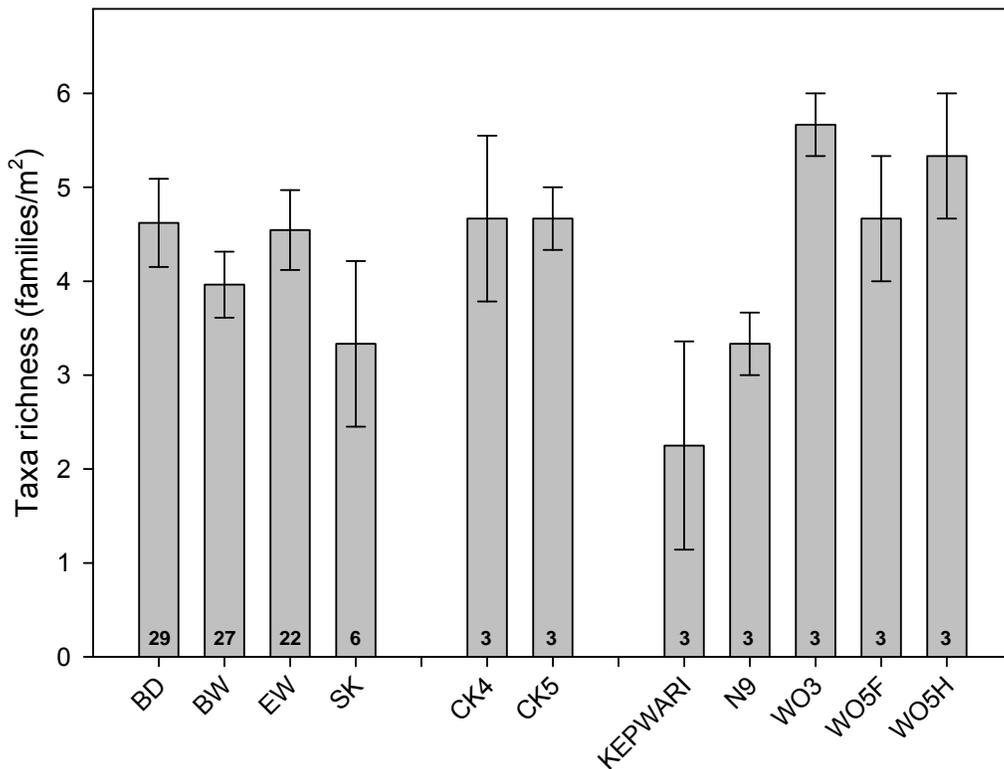
Mean aquatic macroinvertebrate abundance ranged from <5 to >200 m<sup>-2</sup> across all the Collie pit lakes (Figure 70). Mean aquatic macroinvertebrate abundance of historic pit lakes was the lowest (68 m<sup>-2</sup>) compared with new Premier pit lakes (115 m<sup>-2</sup>) and the Cardiff pit lakes (183 m<sup>-2</sup>). Higher macroinvertebrate biomass in newer lakes (particularly the Cardiff pit lakes) this may be due to rehabilitation efforts in these lake catchments increasing the size of catchment and the planting of vegetation in the catchment leading to more nutrients in these younger lakes. Detritus is likely to have particularly contributed the limiting nutrient of carbon to these new lakes. Macroinvertebrate mean abundance was lowest in mid-range pH lakes of Stockton and Kepwari (4.5-5.5) and this may be due to mono-valent aluminium (Al(OH)<sup>4-</sup>) toxicity being highest at this pH range (Neil *et al.*, 2009).

However, new pit lakes also had relatively higher variability in macroinvertebrate abundances also. This may be due to higher heterogeneity of littoral margin habitat resulting from the high rate of lake edge erosion currently taking place and the recently flooded riparian vegetation in younger Cardiff lakes.



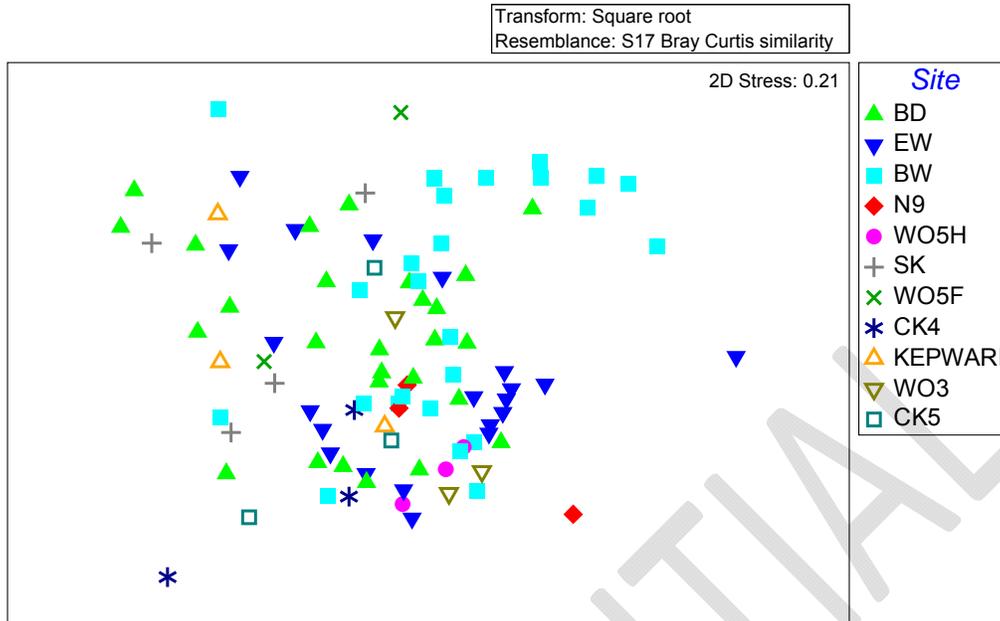
**Figure 70.** Mean abundance of aquatic macroinvertebrates (family level) in historic, Premier and, new Cardiff pit lakes (2003–2009). Error bars are standard errors of the mean, number in bar indicates number of samples.

Mean aquatic macroinvertebrate taxa richness was low across all pit lakes, with no obvious trend in taxa richness mean or variability between lake age and location (Figure 71). For example, even though the new Lake Kepwari had the lowest mean taxa richness (2 families/m<sup>2</sup>), new Lake WO3 had the highest mean taxa richness (6 families/m<sup>2</sup>).



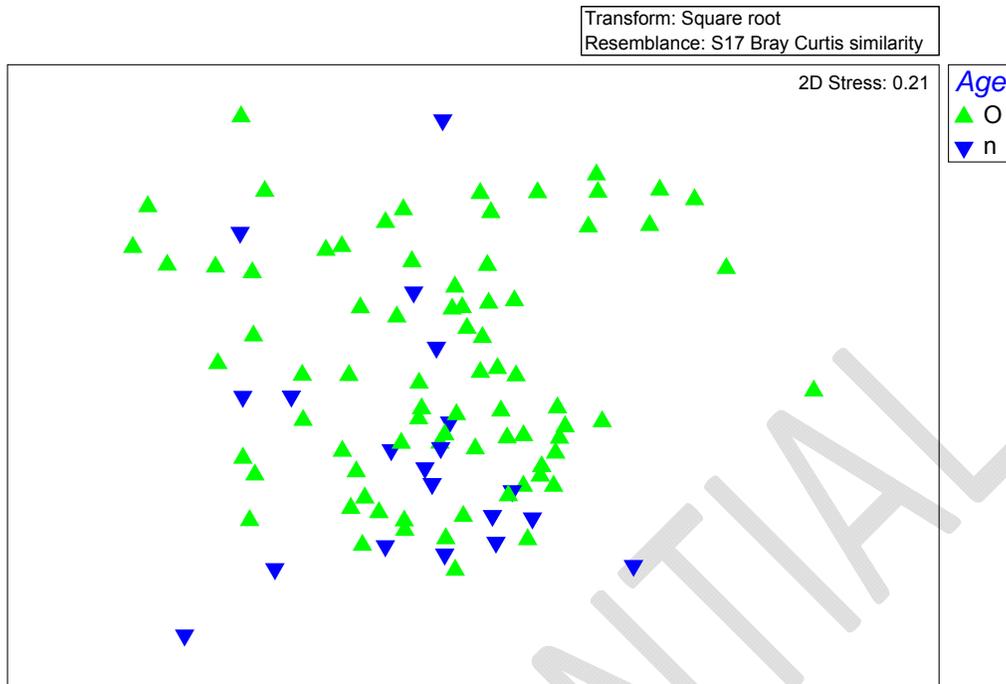
**Figure 71.** Mean taxa richness of aquatic macroinvertebrates (family level) in historic, Premier and new Cardiff pit lakes (2003–2009). Error bars are standard errors of the mean, number in bar indicates number of samples.

Nevertheless, an nMDS ordination of aquatic macroinvertebrate assemblage data from 2003–2009 did not show any clear grouping of pit lakes based upon their aquatic macroinvertebrate assemblages (Figure 72). This high degree of similarity between all pit lakes across these years suggests that there is a core community of invertebrates that occur in the varying water qualities across these different pit lakes. This commonality within the macroinvertebrate assemblages from these pit lakes is most likely due to the cosmopolitan and tolerant nature of the taxa found there such as chironomid midge, and beetle and dragonfly larvae.



**Figure 72.** nMDS ordination of aquatic benthic macroinvertebrate communities of Collie pit lakes from 2003–2009 by pit lake.

There appeared to be a slight difference between macroinvertebrate community assemblages of historic and new pit lakes (Figure 73), but, this difference was not statistically significant (Global  $R = 0.023$ ,  $p = 34.8\%$ ). As was found with the even range of taxa richness across all pit lakes, this lack of difference in macroinvertebrate assemblage between pit lakes of vastly disparate age (over 40 years) is also likely to be due to a cosmopolitan and water quality tolerant generalist macroinvertebrate assemblage dominating the Collie pit lakes.



**Figure 73.** nMDS ordination of aquatic benthic macroinvertebrate communities of Collie pit lakes from 2003–2009 by age of lake (historic = O, or new = n).

## 5.2 Periphytic diatoms

Periphyton is often the greatest source of primary production for communities of both littoral and pelagic habitats (Havens *et al.*, 1996) and may represent the major source of energy to secondary and higher trophic scales (Lewis *et al.*, 2001). Periphytic diatoms (Family Bacillariophyceae) have been especially suitable for the biomonitoring of aquatic ecosystems (Dixit *et al.*, 1992; Reid *et al.*, 1995).

Diatoms occur ubiquitously in high numbers and diversity, are generally relatively sensitive to changes in water chemistry, are easily collected, analysed and preserved, and can be readily identified to species scale (Patrick *et al.*, 1968; Reid *et al.*, 1995). The distributions and associated water chemistry of diatom taxa are cosmopolitan and well documented and there is good information available on their environmental requirements. Furthermore, diatoms often have narrow ranges of tolerance to pH, nutrients and salinity, which have been widely studied and defined (Dixit *et al.*, 1992; Reid *et al.*, 1995).

Nevertheless, the use of diatoms for monitoring may be limited because of their small size and requirements for preparation prior to sorting and expert identification (John & Moore, 1985; Dixit *et al.*, 1992; John, 1993; Reid *et al.*, 1995; John, 2000a, b). Along with macroinvertebrates, periphyton have historically received the most attention in community-scale assessments of environmental quality (Clements, 1994; Clements & Kiffney, 1994).

Although limited to the historic Collie pits lakes Blues Waters, Ewington, Black Diamond and Stockton, a study by Thomas and John (2006) surveyed the periphytic diatoms and water quality during Autumn–Winter 1999. Of the environmental variables which affect diatom community structure, pH has often been found to have the greatest influence, with most species showing a preference for a narrow pH range (Chessman, 1986; Tudor *et al.*, 1991; O'Connell *et al.*, 1997; Denichola, 2000). The study of Thomas and John (2006) similarly found that pH was important for diatom communities, finding two groups of diatoms separated at a threshold of around pH 4.5 (Table 23). Nevertheless, their data may also be interpreted in terms of salinity (as conductivity) as this water quality variable equally separated these two community types by being inversely related to pH.

**Table 27.** Dominant diatom taxa (>20% frequency) from Thomas and John (2006).

pH<4.5	pH>4.8
<i>Achnantheidium oblongella</i>	<i>Achnantheidium oblongella</i>
<i>Brachysira brebissonii</i>	<i>Brachysira brebissonii</i>
<i>Epithmia sores</i>	<i>Eunotia curvata</i>
<i>Navicula aff. Cari</i>	<i>Eunotia exigua</i>
<i>Nitzshia paleaeformis</i>	<i>Frustulia sp.</i>
<i>Pinnularia microstauron</i>	<i>Rhopalodia gibberula</i>
	<i>Surirella tenera</i>
	<i>Tabellaria flocculosa</i>

### 5.3 Marron

The large endemic freshwater crayfish marron (*Cherax cainii*) provides a prized recreational fishery in many regional parts of south-western Australia, including Collie (Whiting *et al.*, 2000). Increasing human populations have impacted on natural marron stocks and the quality of the recreational fishery (Molony *et al.*, 2001). Marron were introduced to Collie pit lakes along with other non-fishery species of crayfish. This marron fishery serves as an example of how mining activities can contribute to sustainable economic opportunities in a post-mining landscape. However, a previous study using solely water quality data suggested Collie pit lake marron were distressed by acidic conditions and that this physiological stress was limiting population sizes (Storer *et al.*, 2002).

McCullough *et al.* (2009) evaluated the marron and other crayfish fisheries of 5 pit lakes over two days in mid-September 2005. Crayfish were captured with three black ‘Opera House’ traps set overnight around the littoral margin of each lake (Campbell & Whisson, 2000). In 2009, crayfish were also surveyed for during April and November 2009 with sweep nets and 10 m Japanese Seine transects along the littoral fringe.

Acidic pit lakes differ from natural water bodies in more ways than just their water chemistry and this current study also simultaneously measured a holistic suite of parameters in addition to water quality; including habitat, inter-specific competition and food resource type and availability. These previously unconsidered environmental parameters may be more important to the crayfish marron fishery in Collie pit lakes. For example, refugia such as fallen logs and rocky outcrops often form important refuge habitat from predation and competition in water bodies (Foster, 1993). Indeed, much like other constructed water bodies (such as dams), pit lakes typically display very poor benthic habitat structure as required by large animals such as fish and crayfish and there is often strong competition for these physical resources (Foster, 1993). Further competition for depauperate food resources by other species of crayfish co-occurring in pit lakes may also limit marron population health (France, 1996). Such competition may be for typically limited food resources in pit lakes of algae and organic detritus (Kalin *et al.*, 2001). These simple ecological principles may

best explain limitations to marron in acidic pit lakes where previous assessment of water quality alone has not (Table 28).

**Table 28.** Marron presence and abundance in Collie pit lakes from 1997–1999 surveys of Storer et al. (2002), McCullough et al. (2009b), September 2005 marron surveying (catch per trap night)\*and April and November 2009 surveying with sweep nets. P = present, - = no data collected.

	Lake	Marron	Gilgies ( <i>C. quinquecarinatus</i> )	Koonacs ( <i>C. plebejus</i> )
1997– 1999	Blue Waters	P	-	-
	Ewington	P	-	-
2005	Black Diamond	4	0	0
	Blue Waters	7	0	0
	Centaur	6	0	0
	Ewington	2	8	1
	Stockton	10	0	0
2009	Lake WO5D*	0	Abundant	0

#### 5.4 Finfish

*Gambusia holbrooki* and an endemic galaxiid fish (probably western minnow, *Galaxias occidentalis*) was first recorded by Lyons (1997) during sweep net sampling of Lake Stockton aquatic vegetation in Spring 1997. C. McCullough (MiWER) has also observed a dead western minnow in Lake Stockton during Spring 2005.

The endemic western pygmy perch (*Nannoperca vittata*, formerly *Edelia vitta*) were also observed in Black Diamond Lake in 2005 coexisting with previously recorded feral freshwater poeciliid *Gambusia* (*Gambusia holbrooki*). Both fish are primarily surface feeders, therefore introduced *Gambusia* probably compete directly with pygmy perch for allochthonous invertebrate foods.

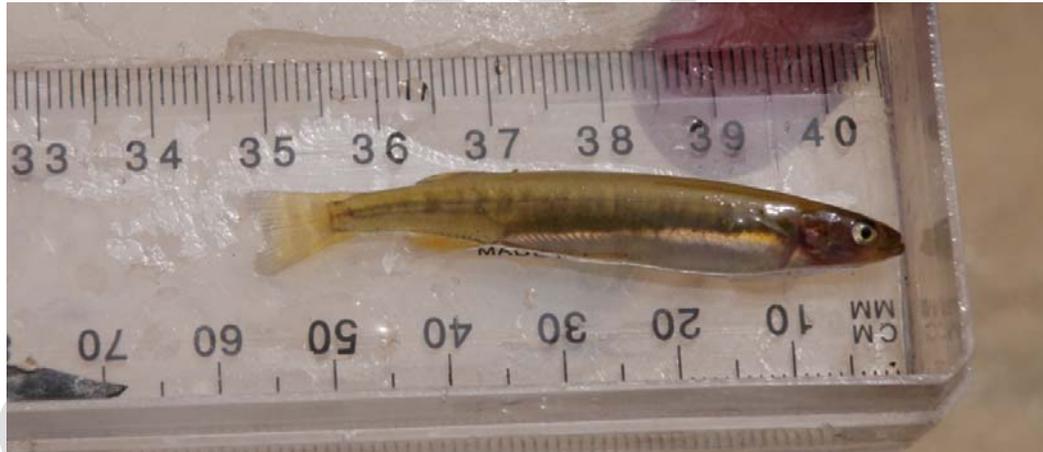
A study by Thomas and John (2006) does not give methods or sources of information but comments that western-pigmy perch were observed in Stockton Lake in 2004.

Finfish diversity and abundance was found to be low in the four pit lakes studied during the November 2009 survey (Table 29, Figure 74, Figure 75, Figure 76). Finfish diversity and abundance also both increased with increasing lake pH, indicating pit lake water toxicity may limit some species. For example, *G. occidentalis* was only

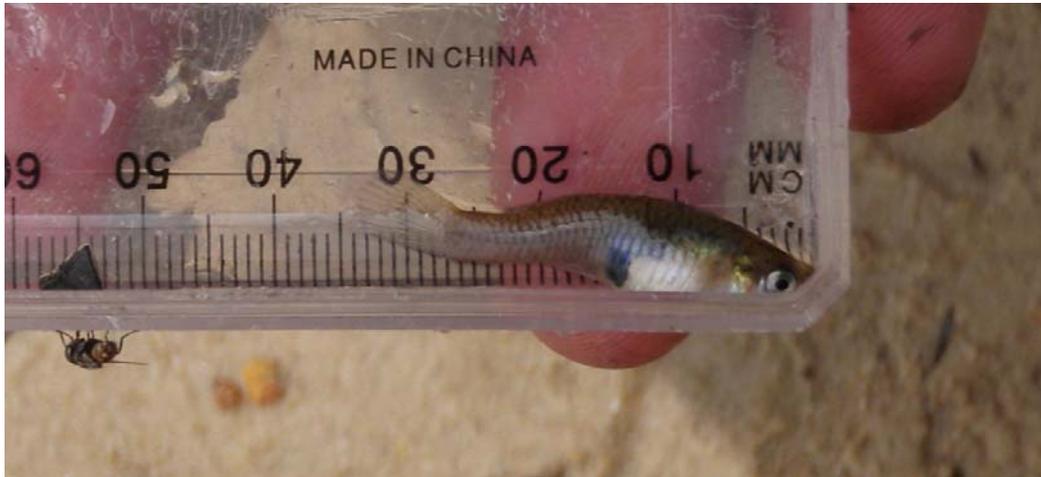
found in Lake Centaur, although individuals have historically be found in more acidic Lake Stockton in 1997 (Lyons, 1997) and a dead individual was collected floating in 2005 (C. McCullough, MiWER/ECU, pers. obs.). Although western pygmy perch were found in Stockton Lake in the November 2009 survey, one of the two individuals showed significant damage to the caudal fin, consistent with lesions resulting from too acidic water. It is also suspected that the beaches where they were captured may have less acidic water as a result of natural stream flow into the lake at these points shown by more turbid and less blue water colour suggesting that they were no surviving in the main lake, just in areas near the stream.

**Table 29.** Results of November 2009 Collie pit lakes fisheries sampling and surface water pH at time of sampling.

Lake	pH	<i>Edelia vittata</i>	<i>Galaxias occidentalis</i>	<i>Gambusia holbrooki</i>
Kepwari	4.3	0	0	0
Black Diamond	4.4	1	0	0
Stockton	4.5	2	0	0
Centaur	6.6	1	8	25



**Figure 74.** Healthy adult Western minnow (Galaxiidae: *Galaxias occidentalis*) caught in Lake Centaur, November 2009.



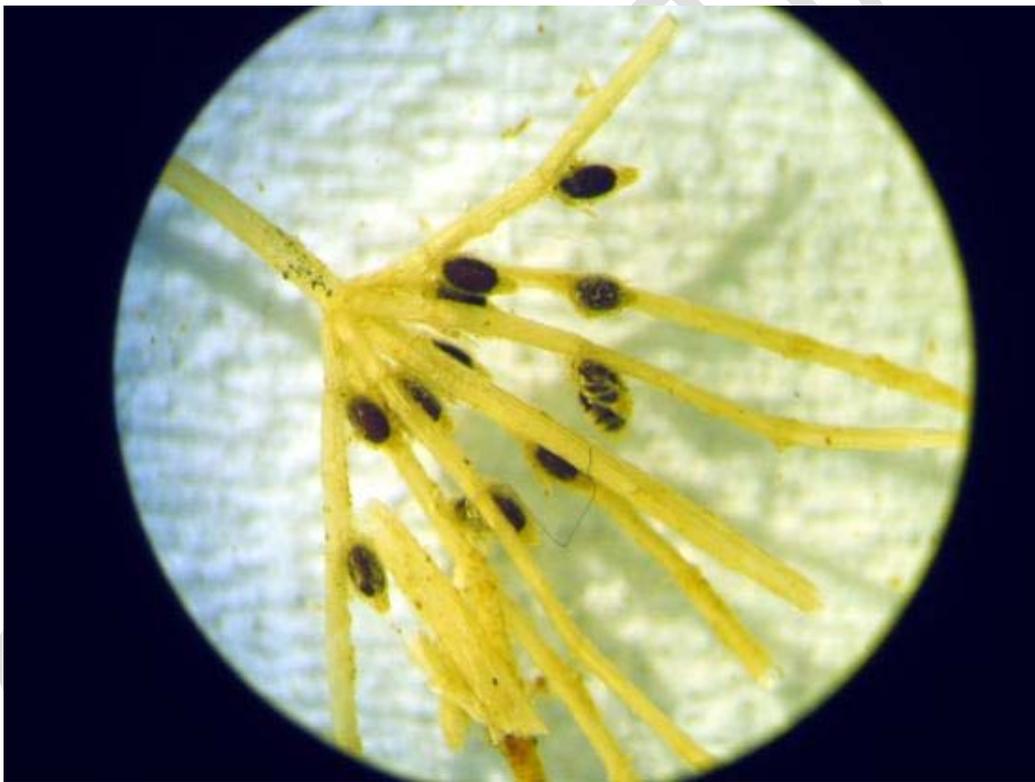
**Figure 75.** One of the very common *Gambusia* (Poeciliidae: *Gambusia holbrooki*) caught in Lake Centaur, November 2009. This individual is a mature gravid female.



**Figure 76.** Western pygmy perch (Nannopercidae: *Nannoperca vittata*) from Lake Stockton, November 2009. Note: caudal fin damage.

## 5.5 Aquatic plants

Characean algae have been observed in Black Diamond Lake during SCUBA surveys since 1997 (Lund *et al.*, 2000b). Although no specific surveys have been carried out for the presence of characean algae, characean vegetation have not been observed in any other lakes which have had work undertaken in them by SCUBA i.e., all of the historic pit lakes and Lake Kepwari. Black Diamond Lake charophytes sampled by grapnel from shore (C. McCullough, MiWER pers. obs.) in Spring 2006 were fertile and were identified as *Chara globularis* sp. and *Nitella* sp (Mary De Winton pers. comm., NIWA, New Zealand) (Figure 77).



**Figure 77.** Fertile Characean algae sampled from Lake Black Diamond in 2006.



## 6 Beneficial End-uses of Pit Lakes

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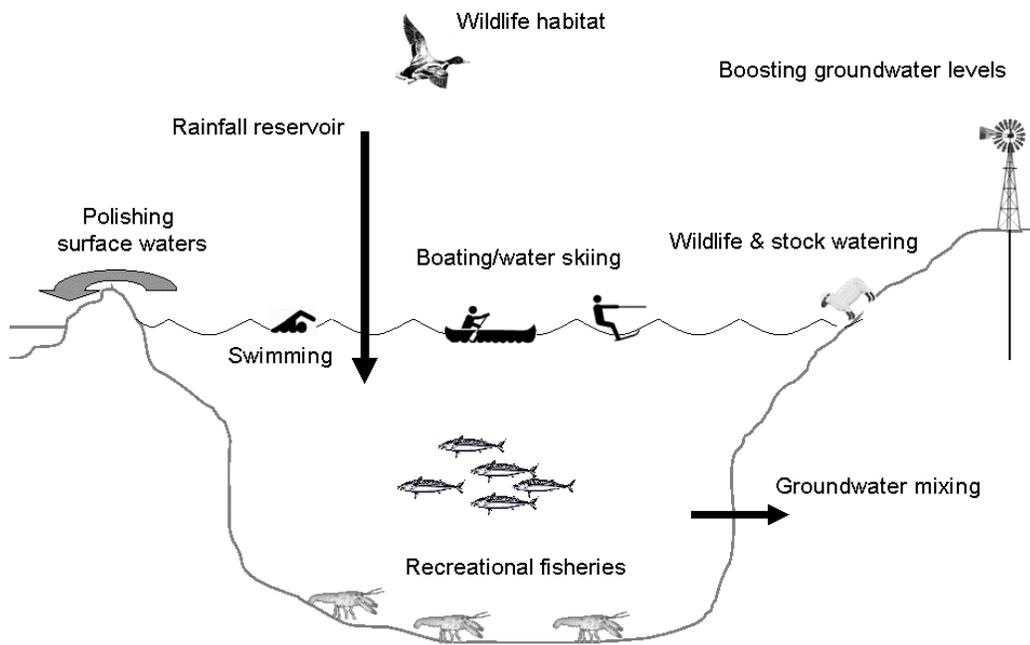
### 6.1 Background

Due to operational and regulatory practicalities, pit lakes will continue to be common legacies of mine lease relinquishments. Unplanned or inappropriate management of these novel geographical features can lead to both short- and long-term liability to mining companies, local communities, the government and the nearby environment during mining operations or after lease relinquishment. However, the potential for pit lakes to provide many and diverse benefits to companies, communities, and the environment is frequently unrecognised and yet may be a vital contribution to the sustainability of the open-cut mining industry (Figure 78). Sustainable pit lake management aims to minimise short and long term pit lake liabilities and maximise short and long term pit lake opportunities. Improved remediation technologies are offering more avenues for pit lakes resource exploitation than ever before, at the same time mining companies, local communities, and regulatory authorities are becoming more aware of the benefit these resources can offer.

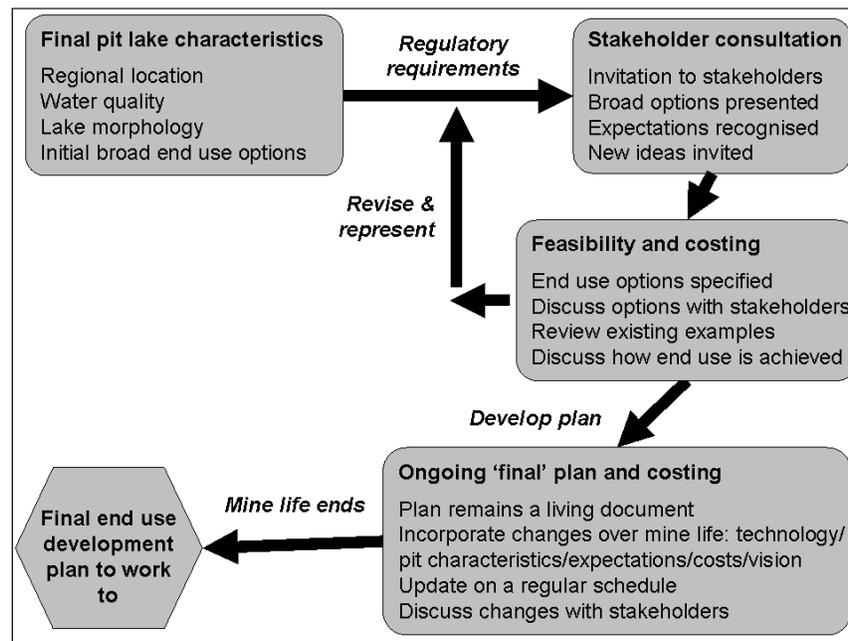
In Australia, as in many countries (McCullough *et al.*, 2009a), mining companies are given no prior advice on acceptable end use options. Rather, mining companies interested in developing an end-use approach regulatory authorities with their preferred option and then these agencies make judgements as to whether this end-use is acceptable (Figure 79). Nevertheless, most developed countries and states are consistent in their requirement for mining companies to plan and/or rehabilitate to minimise or prevent entirely any potential deleterious effects of the pit lake water body on regional ground and surface resources (Miller, 2002). The focus of most general or *ad hoc* pit lake regulation is given to protecting human and ecological communities from effects of the pit lake. For example, in Australasia, closure guidelines are based on ANZECC/ARMCANZ (2000) criteria (generally for a combination of, drinking water, recreation or ecological requirements). Such guidelines generally emphasize either a demonstration of null-negative effects of the lake when treated passively, or require active management to achieve the required level for compliance (Kuipers, 2002). Nevertheless, where regulatory guidelines for natural systems such as natural lakes are applied to pit lakes (e.g., Minnesota (Axler *et*

*al.*, 1998)), end use opportunities may be rendered unavailable if inappropriately high environmental and social values are placed on these artificial systems. However, an onus still remains with industry to demonstrate that such values are not able or viable to be reached.

Lack of knowledge of state-of-the-art rehabilitation strategies and capabilities (such as remediation techniques) by regulators may also produce a strong deterrent for companies wishing to engage in end use development activities (McCullough *et al.*, 2006).



**Figure 78.** Some potential benefits of pit lakes to communities and the environment (after McCullough and Lund, 2006).



**Figure 79.** Planning steps for successful pit lake development and relinquishment to an accepted end use (after McCullough *et al.* (2009a).

Social pit lake amenity opportunities, such as recreational swimming, are organic developments of their communities and, whilst often unrecognised and unregulated by local authorities, are already well-established in many mining regions with reasonable pit lake water quality. However, health risks associated with pit wall failures can limit public access to lakes. Other pit lake amenity developments will require more foresight and planning, for example sailing and water skiing activities require access roads, boat ramps and other such infrastructure. To be successful, such planned opportunities require specific and direct support from mining companies, regulatory authorities; and most importantly, the willingness and acceptance of the local communities that they are intended to benefit. Where social and economical benefit can be demonstrated to communities from such ventures, strong support is likely. Infrastructure also already exists at mine sites for future industry to develop. For example, aquaculture and irrigation may provide for either new industries, or extensions to existing industries, directly contributing to local business ventures, employment and income.

In order for pit lakes to be a viable relinquishment option for a company, community and the environment, a management strategy for the development and final form of the pit lake should be considered well before rehabilitation operations have begun (Evans & Ashton, 2000; Evans, 2006). If a new mine is considered from the perspective of a beneficial landscape following mining in addition to extracting resources, then there is a much greater chance of obtaining an economically feasible and sustainable outcome. Generally, unless the company is conducting multiple mining operations in the vicinity of an abandoned mine, it becomes much more difficult economically to undertake major rehabilitation or remediation works as plant and labour for earthworks then must be specially brought in (Beutler, 2003). In summary, it is clear that pit lakes need to be planned for, not only to minimise risks, but also to maximise opportunities for end-use benefit.

Beneficial end-uses investigated for Collie pit lakes to date 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. 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.*, 2009a). Although the generally high water quality of the Collie 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).

## **6.2 Suitability of pit lakes for likely enduses**

In order to provide a resource for both pit lake managers (industry and government) and also potential users of this vast resource, the pit lake water quality database collated in this study was compared with various published end-use guidelines for different likely end-uses for that area to determine how useful each lake is for that particular end-use. The end-uses examined for the Collie Pit Lake District were for short/long-term irrigation, freshwater aquaculture and livestock drinking water, and aquatic biota environmental guidelines. Human beneficial end use activities including drinking and primary and secondary contact were not included in this study as they are considered in Task 2 of this programme (see Hinwood *et al.* in prep.). Although

this approach can suggest potential end uses for specific pit lakes, social and economic considerations are over-riding drivers in determining final appropriateness of actual lake end use.

### **6.2.1 Crop Irrigation**

#### *6.2.1.1 Long-Term Irrigation*

In order to ascertain the usefulness of the water reserve in the Collie Lake District for long and short-term irrigation of crops, the water quality of Collie pit lakes was compared to default ANZECC/ARMCANZ guideline trigger values for primary production (2000c).

Water quality in historic Collie pit lakes for long-term plant irrigation appears to be primarily limited by low pH and associated high iron and manganese concentrations (Table 30, Table 31). Although high salinity (measured as EC) appeared high across all historic pit lakes, only one pit lake (Blue Waters Lake) has sodium concentrations exceeding long-term irrigation guidelines. High total phosphorus concentrations also appear to limit use of Collie pit lake water from historic lakes.

New Collie pit lakes have the same limitations to end use as sources of long-term irrigation waters as the historic pit lakes (Table 32, Table 33). However, salinity is more likely to be restrictive (particularly in Chicken Creek 4 and in Lake Kepwari) as result of Collie River diversion activities. In addition to the high iron concentration issues of the historic pit lakes, light and heavy metal concentrations in the new pit lakes are also higher than long-term irrigation guidelines by a factor of two or more.

**Table 30.** Suitability of historic and Premier sub-basin pit lake waters for long-term irrigation. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	Irrigation long-term trigger value (up to 100 years)	Black Diamond	Black Diamond	Blue Waters	Centaur	Ewington	Stockton	Chicken Creek 4	Chicken Creek 5
		A	B						
		2009	1994	2009	2009	2008	2009	2009	2009
pH	6 - 9	<b>4.4 (2 3)</b>	—	<b>3.9 (3 3)</b>	6.6 (2)	<b>3.9 (4 4)</b>	<b>4.5 (7 8)</b>	<b>3.3 (3 3)</b>	<b>2.5 (2 2)</b>
EC (mS cm <sup>-1</sup> )	0.95 - 1.9 (moderately sensitive)	0.584 (3)	—	1.880 (3)	<b>3.180 (2 2)</b>	1.490 (4)	0.506 (6)	<b>7.550 (3 3)</b>	<b>2.970 (2 2)</b>
Cl	175 - 350 (moderately sensitive)	144 (2)	—	<b>540 (1 2)</b>	<b>370 (1 1)</b>	—	110 (4)	<b>2017 (2 2)</b>	<b>460 (1 2)</b>
TP (µg L <sup>-1</sup> )	50	<b>206 (2 2)</b>	—	<b>102 (1 1)</b>	<b>73 (1 1)</b>	—	<b>51 (1 3)</b>	<b>68 (2 2)</b>	<b>68 (1 2)</b>
TN (µg L <sup>-1</sup> )	5000	284 (2)	—	237 (1)	651 (1)	—	213 (3)	546 (2)	1469 (2)
As	0.1	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	0.06 (1)	0.08 (1)	<0.05 [2]
Al	5	0.10 (2)	—	3.40 (3)	0.40 (1)	0.90 (1)	1.36 (5)	<b>6.28 (1 3)</b>	<b>11.29 (2 2)</b>
Be	0.1	—	—	—	—	—	—	—	—
B	0.5	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	<0.05 [2]	<0.05 [2]	<0.05 [2]
Cd	0.01	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.001 [1]	0.00 (1)	<0.01 [3]	<0.01 [2]
Co	0.05	<0.01 [2]	—	0.05 (1)	<0.01 [1]	—	0.03 (1)	<b>0.07 (2 2)</b>	<b>0.13 (2 2)</b>
Cr	0.1	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.001 [1]	<0.01 [3]	<0.01 [3]	<0.01 [2]
Cu	0.2	<0.05 [1]	—	<0.05 [2]	<0.05 [1]	0.01 (1)	<0.05 [3]	<0.05 [2]	<0.05 [1]
Fe	0.2	0.05 (2)	—	<b>0.78 (2 3)</b>	<b>0.58 (1 1)</b>	<b>0.40 (1 1)</b>	0.14 (3)	<b>4.18 (3 3)</b>	<b>19.12 (2 2)</b>
Hg	0.002	0.24 (1)	—	<0.1 [1]	<0.1 [1]	—	<0.1 [2]	<0.1 [2]	<0.1 [2]
Li	2.5 (0.075 Citrus crops)	—	—	—	—	—	—	—	—

Parameter (mg L <sup>-1</sup> )	Irrigation long-term trigger value (up to 100 years)	Black Diamond	Black Diamond	Blue Waters	Centaur	Ewington	Stockton	Chicken Creek 4	Chicken Creek 5
		A	B						
		2009	1994	2009	2009	2008	2009	2009	2009
Mn	0.2	<b>0.22 (1 2)</b>	—	<b>0.25 (1 2)</b>	0.11 (2)	0.02 (1)	0.14 (3)	<b>0.30 (2 3)</b>	<b>1.05 (2 2)</b>
Mo	0.01	—	—	—	—	—	—	—	—
Na	115 - 230 (moderately sensitive)	42 (2)	—	<b>250 (1 2)</b>	<b>406 (1 1)</b>	—	47 (2)	<b>1098 (2 2)</b>	<b>887 (2 2)</b>
Ni	0.2	0.04 (2)	—	0.06 (1)	0.05 (1)	0.02 (1)	0.08 (3)	0.12 (3)	<b>0.21 (1 2)</b>
Pb	2	<0.1 [1]	0.050 (4)	0.004 (1)	<0.1 [1]	0.003 (1)	<0.1 [1]	0.001 (1)	<0.1 [1]
Se	0.02	<0.2 [1]	—	—	<0.2 [1]	—	<0.2 [1]	<0.2 [1]	<0.2 [1]
U	0.01	<0.05 [1]	—	0.0001 (1)	<0.05 [1]	—	<0.05 [1]	<b>0.1234 (1 1)</b>	<0.05 [1]
V	0.1	—	0.10 (1)	—	—	—	—	0.00 (1)	—
Zn	2	<0.05 [1]	0.36 (4)	0.05 (1)	<0.05 [1]	0.02 (1)	0.12 (1)	0.32 (2)	0.69 (2)

**Table 31.** Suitability of Cardiff sub-basin pit lake waters for long-term irrigation. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Irrigation		Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
Parameter	long-term trigger value	2009	2009	2009	2009	2009	2009	2009
(mg L <sup>-1</sup> )	(up to 100 years)							
pH	6 - 9	<b>4.3 (7 7)</b>	<b>3.6 (2 2)</b>	<b>3.8 (2 2)</b>	<b>3.2 (1 1)</b>	<b>3.9 (2 2)</b>	<b>5.1 (1 2)</b>	<b>3.0 (6 6)</b>
EC (mS cm <sup>-1</sup> )	0.95 - 1.9 (moderately sensitive)	<b>3.000 (3 3)</b>	1.330 (2)	<b>2.140 (1 2)</b>	1.670 (1)	0.880 (2)	0.435 (2)	1.496 (2)
Cl	175 - 350 (moderately sensitive)	<b>846 (6 6)</b>	123 (2)	274 (2)	161 (2)	105 (2)	94 (2)	190 (6)
TP (µg L <sup>-1</sup> )	50	<b>68 (1 2)</b>	<b>128 (2 2)</b>	<b>176 (1 2)</b>	<b>59 (1 2)</b>	<b>55 (1 2)</b>	50 (2)	<b>61 (1 2)</b>
TN (µg L <sup>-1</sup> )	5000	1164 (2)	748 (2)	<b>26792 (2 2)</b>	2890 (2)	1199 (2)	1227 (2)	735 (2)
As	0.1	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	0.06 (1)
Al	5	<b>5.51 (1 2)</b>	<b>38.93 (2 2)</b>	<b>19.08 (2 2)</b>	<b>75.95 (2 2)</b>	<b>6.93 (1 1)</b>	0.37 (2)	<b>23.65 (2 2)</b>
Be	0.1	–	–	–	–	–	–	–
B	0.5	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	<0.05 [2]
Cd	0.01	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Co	0.05	<b>0.10 (2 2)</b>	<b>0.51 (2 2)</b>	<b>0.30 (2 2)</b>	<b>0.70 (2 2)</b>	<b>0.17 (1 1)</b>	<0.01 [2]	<b>0.29 (2 2)</b>
Cr	0.1	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Cu	0.2	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	–	<0.05 [1]	<0.05 [1]
Fe	0.2	<b>6.93 (5 6)</b>	<b>2.31 (2 2)</b>	<b>1.19 (2 2)</b>	<b>6.13 (2 2)</b>	0.05 (1)	0.05 (2)	<b>7.76 (6 6)</b>
Hg	0.002	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [1]	<0.1 [2]	<0.1 [2]
Li	2.5 (0.075 Citrus crops)	–	–	–	–	–	–	–
Mn	0.2	<b>0.62 (6 6)</b>	<b>0.46 (2 2)</b>	<b>1.55 (2 2)</b>	0.11 (1)	0.06 (1)	0.06 (2)	<b>2.36 (6 6)</b>
Mo	0.01	–	–	–	–	–	–	–
Na	115 - 230 (moderately)	<b>427 (6 6)</b>	103 (2)	196 (2)	101 (2)	41 (1)	63 (2)	153 (6)

	Irrigation	Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
Parameter	long-term trigger value	2009	2009	2009	2009	2009	2009	2009
(mg L <sup>-1</sup> )	(up to 100 years sensitive)							
Ni	0.2	0.09 (2)	<b>0.51 (2 2)</b>	<b>0.24 (2 2)</b>	<b>0.65 (1 2)</b>	0.12 (1)	0.07 (2)	<b>0.39 (2 2)</b>
Pb	2	<0.1 [2]	0.005 (1)	<0.1 [1]	<0.1 [1]	<0.1 [1]	<0.1 [1]	0.012 (2)
Se	0.02	<0.2 [2]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	0.00 (2)
U	0.01	<b>0.0606 (2 2)</b>	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]
V	0.1	—	—	—	—	—	—	0.00 (2)
Zn	2	0.57 (2)	<b>4.00 (1 2)</b>	1.33 (1)	<b>4.09 (1 1)</b>	0.68 (1)	<0.05 [1]	<b>2.02 (1 3)</b>

6.2.1.2 *Short-Term Irrigation*

Short-term irrigation end use opportunities for historic Collie pit lakes show little issue with the use of this water resource (Table 28 and 29). Although there are salinity issues with all pit lakes, this is likely simply due to the use of electrical conductivity as a measure for salinity rather than any real issues as (aside from sodium in Blue Waters Lake) both sodium and chloride concentrations of all historic lakes are at acceptable levels for short term irrigation. Although there are no current ANZECC/ARMCANZ (2000c) guidelines for short-term irrigation by acidic waters, this parameter is likely to be an important requirement for validation, however, before historic Collie pit lake water was used for this end-use.

Short-term irrigation use of water from new Collie pit lakes is also limited by the high sodium chloride concentrations in Chicken Creek 4, and 5 and Lake Kepwari. There may also be potential high salinity issues of the other new pit lake waters as well due to their high EC although sodium and chloride concentrations of these other lakes are generally low (Table 29). Nevertheless, both high concentrations of aluminium and also of cobalt may be of more serious concern to limiting short term irrigation by new mine lakes in Collie.

**Table 32.** Suitability of historic and Premier sub-basin pit lake water for short-term irrigation. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	Irrigation short-term trigger value (up to 20 years)	Black Diamond	Black Diamond	Blue Waters	Centaur	Ewington	Stockton	Chicken Creek 4	Chicken Creek 5
		A	B						
		2009	1994	2009	2009	2008	2009	2009	2009
pH	nd 1.9 - 4.5 (moderately tolerant)	4.4 (3)	—	3.9 (3)	6.6 (2)	3.9 (4)	4.5 (8)	3.3 (3)	2.5 (2)
EC (mS cm <sup>-1</sup> )	350 - 700 (moderately tolerant)	0.584 (3)	—	1.880 (3)	3.180 (2)	1.490 (4)	0.506 (6)	<b>7.550 (3 3)</b>	2.970 (2)
Cl	800 - 12000	144 (2)	—	540 (2)	370 (1)	—	110 (4)	<b>2017 (2 2)</b>	460 (2)
TP (µg L <sup>-1</sup> )	25000 - 125000	206 (2)	—	102 (1)	73 (1)	—	51 (3)	68 (2)	68 (2)
TN (µg L <sup>-1</sup> )	2	284 (2)	—	237 (1)	651 (1)	—	213 (3)	546 (2)	1469 (2)
As	20	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	0.1 (1)	0.1 (1)	<0.05 [2]
Al	0.5	0.1 (2)	—	3.4 (3)	0.4 (1)	0.9 (1)	1.4 (5)	6.3 (3)	11.3 (2)
Be	1.0 (Sensitive crops)	—	—	—	—	—	—	—	—
B	0.05	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	<0.05 [2]	<0.05 [2]	<0.05 [2]
Cd	0.1	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.001 [1]	0.00 (1)	<0.01 [3]	<0.01 [2]
Co	1	<0.01 [2]	—	0.05 (1)	<0.01 [1]	—	0.03 (1)	0.07 (2)	<b>0.13 (1 2)</b>
Cr	5	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.001 [1]	<0.01 [3]	<0.01 [3]	<0.01 [2]
Cu	10	<0.05 [1]	—	<0.05 [2]	<0.05 [1]	0.01 (1)	<0.05 [3]	<0.05 [2]	<0.05 [1]
Fe	0.002	0.05 (2)	—	0.78 (3)	0.58 (1)	0.40 (1)	0.14 (3)	4.18 (3)	<b>19.12 (1 2)</b>
Hg	2.5 (0.075 Citrus)	<b>0.24 (1 1)</b>	—	<0.1 [1]	<0.1 [1]	—	<0.1 [2]	<0.1 [2]	<0.1 [2]
Li		—	—	—	—	—	—	—	—

Parameter (mg L <sup>-1</sup> )	Irrigation short-term trigger value (up to 20 years) crops)	Black Diamond	Black Diamond	Blue Waters	Centaur	Ewington	Stockton	Chicken Creek 4	Chicken Creek 5
		A	B						
		2009	1994	2009	2009	2008	2009	2009	2009
Mn	10	0.22 (2)	—	0.25 (2)	0.11 (2)	0.02 (1)	0.14 (3)	0.30 (3)	1.05 (2)
Mo	0.05	—	—	—	—	—	—	—	—
Na	230 - 460 (moderately tolerant )	42 (2)	—	250 (2)	406 (1)	—	47 (2)	<b>1098 (2 2)</b>	<b>887 (1 2)</b>
Ni	2	0.04 (2)	—	0.06 (1)	0.05 (1)	0.02 (1)	0.08 (3)	0.12 (3)	0.21 (2)
Pb	5	<0.1 [1]	0.050 (4)	0.004 (1)	<0.1 [1]	0.003 (1)	<0.1 [1]	0.001 (1)	<0.1 [1]
Se	0.05	<0.2 [1]	—	—	<0.2 [1]	—	<0.2 [1]	<0.2 [1]	<0.2 [1]
U	0.1	<0.05 [1]	—	0.0001 (1)	<0.05 [1]	—	<0.05 [1]	<b>0.1234 (1 1)</b>	<0.05 [1]
V	0.5	—	0.10 (1)	—	—	—	—	0.00 (1)	—
Zn	5	<0.05 [1]	0.36 (4)	0.05 (1)	<0.05 [1]	0.02 (1)	0.12 (1)	0.32 (2)	0.69 (2)

**Table 33.** Suitability of Cardiff sub-basin pit lake waters for short-term irrigation. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	Irrigation short-term trigger value (up to 20 years)	Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
		2009	2009	2009	2009	2009	2009	2009
pH	nd	4.3 (7)	3.6 (2)	3.8 (2)	3.2 (1)	3.9 (2)	5.1 (2)	3.0 (6)
EC (mS cm <sup>-1</sup> )	1.9 - 4.5 (moderately tolerant) 350 - 700 (moderately tolerant)	3.000 (3)	1.330 (2)	2.140 (2)	1.670 (1)	0.880 (2)	0.435 (2)	1.496 (2)
Cl	800 - 12000	<b>846 (5 6)</b>	123 (2)	274 (2)	161 (2)	105 (2)	94 (2)	190 (6)
TP (µg L <sup>-1</sup> )	800 - 12000	68 (2)	128 (2)	176 (2)	59 (2)	55 (2)	50 (2)	61 (2)
TN (µg L <sup>-1</sup> )	25000 - 125000	1164 (2)	748 (2)	26792 (2)	2890 (2)	1199 (2)	1227 (2)	735 (2)
As	2	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	0.1 (1)
Al	20	5.5 (2)	<b>38.9 (2 2)</b>	19.1 (2)	<b>76.0 (1 2)</b>	6.9 (1)	0.4 (2)	<b>23.7 (1 2)</b>
Be	0.5	—	—	—	—	—	—	—
B	1.0 (Sensitive crops)	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	<0.05 [2]
Cd	0.05	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Co	0.1	<b>0.10 (1 2)</b>	<b>0.51 (2 2)</b>	<b>0.30 (2 2)</b>	<b>0.70 (1 2)</b>	<b>0.17 (1 1)</b>	<0.01 [2]	<b>0.29 (2 2)</b>
Cr	1	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Cu	5	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	—	<0.05 [1]	<0.05 [1]
Fe	10	6.93 (6)	2.31 (2)	1.19 (2)	6.13 (2)	0.05 (1)	0.05 (2)	7.76 (6)
Hg	0.002	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [1]	<0.1 [2]	<0.1 [2]
Li	2.5 (0.075 Citrus crops)	—	—	—	—	—	—	—
Mn	10	0.62 (6)	0.46 (2)	1.55 (2)	0.11 (1)	0.06 (1)	0.06 (2)	2.36 (6)
Mo	0.05	—	—	—	—	—	—	—

Parameter (mg L <sup>-1</sup> )	Irrigation short-term trigger value (up to 20 years)	Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
		2009	2009	2009	2009	2009	2009	2009
Na	230 - 460 (moderately tolerant )	427 (6)	103 (2)	196 (2)	101 (2)	41 (1)	63 (2)	153 (6)
Ni	2	0.09 (2)	0.51 (2)	0.24 (2)	0.65 (2)	0.12 (1)	0.07 (2)	0.39 (2)
Pb	5	<0.1 [2]	0.005 (1)	<0.1 [1]	<0.1 [1]	<0.1 [1]	<0.1 [1]	0.012 (2)
Se	0.05	<0.2 [2]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	0.00 (2)
U	0.1	0.0606 (2)	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]
V	0.5	—	—	—	—	—	—	0.00 (2)
Zn	5	0.57 (2)	4.00 (2)	1.33 (1)	4.09 (1)	0.68 (1)	<0.05 [1]	2.02 (3)

### 6.2.2 Freshwater Aquaculture Values

Aquaculture is already an option that has, and is currently, being explored in the Collie region with water from mining lakes. In order to determine the potential for Collie pit lake water for direct application to aquaculture the water quality of Collie pit lakes was compared to default ANZECC/ARMCANZ guideline trigger values for protection of 90% of aquaculture species (2000c). Nevertheless, it should be emphasised that aquaculture in its current form in Collie has used a simple remediation system of limestone chip acidity neutralisation which has been found to increase pH and reduce concentrations of both light and heavy toxic metals (Evans *et al.*, 2005) rather than direct pit lake water application. Where this remediation system has failed, the pit lake water has been shown to be highly toxic to typical aquaculture species (Stephens & Ingram, 2006).

Historic Collie pit lakes appear to be limited in their current potential for freshwater aquaculture without remediation due to a number of water quality parameters failing to be met (Table 30). Not surprisingly given the acidic nature of Collie pit lakes, pH is limiting to aquaculture end-use opportunities in all historic pit lakes but more circum-neutral Centaur. Chloride concentrations are known to be exceeded in most water bodies as are total phosphorus, NO<sub>x</sub> and ammonia nutrients. Where data are available, most light and heavy metals also appear to be above ANZECC/ARMCANZ (2000c) guidelines.

The new Collie pit lake water resources appear to require more treatment of water quality to be suitable for use in aquaculture than historic pit lakes (Table 31). Almost every single parameter required meet for 90% aquaculture species protection is exceeded by most new pit lakes; from basic physico-chemistry to concentrations of nutrients and metals.

Nevertheless, as seen by previous and current aquaculture of silver perch and marron, remediation of low pH e.g., by limestone neutralisation, may resolve many of these water quality issues and allow use of the pit lake resource for the extensive aquaculture opportunities that may exist in this region.

**Table 34.** Useability of historic and Premier sub-basin pit lake waters for freshwater aquaculture. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	90% Aquaculture Species Freshwater	Black Diamond	Black Diamond	Blue Waters 2009	Centaur 2009	Ewington 2008	Stockton 2009	Chicken Creek 4 2009	Chicken Creek 5 2009
		A 2009	B 1994						
Temp (oC)		20.3 (2)	—	20.5 (3)	18.6 (2)	22.2 (2)	20.7 (6)	19.4 (3)	20.8 (2)
pH	5.0 - 9.0	<b>4.4 (1 3)</b>	—	<b>3.9 (1 3)</b>	6.6 (2)	<b>3.9 (4 4)</b>	<b>4.5 (2 8)</b>	<b>3.3 (3 3)</b>	<b>2.5 (2 2)</b>
Salinity (ppt)	<3000	—	—	—	—	—	—	—	—
Dissolved oxygen	>5	8.3 (3)	—	9.2 (2)	7.3 (1)	—	7.5 (6)	8.6 (2)	8.6 (2)
TSS	<40	—	—	16.0 (2)	—	11.0 (1)	10.0 (3)	10.0 (1)	—
Alkalinity	>20	—	—	—	—	—	—	—	—
Cl	3	<b>144 (2 2)</b>	—	<b>540 (2 2)</b>	<b>370 (1 1)</b>	—	<b>110 (4 4)</b>	<b>2017 (2 2)</b>	<b>460 (2 2)</b>
TP (µg L <sup>-1</sup> )	100	<b>206 (2 2)</b>	—	<b>102 (1 1)</b>	73 (1)	—	51 (3)	68 (2)	68 (2)
TN (µg L <sup>-1</sup> )	1000	284 (2)	—	237 (1)	651 (1)	—	213 (3)	546 (2)	<b>1469 (2 2)</b>
NO <sub>x</sub> (µg L <sup>-1</sup> )	100	<b>162 (2 2)</b>	—	<b>181 (1 1)</b>	30 (1)	—	51 (3)	86 (2)	88 (2)
NH <sub>4</sub> (µg L <sup>-1</sup> )	20 (un-ionised) (pH >8.0)	<b>80 (2 2)</b>	<b>66 (6 6)</b>	<b>37 (1 1)</b>	<b>115 (1 1)</b>	—	<b>154 (2 3)</b>	<b>355 (2 2)</b>	<b>1151 (2 2)</b>
NO <sub>3</sub> (µg L <sup>-1</sup> )	50000	—	261 (3)	—	—	—	—	—	—
As	0.05	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	<b>0.06 (1 1)</b>	<b>0.08 (1 1)</b>	<0.05 [2]
Al	0.03 (pH > 6.5) 0.01 (pH < 6.5)	<b>0.10 (2 2)</b>	—	<b>3.40 (3 3)</b>	<b>0.40 (1 1)</b>	<b>0.90 (1 1)</b>	<b>1.36 (5 5)</b>	<b>6.28 (3 3)</b>	<b>11.29 (2 2)</b>
Ag	0.003	—	—	—	—	—	—	—	—
Cd	<0.2–1.8	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.01 [1]	0.00 (1)	<0.01 [3]	<0.01 [2]
Cr	0.02	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.01 [1]	<0.01 [3]	<0.01 [3]	<0.01 [2]
Cu	0.005	<0.05 [1]	—	<0.05 [2]	<0.05 [1]	<b>0.01 (1 1)</b>	<0.05 [3]	<0.05 [2]	<0.05 [1]
Fe	0.01	<b>0.05 (2 2)</b>	—	<b>0.78 (3 3)</b>	<b>0.58 (1 1)</b>	<b>0.40 (1 1)</b>	<b>0.14 (3 3)</b>	<b>4.18 (3 3)</b>	<b>19.12 (2 2)</b>

Parameter (mg L <sup>-1</sup> )	90% Aquaculture Species Freshwater	Black Diamond A 2009	Black Diamond B 1994	Blue Waters 2009	Centaur 2009	Ewington 2008	Stockton 2009	Chicken Creek 4 2009	Chicken Creek 5 2009
Hg	0.001	<b>0.24 (1 1)</b>	—	<0.1 [1]	<0.1 [1]	—	<0.1 [2]	<0.1 [2]	<0.1 [2]
Mg	15	<b>17 (1 2)</b>	—	<b>39 (2 2)</b>	<b>88 (1 1)</b>	—	12 (2)	<b>285 (2 2)</b>	<b>343 (2 2)</b>
Mn	0.01	<b>0.22 (2 2)</b>	—	<b>0.25 (2 2)</b>	<b>0.11 (2 2)</b>	<b>0.02 (1 1)</b>	<b>0.14 (3 3)</b>	<b>0.30 (3 3)</b>	<b>1.05 (2 2)</b>
Ni	0.1	0.04 (2)	—	0.06 (1)	0.05 (1)	0.02 (1)	0.08 (3)	<b>0.12 (1 3)</b>	<b>0.21 (2 2)</b>
Pb	<0.001 - 0.007	<0.1 [1]	<b>0.050 (1 4)</b>	0.004 (1)	<0.1 [1]	0.003 (1)	<0.1 [1]	0.001 (1)	<0.1 [1]
Se	0.01	<0.2 [1]	—	—	<0.2 [1]	—	<0.2 [1]	<0.2 [1]	<0.2 [1]
V	0.1	—	0.10 (1)	—	—	—	—	0.00 (1)	—
Zn	0.005	<0.05 [1]	<b>0.36 (4 4)</b>	<b>0.05 (1 1)</b>	<0.05 [1]	<b>0.02 (1 1)</b>	<b>0.12 (1 1)</b>	<b>0.32 (2 2)</b>	<b>0.69 (2 2)</b>

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**Table 35.** Useability of Cardiff sub-basin pit lakes water for freshwater aquaculture. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	90% Aquaculture Species Freshwater	Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
		2009	2009	2009	2009	2009	2009	2009
Temp (oC)		20.1 (2)	21.0 (2)	20.8 (2)	23.5 (1)	23.7 (2)	20.0 (2)	20.3 (2)
pH	5.0 - 9.0	<b>4.3 (7 7)</b>	<b>3.6 (2 2)</b>	<b>3.8 (2 2)</b>	<b>3.2 (1 1)</b>	<b>3.9 (2 2)</b>	5.1 (2)	<b>3.0 (6 6)</b>
Salinity (ppt)	<3000	—	—	—	—	—	—	—
Dissolved oxygen	>5	7.8 (7)	7.2 (2)	7.1 (2)	7.3 (1)	6.7 (2)	7.4 (2)	7.5 (6)
TSS	<40	—	—	—	—	—	—	—
Alkalinity	>20	—	—	—	—	—	—	—
Cl	3	<b>846 (6 6)</b>	<b>123 (2 2)</b>	<b>274 (2 2)</b>	<b>161 (2 2)</b>	<b>105 (2 2)</b>	<b>94 (2 2)</b>	<b>190 (6 6)</b>
TP (µg L <sup>-1</sup> )	100	68 (2)	<b>128 (1 2)</b>	<b>176 (1 2)</b>	59 (2)	55 (2)	50 (2)	61 (2)
TN (µg L <sup>-1</sup> )	1000	<b>1164 (2 2)</b>	748 (2)	<b>26792 (2 2)</b>	<b>2890 (2 2)</b>	<b>1199 (1 2)</b>	<b>1227 (1 2)</b>	735 (2)
NO <sub>x</sub> (µg L <sup>-1</sup> )	100	<b>755 (2 2)</b>	37 (2)	<b>2865 (2 2)</b>	<b>123 (2 2)</b>	18 (2)	<b>766 (2 2)</b>	<b>160 (2 2)</b>
NH <sub>4</sub> (µg L <sup>-1</sup> )	20 (un-ionised) (pH > 8.0)	<b>73 (2 2)</b>	<b>59 (2 2)</b>	<b>23854 (2 2)</b>	<b>2026 (2 2)</b>	<b>24 (1 2)</b>	<b>206 (2 2)</b>	<b>609 (2 2)</b>
NO <sub>3</sub> (µg L <sup>-1</sup> )	50000	—	—	—	—	—	—	—
As	0.05 0.03 (pH > 6.5)	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	<b>0.06 (1 1)</b>
Al	0.01 (pH < 6.5)	<b>5.51 (2 2)</b>	<b>38.93 (2 2)</b>	<b>19.08 (2 2)</b>	<b>75.95 (2 2)</b>	<b>6.93 (1 1)</b>	<b>0.37 (2 2)</b>	<b>23.65 (2 2)</b>
Ag	0.003	—	—	—	—	—	—	—
Cd	<0.2–1.8	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Cr	0.02	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Cu	0.005	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	—	<0.05 [1]	<0.05 [1]
Fe	0.01	<b>6.93 (6 6)</b>	<b>2.31 (2 2)</b>	<b>1.19 (2 2)</b>	<b>6.13 (2 2)</b>	<b>0.05 (1 1)</b>	<b>0.05 (2 2)</b>	<b>7.76 (6 6)</b>

Parameter (mg L <sup>-1</sup> )	90% Aquaculture Species Freshwater	Kepwari 2009	WON9 2009	WO3 2009	WO5C 2009	WO5D 2009	WO5F 2009	WO5H 2009
Hg	0.001	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [1]	<0.1 [2]	<0.1 [2]
Mg	15	<b>94 (2 2)</b>	<b>51 (2 2)</b>	<b>67 (2 2)</b>	<b>38 (1 2)</b>	<b>21 (1 1)</b>	9 (2)	<b>41 (2 2)</b>
Mn	0.01	<b>0.62 (6 6)</b>	<b>0.46 (2 2)</b>	<b>1.55 (2 2)</b>	<b>0.11 (1 1)</b>	<b>0.06 (1 1)</b>	<b>0.06 (2 2)</b>	<b>2.36 (6 6)</b>
Ni	0.1	0.09 (2)	<b>0.51 (2 2)</b>	<b>0.24 (2 2)</b>	<b>0.65 (1 2)</b>	<b>0.12 (1 1)</b>	0.07 (2)	<b>0.39 (2 2)</b>
Pb	<0.001 - 0.007	<0.1 [2]	0.005 (1)	<0.1 [1]	<0.1 [1]	<0.1 [1]	<0.1 [1]	<b>0.012 (2 2)</b>
Se	0.01	<0.2 [2]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	0.00 (2)
V	0.1	—	—	—	—	—	—	0.00 (2)
Zn	0.005	<b>0.57 (2 2)</b>	<b>4.00 (2 2)</b>	<b>1.33 (1 1)</b>	<b>4.09 (1 1)</b>	<b>0.68 (1 1)</b>	<0.05 [1]	<b>2.02 (3 3)</b>

### **6.2.3 Livestock Drinking Water Values**

The water quality of Collie pit lakes was compared to default ANZECC/ARMCANZ guideline trigger values for physico-chemistry and nutrients for water used for livestock drinking in Australasia (ANZECC/ARMCANZ, 2000c).

Historic Collie pit lakes showed good promise as water resources for livestock (Table 32). Aside from low pH in all lakes except for Lake Centaur (pH 6.6), water quality parameters recommended by ANZECC/ARMCANZ (2000c) were met in all historic Collie pit lakes. The exception was the potentially high mercury (high detection limit data recorded) in Black Diamond A which requires further investigation.

Water quality data from the new Collie pit lakes shows a similar pattern of good water quality for use by livestock (Table 33). New pit lakes all have pH below the guidelines value of 6.0 and (as a result) also have aluminium concentrations that exceed livestock watering guidelines in all lakes except WO5F with a higher pH of 5.1. Lead concentrations may be high in Chicken Creek 4, although the guideline value was not greatly exceeded and the dataset for this parameter was not strong.

**Table 36.** Useability of historic and Premier sub-basin pit lake waters for livestock drinking Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	Livestock Drinking Trigger value (low risk)	Black Diamond A	Black Diamond B	Blue Waters	Centaur	Ewington	Stockton	Chicken Creek 4	Chicken Creek 5
		2009	1994	2009	2009	2008	2009	2009	2009
pH	6 - 9	<b>4.4 (2 3)</b>	—	<b>3.9 (3 3)</b>	6.6 (2)	<b>3.9 (4 4)</b>	<b>4.5 (7 8)</b>	<b>3.3 (3 3)</b>	<b>2.5 (2 2)</b>
TDS	2000	—	—	—	—	580.0 (2)	—	—	—
SO <sub>4</sub>	1000	105 (2)	—	120 (2)	55 (1)	—	118 (4)	312 (2)	675 (2)
NH <sub>4</sub> (µg L <sup>-1</sup> )	30000	162 (2)	—	181 (1)	30 (1)	—	51 (3)	86 (2)	88 (2)
NO <sub>3</sub> (µg L <sup>-1</sup> )	1500000	—	261 (3)	—	—	—	—	—	—
As	0.5 - 5	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	0.06 (1)	0.08 (1)	<0.05 [2]
Al	5	0.10 (2)	—	3.40 (3)	0.40 (1)	0.90 (1)	1.36 (5)	<b>6.28 (1 3)</b>	<b>11.29 (2 2)</b>
B	5	<0.05 [2]	—	<0.05 [1]	<0.05 [1]	—	<0.05 [2]	<0.05 [2]	<0.05 [2]
Ca	1000	9 (2)	—	13 (2)	25 (1)	—	4 (2)	102 (2)	105 (2)
Cd	0.01	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.001 [1]	0.00 (1)	<0.01 [3]	<0.01 [2]
Co	1	<0.01 [2]	—	0.05 (1)	<0.01 [1]	—	0.03 (1)	0.07 (2)	0.13 (2)
Cr	1	<0.01 [2]	—	<0.01 [1]	<0.01 [2]	<0.001 [1]	<0.01 [3]	<0.01 [3]	<0.01 [2]
Cu	0.4 (sheep) 1.0 (cattle) 5.0 (pigs and poultry)	<0.05 [1]	—	<0.05 [2]	<0.05 [1]	0.01 (1)	<0.05 [3]	<0.05 [2]	<0.05 [1]
Hg	0.002	<b>0.24 (1 1)</b>	—	<0.1 [1]	<0.1 [1]	—	<0.1 [2]	<0.1 [2]	<0.1 [2]
Mo	0.15	—	—	—	—	—	—	—	—
Ni	1	0.04 (2)	—	0.06 (1)	0.05 (1)	0.02 (1)	0.08 (3)	0.12 (3)	0.21 (2)
Pb	0.1	<0.1 [1]	0.050 (4)	0.004 (1)	<0.1 [1]	0.003 (1)	<0.1 [1]	0.001 (1)	<0.1 [1]
Se	0.02	<0.2 [1]	—	—	<0.2 [1]	—	<0.2 [1]	<0.2 [1]	<0.2 [1]
U		<0.05 [1]	—	0.0001 (1)	<0.05 [1]	—	<0.05 [1]	0.1234 (1)	<0.05 [1]

Parameter (mg L <sup>-1</sup> )	Livestock Drinking Trigger value (low risk)	Black Diamond A 2009	Black Diamond B 1994	Blue Waters 2009	Centaur 2009	Ewington 2008	Stockton 2009	Chicken Creek 4 2009	Chicken Creek 5 2009
Zn	20	<0.05 [1]	0.36 (4)	0.05 (1)	<0.05 [1]	0.02 (1)	0.12 (1)	0.32 (2)	0.69 (2)

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**Table 37.** Suitability of Cardiff sub-basin pit lake waters for livestock drinking. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter (mg L <sup>-1</sup> )	Livestock Drinking Trigger value (low risk)	Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
		2009	2009	2009	2009	2009	2009	2009
pH	6 - 9	<b>4.3 (7 7)</b>	<b>3.6 (2 2)</b>	<b>3.8 (2 2)</b>	<b>3.2 (1 1)</b>	<b>3.9 (2 2)</b>	<b>5.1 (1 2)</b>	<b>3.0 (6 6)</b>
TDS	2000	1800.0 (4)	—	—	—	—	—	820.0 (4)
SO <sub>4</sub>	1000	308 (2)	900 (2)	790 (2)	<b>1216 (1 2)</b>	551 (2)	110 (2)	773 (2)
NH <sub>4</sub> (µg L <sup>-1</sup> )	30000	755 (2)	37 (2)	2865 (2)	123 (2)	18 (2)	766 (2)	160 (2)
NO <sub>3</sub> (µg L <sup>-1</sup> )	1500000	—	—	—	—	—	—	—
As	0.5 - 5	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	0.06 (1)
Al	5	<b>5.51 (1 2)</b>	<b>38.93 (2 2)</b>	<b>19.08 (2 2)</b>	<b>75.95 (2 2)</b>	<b>6.93 (1 1)</b>	0.37 (2)	<b>23.65 (2 2)</b>
B	5	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [2]	<0.05 [1]	<0.05 [2]	<0.05 [2]
Ca	1000	37 (6)	19 (2)	28 (2)	15 (2)	8 (1)	6 (2)	26 (6)
Cd	0.01	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Co	1	0.10 (2)	0.51 (2)	0.30 (2)	0.70 (2)	0.17 (1)	<0.01 [2]	0.29 (2)
Cr	1	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [2]	<0.01 [1]	<0.01 [2]	<0.01 [2]
Cu	0.4 (sheep) 1.0 (cattle) 5.0 (pigs and poultry)	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	—	<0.05 [1]	<0.05 [1]
Hg	0.002	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [2]	<0.1 [1]	<0.1 [2]	<0.1 [2]
Mo	0.15	—	—	—	—	—	—	—
Ni	1	0.09 (2)	0.51 (2)	0.24 (2)	0.65 (2)	0.12 (1)	0.07 (2)	0.39 (2)
Pb	0.1	<0.1 [2]	0.005 (1)	<0.1 [1]	<0.1 [1]	<0.1 [1]	<0.1 [1]	0.012 (2)
Se	0.02	<0.2 [2]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	<0.2 [1]	0.00 (2)
U		0.0606 (2)	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]	<0.05 [1]

Parameter (mg L <sup>-1</sup> )	Livestock Drinking Trigger value (low risk)	Kepwari 2009	WON9 2009	WO3 2009	WO5C 2009	WO5D 2009	WO5F 2009	WO5H 2009
Zn	20	0.57 (2)	4.00 (2)	1.33 (1)	4.09 (1)	0.68 (1)	<0.05 [1]	2.02 (3)

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#### **6.2.4 Aquatic Biota Environmental Values**

The water quality of Collie pit lakes was compared to default ANZECC/ARMCANZ guideline trigger values for freshwater lakes of the south-west of Australia (Chlorophyll *a*, TP, FRP, TN, NO<sub>x</sub>, NH<sub>4</sub>, DO (% saturation), pH, salinity and turbidity) for physico-chemistry and nutrients. Water quality of each pit lake was also compared to high-reliability trigger values applying to typical slightly–moderately disturbed ecosystems (90%) for metals and metalloids (ANZECC/ARMCANZ, 2000a). Where high-reliability trigger values were not available for a given parameter, low-reliability (LR) or Environmental Concentration Level (ECL) values were compared with instead (ANZECC/ARMCANZ, 2000b).

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**Table 38.** Modified guidelines for 90% protection of aquatic systems for metals whose toxicity is reduced by water hardness. Hardness calculated as per APHA (1998) based on mean values (presented as Ca<sup>2+</sup> hardness only, Ca<sup>2+</sup> and Mg<sup>2+</sup> hardness and total hardness (including Ca<sup>2+</sup>, Mg<sup>2+</sup>, Sr<sup>2+</sup>, Fe<sup>2+</sup>, Al<sup>2+</sup>, Zn<sup>2+</sup> and Mn<sup>2+</sup>; in most cases, calculation could not include Sr (\*) and in some cases Zn (^) was below detection and a value of half the detection limit was used). Adjustments as multipliers (based on Ca<sup>2+</sup> hardness) are provided for increasing guideline value as recommended in ANZECC/ARMCANZ (2000b), NCR is no recommended change. There were insufficient parameters to calculate hardness for Black Diamond B and Ewington.

Parameter	Black Diamond A	Blue Waters	Centaur	Lake Stockton	Chicken Creek 4	Chicken Creek 5	Lake Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
	2009	2009	2009	2009	2009	2009	2009	2009	2009	2009	2009	2009	2009
Cd	NCR	NCR	x2.7	NCR	x5.7	x4.2	x2.7	NCR	x2.7	NCR	NCR	NCR	NCR
Cu	NCR	NCR	x2.5	NCR	x5.2	x3.9	x2.5	NCR	x2.5	NCR	NCR	NCR	NCR
Pb	NCR	NCR	x4	NCR	x11.8	x7.6	x4	NCR	x4	NCR	NCR	NCR	NCR
Ni	NCR	NCR	x2.5	NCR	x5.2	x3.9	x2.5	NCR	x2.5	NCR	NCR	NCR	NCR
Zn	NCR	NCR	x2.5	NCR	x5.2	x3.9	x2.5	NCR	x2.5	NCR	NCR	NCR	NCR
Ca <sup>2+</sup> Hardness	13	31	63	5	199	161	80	46	69	20	19	11	11
Ca <sup>2+</sup> +Mg <sup>2+</sup> Hardness	72	187	425	30	1215	1055	366	248	316	106	106	36	36
Total Hardness (mg CaCO <sub>3</sub> L <sup>-1</sup> )	56*^	199	427*^	33*	1249*	1122*	470*	466*	425*	348*	145*	37*	307^

Not surprisingly given the influence of AMD in the area, all historic lakes, except for Lake Centaur, fell below recommended pH levels of 6.5–8.0 (Table 34). More surprisingly, however were where dissolved oxygen concentrations with values of as low as 80% were recorded from many lakes, and Lake Centaur in particular below the guideline value of 90–95%. Except for total nitrogen, all other nutrients generally exceeded guideline levels in all lakes. FRP was the only lake that exceeded guidelines, this may be due to the relatively large agricultural inputs in its catchment relative to its small volume exceeded. However, even with these high nutrient levels, water column chlorophyll a concentration was low in all historic lakes. This lack of primary productivity in historic pit lakes is likely because of low FRP and also because of toxicity in many cases from the elevated aluminium concentrations (Lund & McCullough, 2009; Neil *et al.*, 2009). Salinity was high in all historic pit lakes; however (with the exception of Lake Centaur) this is likely to be a result of low pH (hydronium concentration) rather than sodium salt salinity *per se*. Turbidity was very low (consistently at detection limit) in all historic pit lakes and would demonstrate no light limitation to either water column or lake bottom algae and plant communities. Unlike most other pit lake situations with AMD considerations in Australia (Kumar *et al.*, 2009), heavy metals are generally very low and well below toxic thresholds. However, there are numerous data gaps for many heavy metal analytes that should be screened for in future environmental monitoring assessments of the historic Collie pit lakes.

New Collie pit lakes demonstrate a similar pattern to environmental water quality guidelines as did historic pit lakes (Table 35). New pit lakes also have high levels of nutrients; although in this case FRP levels also generally exceed water quality guidelines for environmental values. Turbidity was also very low, again indicating very low productivity of the water with the new lakes also clear of a lot of algae in the water column. Salinity is also very high, although again with an exception of one lake (Chicken Creek 4) this is due to the low pH of the lakes rather than sodium salts. Aluminium is at environmentally toxic concentrations in all lakes; however, heavy metals are again very low. As with historic pit lakes, there are many monitoring data gaps in the heavy metal suite.

**Table 39.** Useability of historic and Premier sub-basin pit lake water for aquatic biota. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter ( $\mu\text{g L}^{-1}$ )	Protection of Aquatic Biota (90%)	Black Diamond	Black Diamond	Blue Waters	Centaur	Ewington	Stockton	Chicken Creek 4	Chicken Creek 5
		A	B						
		2009	1994	2009	2009	2008	2009	2009	2009
pH	6.5 - 8	<b>4.4 (2 3)</b>	—	<b>3.9 (3 3)</b>	6.6 (2)	<b>3.9 (4 4)</b>	<b>4.5 (8 8)</b>	<b>3.3 (3 3)</b>	<b>2.5 (2 2)</b>
Dissolved oxygen (%)	<90	96 (2)	—	104 (1)	<b>87 (1 1)</b>	—	<b>97 (1 2)</b>	103 (2)	142 (2)
Total P	10	<b>206 (2 2)</b>	—	<b>102 (1 1)</b>	<b>73 (1 1)</b>	—	<b>51 (3 3)</b>	<b>68 (2 2)</b>	<b>68 (2 2)</b>
FRP	5	4 (2)	<b>10 (3 6)</b>	5 (1)	<b>10 (1 1)</b>	—	4 (1)	<b>23 (2 2)</b>	<b>19 (2 2)</b>
Total N	350	284 (2)	—	237 (1)	<b>651 (1 1)</b>	—	213 (3)	<b>546 (2 2)</b>	<b>1469 (2 2)</b>
NOx	10	<b>162 (2 2)</b>	—	<b>181 (1 1)</b>	<b>30 (1 1)</b>	—	<b>51 (3 3)</b>	<b>86 (2 2)</b>	<b>88 (2 2)</b>
NH <sub>4</sub>	10	<b>80 (2 2)</b>	<b>66 (6 6)</b>	<b>37 (1 1)</b>	<b>115 (1 1)</b>	—	<b>154 (3 3)</b>	<b>355 (2 2)</b>	<b>1151 (2 2)</b>
Chlorophyll <i>a</i>	3 - 5	0.000 (2)	—	0.000 (1)	1.370 (1)	—	0.000 (2)	0.000 (2)	0.000 (2)
EC (mS cm <sup>-1</sup> )	0.3-1.5	0.584 (3)	—	<b>1.880 (1 3)</b>	<b>3.180 (2 2)</b>	1.490 (4)	0.506 (6)	<b>7.550 (3 3)</b>	<b>2.970 (2 2)</b>
Turbidity (NTU)	10-100	1 (2)	—	0 (1)	1 (1)	—	1 (4)	2 (2)	0 (2)
As	42 (as AsV)	<50 [2]	—	<50 [1]	<50 [1]	—	<b>64 (1 1)</b>	<b>80 (1 1)</b>	<50 [2]
Al	pH <6.5 = ID, pH >6.5 = 80	100 (2)	—	3400 (3)	403 (1)	900 (1)	1360 (5)	6279 (3)	11290 (2)
B	680 <sup>c</sup>	<50 [2]	—	<50 [1]	<50 [1]	—	<50 [2]	<50 [2]	<50 [2]
Cd	0.4 <sup>h</sup>	<10 [2]	—	<10 [1]	<10 [2]	<1 [1]	0 (1)	<10 [3]	<10 [2]
Cr	6 <sup>A</sup> (as Cr VI), ID Cr III	<10 [2]	—	<10 [1]	<10 [2]	<1 [1]	<10 [3]	<10 [3]	<10 [2]
Cu	1.8 <sup>h</sup>	<50 [1]	—	<50 [2]	<50 [1]	<b>10 (1 1)</b>	<50 [3]	<50 [2]	<50 [1]
Hg	1.9 <sup>CB</sup> (as inorganic Hg), methyl Hg =ID	<b>241 (1 1)</b>	—	<100 [1]	<100 [1]	—	<100 [2]	<100 [2]	<100 [2]
Mn	2500 <sup>c</sup>	217 (2)	—	247 (2)	111 (2)	20 (1)	140 (3)	300 (3)	1047 (2)

Parameter ( $\mu\text{g L}^{-1}$ )	Protection of Aquatic Biota (90%)	Black Diamond	Black Diamond	Blue Waters 2009	Centaur 2009	Ewington 2008	Stockton 2009	Chicken Creek 4 2009	Chicken Creek 5 2009
		A 2009	B 1994						
Ni	13 <sup>H</sup>	<b>42 (2 2)</b>	—	<b>55 (1 1)</b>	<b>52 (1 1)</b>	<b>20 (1 1)</b>	<b>81 (3 3)</b>	<b>116 (3 3)</b>	<b>213 (2 2)</b>
Pb	5.6 <sup>H</sup>	<100 [1]	<b>50 (1 4)</b>	4 (1)	<100 [1]	3 (1)	<100 [1]	1 (1)	<100 [1]
Se	18 <sup>B</sup> (Total)	<200 [1]	—	—	<200 [1]	—	<200 [1]	<200 [1]	<200 [1]
U	6 <sup>*</sup>	<50 [1]	—	0.1 (1)	— [1]	—	<50 [1]	<b>123.4 (1 1)</b>	<50 [1]
Zn	15 <sup>C</sup>	<50 [1]	<b>360 (4 4)</b>	<b>51 (1 1)</b>	<50 [1]	<b>20 (1 1)</b>	<b>117 (1 1)</b>	<b>321 (2 2)</b>	<b>687 (2 2)</b>

<sup>A</sup> Figure may not protect key test species from acute toxicity (and chronic). ‘A’ indicates that trigger value > acute toxicity figure; note that trigger value should be <1/3 of acute figure (ANZECC/ARMCANZ, 2000b).

<sup>B</sup> Chemicals for which possible bioaccumulation and secondary poisoning effects should be considered (ANZECC/ARMCANZ, 2000b).

<sup>C</sup> Figure may not protect key test species from chronic toxicity (this refers to experimental chronic figures or geometric mean for species (ANZECC/ARMCANZ, 2000b).

<sup>H</sup> The values have been calculated using a hardness of 30 mg/L CaCO<sub>3</sub>. These should be adjusted to the site-specific hardness (ANZECC/ARMCANZ, 2000b).

<sup>\*</sup> 99% protection level; guideline from Hogan *et al.* (2005).

ID Guideline value indeterminate (ANZECC/ARMCANZ, 2000b).

**Table 40.** Useability of Cardiff sub-basin pit lake water for aquatic biota. Year indicates most recent year of data collection, minimum or maximum (as appropriate) value, with in parentheses the total number of data points for the given year, where values exceeded the guideline the number that did are presented first (|), bold type indicates parameter exceeds the ANZECC/ARMCANZ (2000b) guideline listed, – indicates no data available.

Parameter ( $\mu\text{g L}^{-1}$ )	Protection of Aquatic Biota (90%)	Kepwari	WON9	WO3	WO5C	WO5D	WO5F	WO5H
		2009	2009	2009	2009	2009	2009	2009
pH	6.5 - 8	<b>4.3 (7 7)</b>	<b>3.6 (2 2)</b>	<b>3.8 (2 2)</b>	<b>3.2 (1 1)</b>	<b>3.9 (2 2)</b>	<b>5.1 (2 2)</b>	<b>3.0 (6 6)</b>
Dissolved oxygen (%)	<90	<b>111 (1 2)</b>	<b>102 (1 2)</b>	<b>96 (1 2)</b>	<b>86 (1 1)</b>	<b>88 (2 2)</b>	<b>94 (1 2)</b>	<b>97 (1 2)</b>
Total P	10	<b>68 (2 2)</b>	<b>128 (2 2)</b>	<b>176 (2 2)</b>	<b>59 (2 2)</b>	<b>55 (2 2)</b>	<b>50 (2 2)</b>	<b>61 (2 2)</b>
FRP	5	5 (1)	<b>47 (2 2)</b>	<b>17 (1 2)</b>	<b>25 (2 2)</b>	<b>7 (1 2)</b>	2 (1)	<b>25 (2 2)</b>
Total N	350	<b>1164 (2 2)</b>	<b>748 (1 2)</b>	<b>26792 (2 2)</b>	<b>2890 (2 2)</b>	<b>1199 (1 2)</b>	<b>1227 (2 2)</b>	<b>735 (2 2)</b>
NOx	10	<b>755 (2 2)</b>	<b>37 (2 2)</b>	<b>2865 (2 2)</b>	<b>123 (2 2)</b>	<b>18 (1 2)</b>	<b>766 (2 2)</b>	<b>160 (2 2)</b>
NH <sub>4</sub>	10	<b>73 (2 2)</b>	<b>59 (2 2)</b>	<b>23854 (2 2)</b>	<b>2026 (2 2)</b>	<b>24 (2 2)</b>	<b>206 (2 2)</b>	<b>609 (2 2)</b>
Chlorophyll <i>a</i>	3 - 5	0.000 (2)	0.000 (2)	<b>11.970 (1 2)</b>	0.000 (1)	0.000 (2)	0.000 (2)	0.000 (2)
EC (mS cm <sup>-1</sup> )	0.3-1.5	<b>3.000 (3 3)</b>	1.330 (2)	<b>2.140 (2 2)</b>	<b>1.670 (1 1)</b>	0.880 (2)	0.435 (2)	1.496 (2)
Turbidity (NTU)	10-100	0 (2)	0 (2)	0 (2)	0 (1)	0 (2)	0 (2)	0 (2)
As	42 (as AsV)	<50 [2]	<50 [2]	<50 [2]	<50 [2]	<50 [1]	<50 [2]	<b>62 (1 1)</b>
Al	pH <6.5 = ID, pH >6.5 = 80	5506 (2)	38930 (2)	19080 (2)	75950 (2)	6928 (1)	367 (2)	23650 (2)
B	680 <sup>C</sup>	<50 [2]	<50 [2]	<50 [2]	<50 [2]	<50 [1]	<50 [2]	<50 [2]
Cd	0.4 <sup>H</sup>	<10 [2]	<10 [2]	<10 [2]	<10 [2]	<10 [1]	<10 [2]	<10 [2]
Cr	6 <sup>A</sup> (as Cr VI), ID Cr III	<10 [2]	<10 [2]	<10 [2]	<10 [2]	<10 [1]	<10 [2]	<10 [2]
Cu	1.8 <sup>H</sup>	<50 [1]	<50 [1]	<50 [1]	<50 [1]	—	<50 [1]	<50 [1]
Hg	1.9 <sup>CB</sup> (as inorganic Hg), methyl Hg =ID	<100 [2]	<100 [2]	<100 [2]	<100 [2]	<100 [1]	<100 [2]	<100 [2]

Parameter ( $\mu\text{g L}^{-1}$ )	Protection of Aquatic Biota (90%)	Protection of Aquatic Biota (90%)						
		Kepwari 2009	WON9 2009	WO3 2009	WO5C 2009	WO5D 2009	WO5F 2009	WO5H 2009
Mn	2500 <sup>C</sup>	616 (6)	458 (2)	1551 (2)	109 (1)	60 (1)	61 (2)	2364 (6)
Ni	13 <sup>H</sup>	<b>94 (2 2)</b>	<b>512 (2 2)</b>	<b>243 (2 2)</b>	<b>650 (2 2)</b>	<b>118 (1 1)</b>	<b>68 (2 2)</b>	<b>392 (2 2)</b>
Pb	5.6 <sup>H</sup>	<100 [2]	5 (1)	<100 [1]	<100 [1]	<100 [1]	<100 [1]	<b>12 (2 2)</b>
Se	18 <sup>B</sup> (Total)	<200 [2]	<200 [1]	<200 [1]	<200 [1]	<200 [1]	<200 [1]	1000 (2)
U	6 <sup>*</sup>	<b>60.6 (2 2)</b>	<50 [1]	<50 [1]	<50 [1]	<50 [1]	<50 [1]	<50 [1]
Zn	15 <sup>C</sup>	<b>571 (2 2)</b>	<b>3996 (2 2)</b>	<b>1329 (1 1)</b>	<b>4093 (1 1)</b>	<b>675 (1 1)</b>	<50 [1]	<b>2019 (3 3)</b>

<sup>A</sup> Figure may not protect key test species from acute toxicity (and chronic). 'A' indicates that trigger value > acute toxicity figure; note that trigger value should be <1/3 of acute figure (ANZECC/ARMCANZ, 2000b).

<sup>B</sup> Chemicals for which possible bioaccumulation and secondary poisoning effects should be considered (ANZECC/ARMCANZ, 2000b).

<sup>C</sup> Figure may not protect key test species from chronic toxicity (this refers to experimental chronic figures or geometric mean for species (ANZECC/ARMCANZ, 2000b).

<sup>H</sup> The values have been calculated using a hardness of 30 mg/L CaCO<sub>3</sub>. These should be adjusted to the site-specific hardness (ANZECC/ARMCANZ, 2000b).

\* 99% protection level; guideline from Hogan *et al.* (2005).

ID Guideline value indeterminate (ANZECC/ARMCANZ, 2000b).

## 7 Conclusions

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### 7.1 Water quality

The water quality of pit lakes in Collie differs between lakes but there are apparent groupings. For example, historic lakes tend to have better water quality than new pit lakes. This appears to be due to the formation of secondary minerals which are buried by kaolin clays eroding from the catchment.

Among the historic lakes, some lakes still have remained low in pH over many decades. In general, however, all Collie pit lakes are acidic with Al buffering around 3.0–5.0, a general lack of nutrients and biota and moderate toxicity from elevated concentrations of Al, Co, Fe, Mg, Mn, Ni, Pb, U and Zn. Data shows these lakes do not support aquatic ecosystems representative of natural lakes.

The low pH in pit lake water is the main problem for the pit lakes in Collie, together with some resulting metal toxicity. The pH is buffered around 3.0 to 5.0 with high concentrations of aluminium in the water. Aluminium is likely to be the most limiting toxicant for development of a natural ecosystem in Collie pit lakes (Neil *et al.*, 2009). Inputs from groundwater or surface water discharge over time may reduce the pH buffering effects of aluminium and increase lake water pH, therefore reducing the concentrations of heavy metals in water by dilution and altered chemical speciation into less soluble forms.

Furthermore, to build a self sustaining ecosystem in pit lakes, there are other factors that need to take to be taking into account other than just metal and pH toxicity. Apart from the pH being buffered by Al in water, which is the main toxicant to biota; a lack of nutrients (in particular dissolved forms of phosphorus, FRP) are also a key factor likely to be restricting more natural and productive ecosystem development in Collie pit lakes (Lund & McCullough, 2009). Unlike natural lakes which have acted as a sink of nutrients for much longer and from relatively larger catchments, the catchment of pit lakes is generally small and they are generally recent geological features in their landscapes. Data showing concentrations of nitrogen and phosphorus showed that there were many lakes with adequate concentrations of these nutrients, yet phytoplankton and other algae still have very low concentrations in them. This is likely due to the critical limits for one or other nutrients not being met e.g., high total

phosphorus yet low bioavailable phosphorus as dissolved FRP. It is therefore necessary to study both water quality data and biota data from these pit lakes and also biotic data from different biological levels of organisation in order to and try to define the restraining factors in these unusual aquatic environments.

Consequently, understanding the hydrological environment of recharge and discharge of all Collie pit lakes is essential for understanding the likely evolution of water quality in the pit lakes; historic and new. Although empirical modelling will assist with this task, the paucity of data on many Collie pit lakes (in particular the new pit lakes of the Cardiff sub-basin) will require collection of a greater dataset than currently exists. For many of these lakes, this is only two data points for basic water quality variables thus far. Consequently, an ongoing monitoring strategy for water quality and aquatic ecology for the Collie Pit lakes is a must in order to be able predict, manage risks and best utilise the opportunities the Collie Lake District represents to both the Collie region and also to the south-west Australian economy and environment.

## 7.2 Aquatic biota

Very little aquatic ecology is known for Australian pit lakes (Kumar *et al.*, in press). Proctor & Grigg (2006) have published one of the few studies to examine macroinvertebrate communities. Collectively, the Collie pit lake aquatic ecology studies have shown macroinvertebrate communities of limited diversity dominated by cosmopolitan and pollution tolerant taxa. These findings suggest that, regardless of water quality, pit lakes do not appear to have macroinvertebrate communities representative of natural water bodies, possibly due to poor habitat diversity within the lakes.

## 8 Recommendations

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- The Collie pit lakes have and will continue to interact with their surrounding environment over time. Considering the complexities of the recharging and discharging with surface water and ground water in the Collie region it is necessary to continue monitoring of pit lake water quality and its aquatic biota. The risk assessment and management strategies will be beneficial from the investigation by better understanding and better prediction.
  - A comprehensive routine monitoring needs to developed for the pit lakes and connected waters (this will form Task 4 of the programme) and then implemented.
- The Collie Region's groundwater is thought to be the main recharge and discharge source of pit lakes. A better knowledge of groundwater near pit lakes; especially with regard to newly forming new pit lakes is essential.
  - A study is needed to understand groundwater flow in and out of Collie pit lakes.
  - Information on the quality and quantity of groundwater entering and leaving pit lakes is essential to allow proper acidity and water balance budgeting.
- A number of the pit lakes are capable of discharging into natural water bodies (Stockton, WO5F, Lake Kepwari, Black Diamond A). No assessments appear to have been undertaken of the ecological impacts of this discharge on downstream receiving environments
  - The quality and quantity of surface discharge from pit lakes needs to be determined.
  - The downstream impacts of surface discharge needs to be fully investigated.

- Very limited research has been carried to understand environmental limitations of the poor water quality of the Collie pit lakes on their biota.
  - Ultimately pit lakes will most likely evolve to become dominated by biological rather than chemical processes as organic matter builds up from natural sources; the consequence of this is unknown. A detailed monitoring program for this an connected waters to monitor changes in biological communities is needed and will be considered in Task 4.
- In addition to improving water quality of Collie pit lakes through environmental sustainable passive remediation strategies, it is necessary to also consider an ecological view to understand the environmental limitations due to ecological quality, such as food resources and habitat requirements.
  - Remediation approaches are in their infancy that might be successfully be employed to treat water quality issues in Collie pit lakes. Research is required to further develop a range of cost-effective approaches.



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