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EDITH COWAN UNIVERSITY
PERTH WESTERN AUSTRALIA

June 2010

Mine Voids Management Strategy (IV): Conceptual Models of Collie Basin Pit Lakes

By, Dr. C. D. McCullough
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Prepared for,

Department of Water (Western Australia)

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Frontispiece

Plate 1. Collie pit lake ERA Workshop delegates discussing new Premier pit lake WON9 in Spring 2009.

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Australian Government

Water for the Future

Executive Summary

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 form a lake district consisting of 15 lakes, although two are currently being re-mined. 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 exceeds 40 GL. The current demand for water in WA and its increasing scarcity mean that Collie pit lakes represent a potentially valuable resource to both the environment and the community.

3. This report is Report Four of a series of five reports on water resources of the Collie Lake District that were all commissioned together by the Western Australian Government Department of Water.

4. 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. Water quality is largely stable as abiotic processes are currently the major determinator of water chemistry in the lakes.

5. To ensure greatest scientific robustness of conceptual model processes we held a site visit and workshop with an expert panel from nationally recognised experts from universities, Griffin and Premier mining companies, DOW staff and SKM groundwater consultants to best understand how these processes are likely working in different pit lakes.

6. Conceptual models were constructed as diagrammatic representations highlighting the nature of relationships between parameters and processes. Empirical and conceptual modelling of Collie pit lake hydrochemistry and lake system environments identified three major lake types; “historic”, “new rehabilitated” and “new un-rehabilitated”. Differences between pit lakes appeared to be predominantly due to higher pH and lower ORP in historic pit lakes, high salinity in rehabilitated pit lakes and lower salinity and pH in un-rehabilitated pit lakes.

7. An ecological risk assessment undertaken during the workshop highlighted major knowledge gaps relating to discharges (groundwater and surface water) from pit lakes, in remediation approaches, and in the ecology of biota in the lakes. Key risks were associated with discharges, although the lack of knowledge was one of the major drivers of the high risk rating.

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1 Background

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 1). 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.

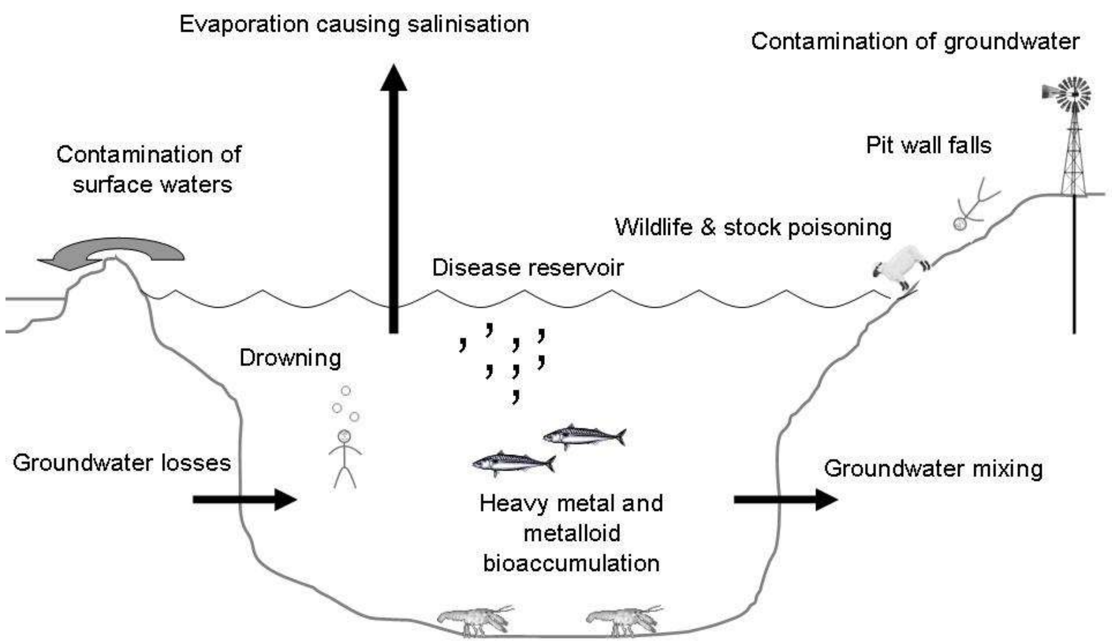

Figure 1. A conceptual model of the risks of pit lakes (after McCullough & Lund, 2006).

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 (FeS_2) in the following two reactions (Castro *et al.*, 1999).

(1) $FeS_2 + 7/2\ O_{2(aq)} + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2H^+$

(2) $Fe^{2+} + 1/4\ O_{2(aq)} + 5/2\ H_2O \rightarrow Fe(OH)_3 + 2H^+$

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 2). Tasmania, Victoria, South Australia (SA) and Northern Territory (NT) are generally only important for certain minerals i.e., copper, gold, uranium, etc. (Mudd, 2007).

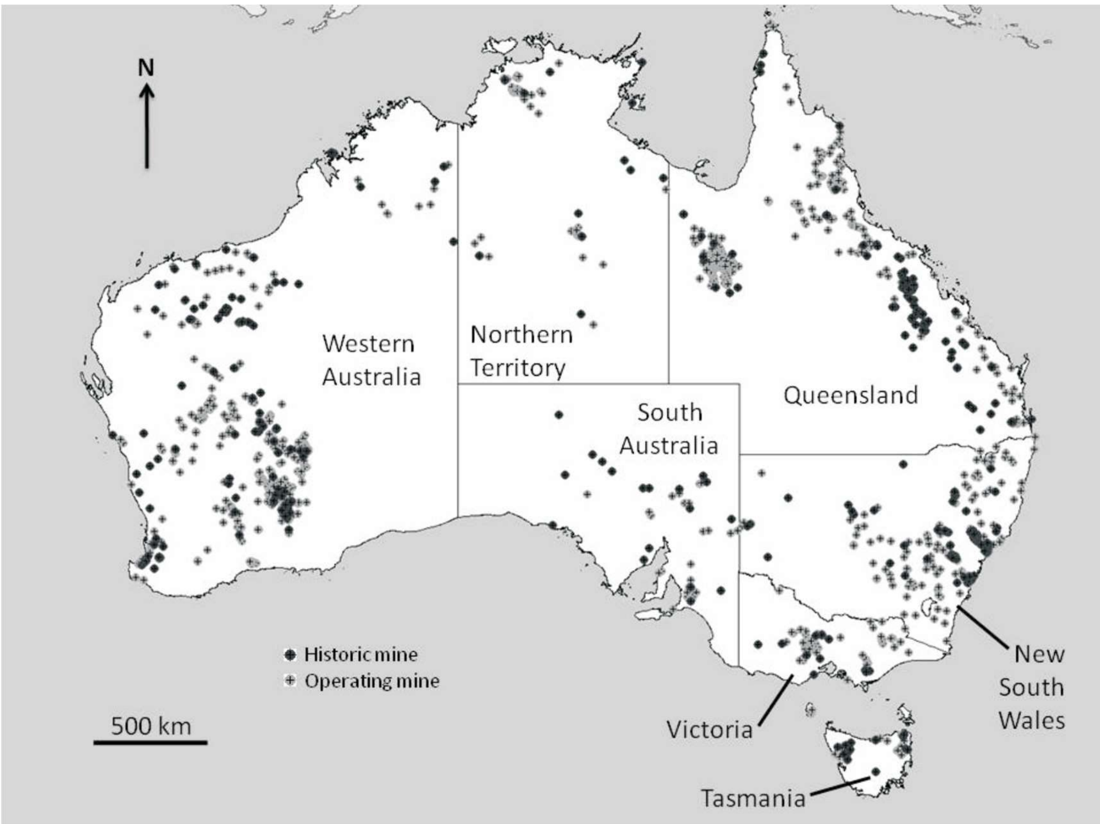

Figure 2. Distribution of historic and operating mines in Australia (after Kumar *et al.*, in press).

The mining areas also occur across a broad range of climatic regions (Figure 3). 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 climes. 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.

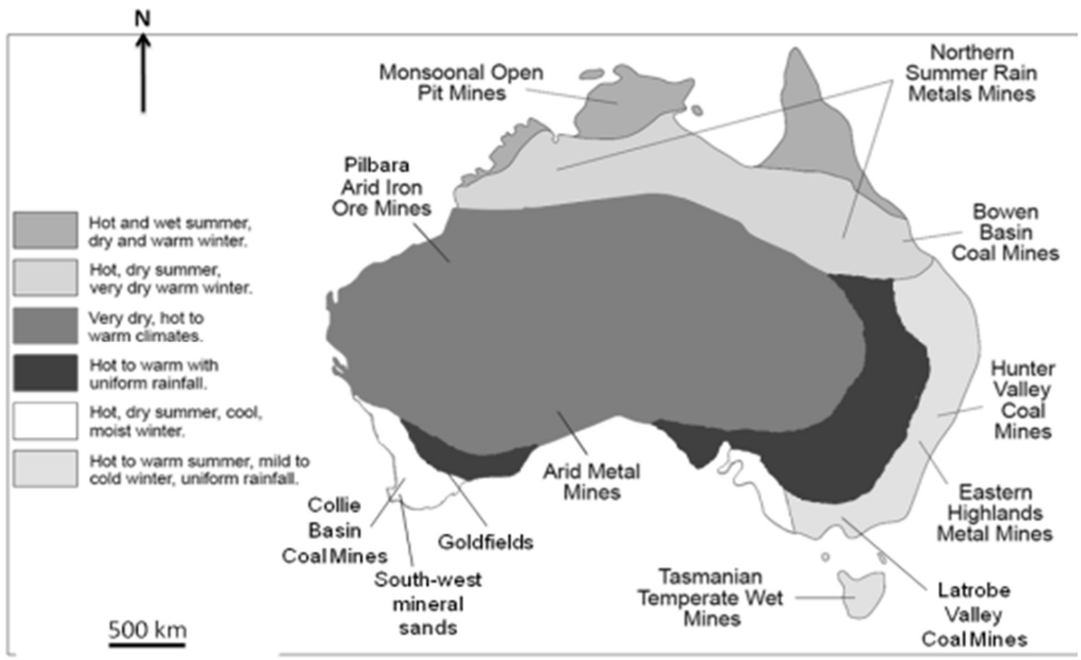

Figure 3. Australian pit lake classification after Mallet and Mark (1995), Johnson and Wright (2003) and (Kumar *et al.*, in press).

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 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 x 10^6 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.*, 2009a). 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. D. 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 15 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 15 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.*, 2009a).

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 (Zhao *et al.*, 2009). 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.

2 The Collie Coal Basin

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 4). 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^2, 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^2) to the west and the Premier sub-basin (74 km^2) to the east, in part separated by a faulted basement high, known as the Stockton Ridge (Moncrieff, 1993).

The Collie coal basin is a small sedimentary basin occurring in the Collie River catchment (Figure 4; (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).

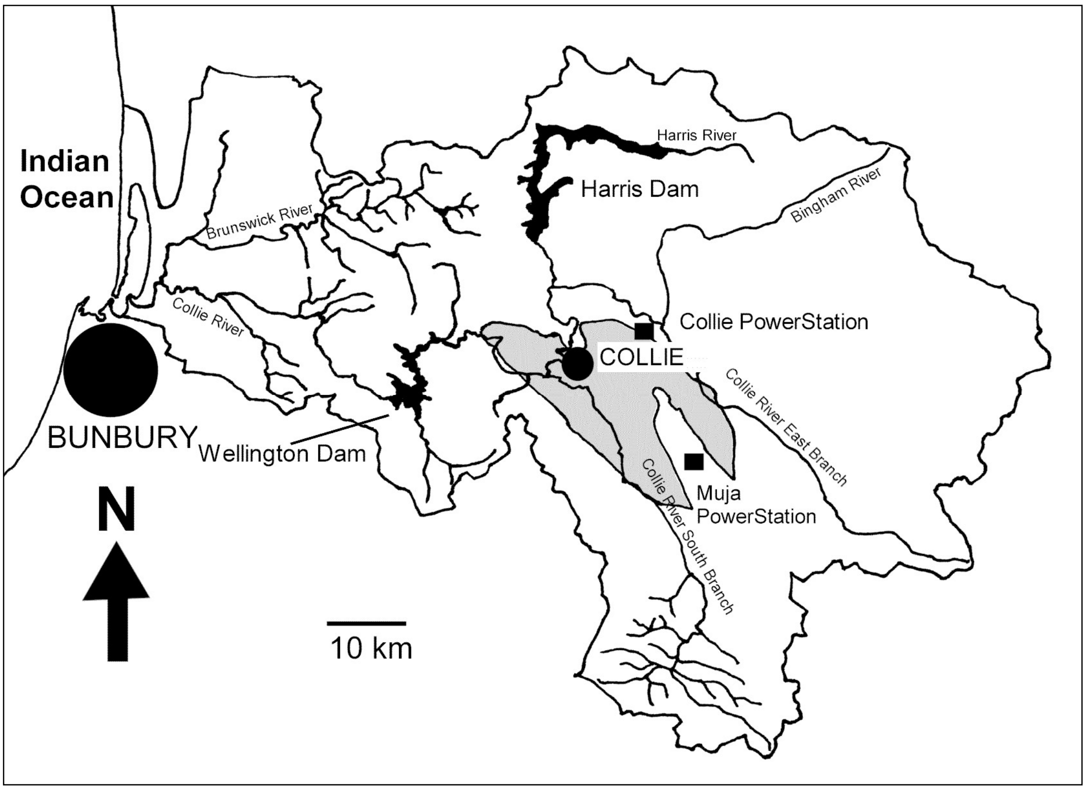

Figure 4. Location of the Collie Basin (after Neil *et al.* 2009).

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 5). 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).

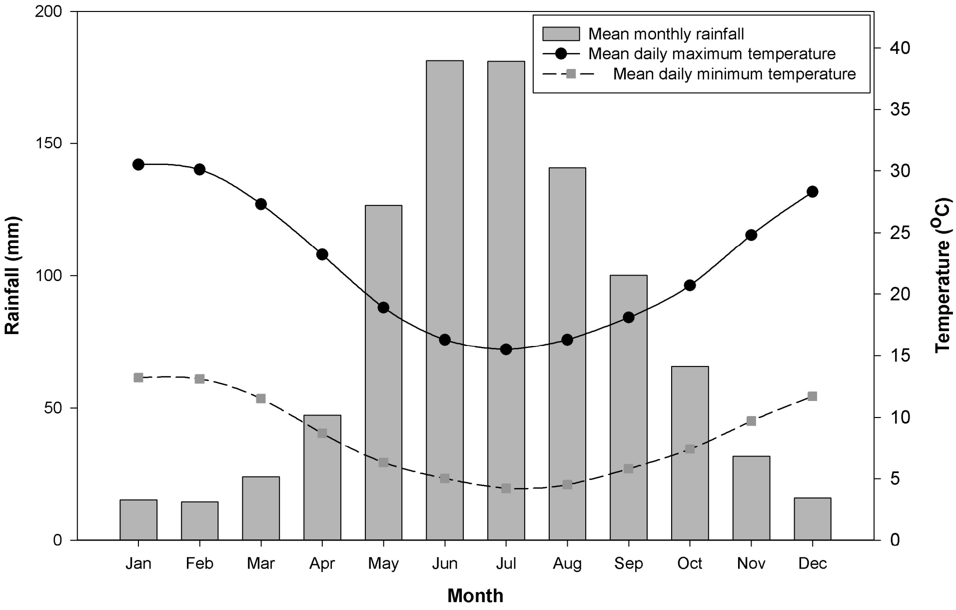

Figure 5. Mean temperature and rainfall climate of Collie (Commonwealth of Australia Bureau of Meteorology, 05/10/2005).

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^{-1} (Mauger *et al.*, 2001). Total phosphorus levels were recorded at over 18 $\mu g\,L^{-1}$ 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 6).

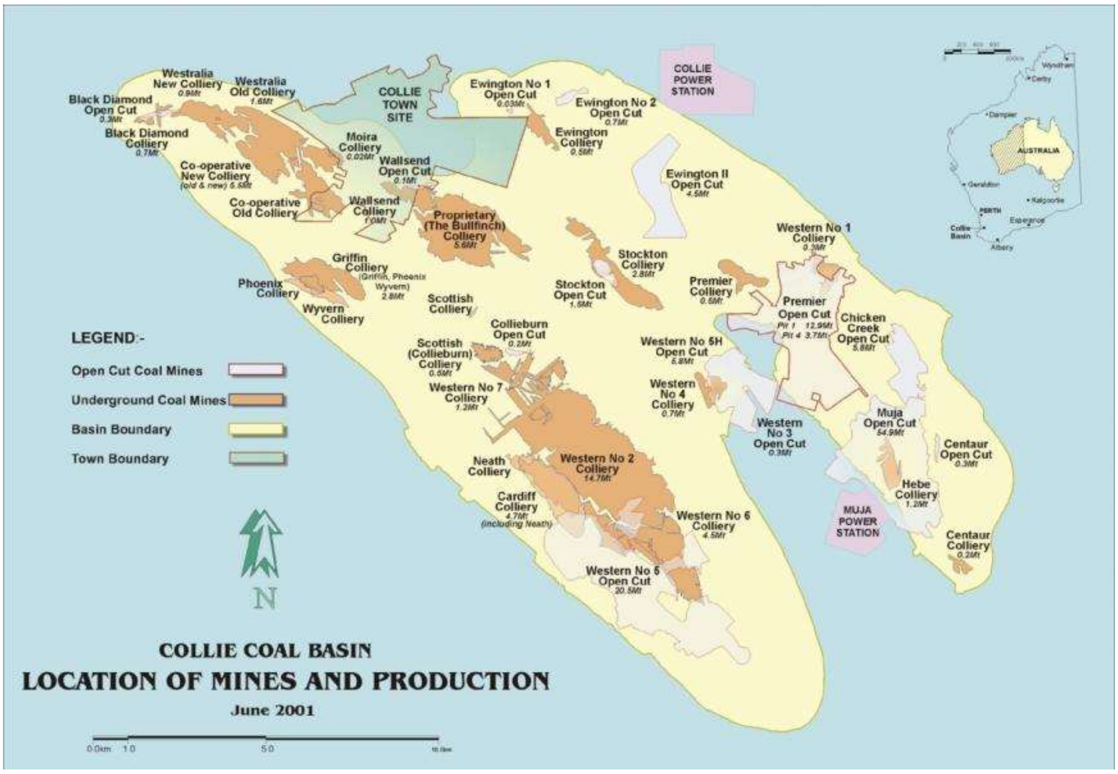

Figure 6. Historical mine workings in the Collie Basin (source unknown).

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 7).

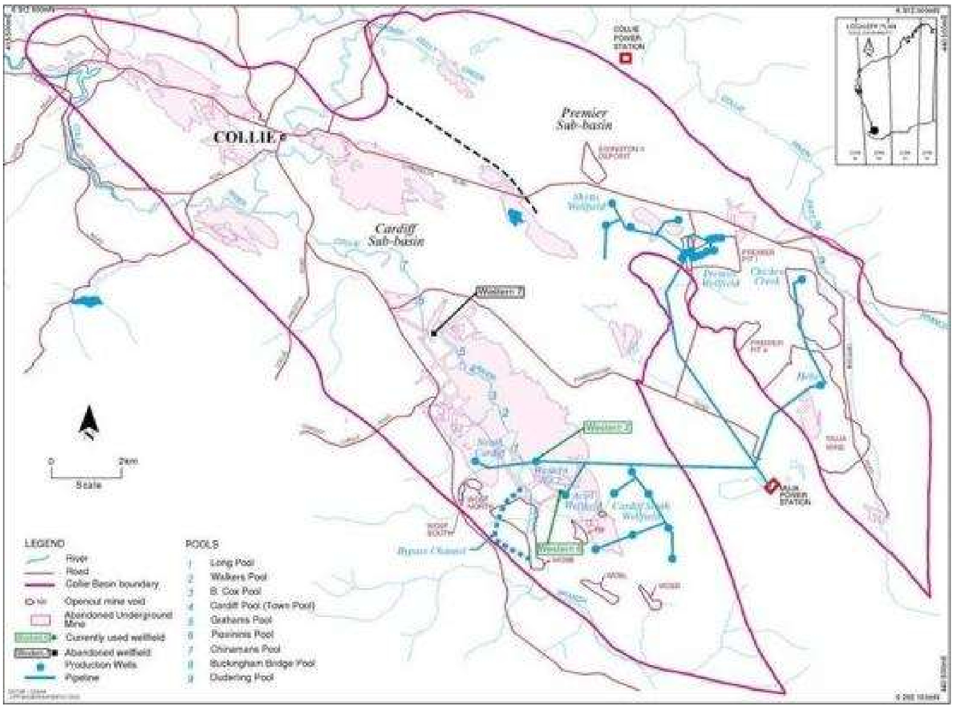

Figure 7. Current mining activities in the Collie Basin (source unknown).

2.7 Collie Pit Lakes

There are more than 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 8). Water quality of Collie pit lakes 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, ferrolysis and secondary mineralization. This low acidity is still sufficient to generate low pH in pit lakes due to low buffering capacity of surrounding geologies. These pit lakes also have very low nutrient concentrations of carbon, particularly in historic lakes where it may be at detection level of <1 mg L^{-1} (Zhao *et al.*, 2009). 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 8. Location of current Collie pit lakes (sourced from Google Earth). Note: Wellington Dam is a reservoir.

3 Hydro-chemical conceptual modelling

3.1 Introduction

Conceptual models may be either pictorial or verbal descriptions of systems and process. They may represent biological, chemical or physical systems, or a combination of these. In the case of pit lakes, conceptual models are often used to represent the pit lake system and show processes that are thought to influence lake water quality. Management of rehabilitation/remediation scenarios may be explored and their outcomes deduced through expert consensus. Conceptual models, particularly in pictorial form, may also form a useful visual tool for explaining these pit lake concepts to mining industry, regulators and researchers and local communities. Some of these models serve as research tools which are useful in developing and testing theoretical insight and they may also play a critically important role in the development, implementation and enforcement of environmental regulatory policy (Morgan & McMichael, 1981).

Early physico-chemical conceptual modelling may make use of simplified pit lake cross-sections with broad descriptions groundwater and surface flows in and out of the lake (Rushton, 2003). As such, a pit lake conceptual model will necessarily consist of descriptions of lake morphology (including depth and volume and sometimes as detailed as bathymetry), pit wall geochemistry and mineralogy. Although oversimplification of the system can generate errors in the water quality prediction, conceptual models may be able to more broadly account for geochemical mechanisms that are not well understood or difficult to model e.g., adsorption to mineral surfaces (Tempel *et al.*, 2000). A conceptual model will therefore require a broad understanding of dominant hydrological, limnological and geochemical processes occurring within the lake (Castendyk, 2009).

Alternatively, a staged approach may be taken where individual pit lake processes are treated separately in their own conceptual models e.g., Castendyk *et al.* (2005). Acidity flux and buffering may thus constitute a separate model, referring to but separate from a hydrological model which accounts for surface and groundwater inputs to an acidic pit lake. This staged approach may be particularly useful where a pit lake system is considered very complex and involving many or disparate processes or where high details of individual processes are required e.g., cycling of a single nutrient. Numerical modelling will often then follow in a staged approach using separate but coupled numerical models (Salmon et al., 2008).

Development of a conceptual model is often a first step in development of a numerical model for pit lake water quality prediction (Castendyk, 2009) (Figure 9). Simplification of actual processes will be necessary both as a complete reconstruction of the pit lake system is not possible due to software limitations but also due to dataset limitations of the system in question. Ideally, even though the conceptual model has simplified the pit lake significantly it has retained enough fundamental processes that it will still accurately represent pit lake behaviour for the relevant modelling processes expected of it (Anderson & Woessner, 1992).

Regardless of how well the conceptual model fits numerical modelling, a conceptual model should be updated as knowledge in both the relevant sciences and the system involved develop (Castendyk & Webster-Brown, 2007). Although further addition of data is one way to improve upon conceptual models, just as importantly, the conceptual model must remain open to improvement and refinement as both new knowledge comes to light and if the conceptual model is found to fail to explain important processes (Bredehoft, 2005). For example, new data becoming available following placement of groundwater bores around a pit lake may significantly change the understanding of local groundwater quality from areas of acid-generating backfill within a pit lake catchment compared to regional groundwater quality which typically dominates pit lakes geo-chemical modelling. Without a well-thought conceptual model underpinning it, numerical models may run the risk of moving straight into modelling and ignoring “inconvenient” data gaps. Additionally, they may run the risk of assuming prior knowledge of a particular system that is already adequately accounted for in the broad scope of the modelling software.

However, in a staged conceptual model, consideration must be given to the hierarchy of physical, chemical and biological processes occurring within pit lakes that advises a logical modelling sequence to ultimately reach prediction of pit lake water quality (Figure 10).

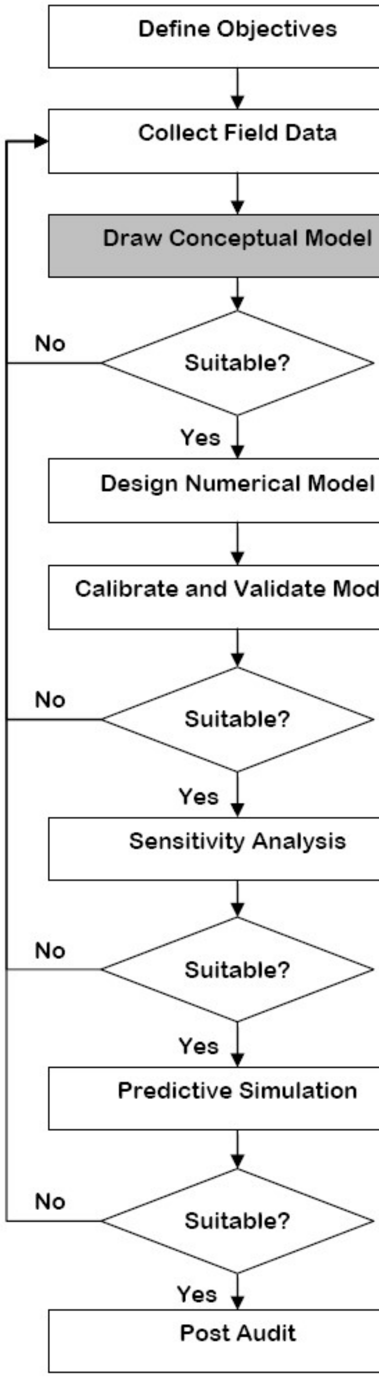

Figure 9. Flow chart showing the procedure used to model major processes that influence pit lake water quality (from Castendyk, 2009).

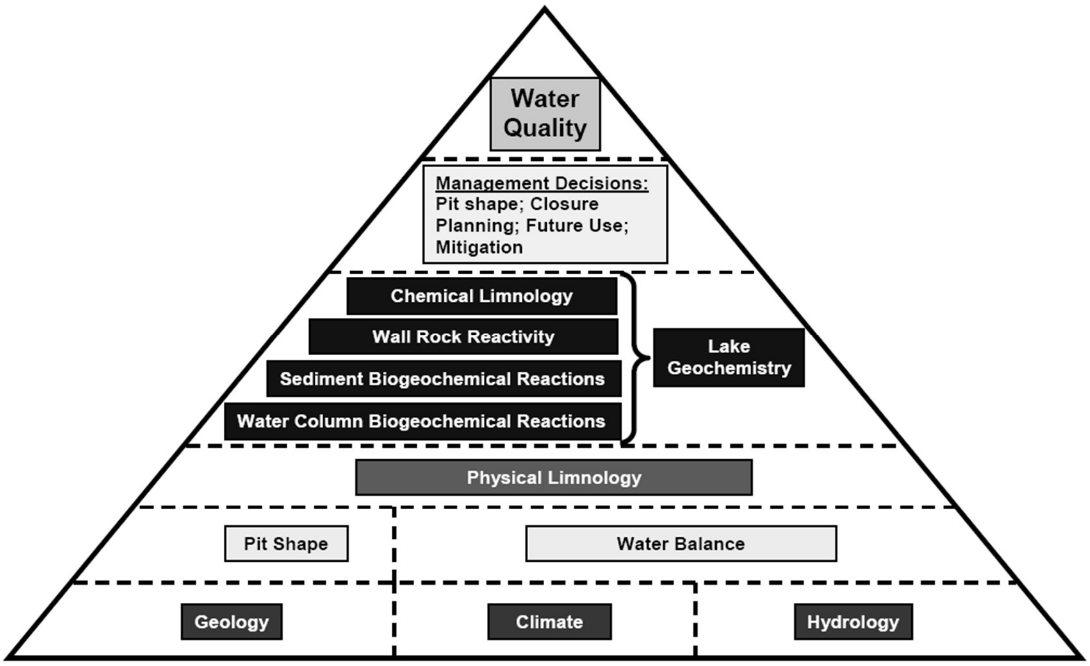

Figure 10. Hierarchy of processes occurring within pit lakes ultimately leading to pit lake water quality (Castendyk & Eary, 2009).

3.2 Methods

3.2.1 Empirical modelling

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 & Gorley, 2006). 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 in 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 similar the data points are.

Ordination by Principal Components Analysis (PCA) was specifically used to produce ordination graphs of water quality data to illustrate how lakes differed from each other and over different sampling times. Prior to PCA analysis, water quality data were $\log_{10}$ transformed and normalised to the maximum value encountered (Olsgard *et al.*, 1997; Clarke & Warwick, 2001). A hierarchical agglomerative clustering dendrogram was then used to produce cladistic cluster groupings of similar pit lake type from the 2-dimensional PCA plots.

Water quality parameters most contributing to the differences seen between seasons and lakes in the ordination graphs were determined by the SIMilarity-PERcentages (SIMPER) routine (Clarke, 1999). Transformations of abundance data for multivariate analysis were chosen from those that best maximise differences between groups and improved water quality variable colinearity (Faith *et al.*, 1987; Austen & Somerfield, 1997; Stark, 1998).

3.2.2 Conceptual modelling

These cladistic groupings were then compared with general environmental observations that had been collected at the pit lakes of the Collie Lake District during monitoring as recommended by Zhao *et al.* (2010). Observations included age of lakes, whether lakes had previous underground workings and whether lakes received significant surface water inputs or not. Absence, presence and degree or mode of catchment rehabilitation was also noted.

A summary table of these observations was then constructed from the combined corporate knowledge of the MiWER, DoW and mining company staff (see Chapter 8).

3.3 Results

3.3.1 Empirical modelling

Survey data from the two different sampling events of the Lake District in 2009 (Zhao *et al.*, 2009) showed an overlay between the two different sampling seasons of this survey. This indicated that what seasonal differences there may be between autumn and spring are relatively less significant on fundamental water chemistry of the Collie pit lakes than differences between individual lakes (Figure 11, Table 1).

The cluster analysis grouped lakes based upon their basic physico-chemical water column chemistry averaged over the two 2009 sampling seasons (Figure 12). A PCA of pit lake basic surface water physico-chemistry across both sampling 2009 seasons then showed what factors appeared to be driving the differences between individual lakes (Figure 13).

Lake Centaur appeared to be a clear outlier lake type as the first sole lake splitting off from the grouping. The early separation of Lake Centaur is likely due to its high tannins and salinity as a result of Chicken Creek flowing into it seasonally. It was therefore determined that Lake Centaur should not be a consideration for incorporation in the numerical modelling as it was not representative of the other Collie Lake District water chemistries.

The next group of pit lakes to split off consisted of the south-eastern Premier pit lakes WO5C and WO5D. There is little data for these two lakes, but they are close together on the Premier lease so likely share similar geologies, were rehabilitated similarly and were withdrawn from operation at around the same time.

The third group appearing consisted of the historic lakes and also the new Premier lake WO5F. This new pit lake may occur with the grouping of historic lakes because it was still filling and appears to have a large catchment/volume ratio. This means that surface water may be the most important water input now which may also be true of completely-filled historic voids. It also means that water here is probably of higher quality (higher pH and lower ORP).

The fourth group showed the remaining new lakes from both mining company leases. These pit lakes were all higher in ORP and lower in pH. This lower water quality may be due to the recent legacy of groundwater filling. Wall and catchment waste rock exposure is expected to have produced acidity during this filling process and was not likely to have had time to be diluted by local more alkaline surface water flowing over rehabilitated catchment topsoils and less acidic regional groundwaters.

However, the fourth group also shows pit lake WO3 as slightly different within this group. WO3 is unusual in that it is an old (*ca*. 50 years) Premier pit lake. It has a slightly different physico-chemistry in that it has a slightly higher pH and ORP and also a higher chlorophyll *a* concentration. This may be interpreted as a lower acidity and may be due to the many decades of surface flow into and thru-flow of less-acidic groundwater improving water quality over the years since it was completed. In this sense, although belonging to this group of new pit lakes, WO3 may be seen as an example of the younger Premier pit lakes that has developed (albeit only a moderate amount) slightly better water quality through natural dilution processes.

Given that one group consisted of only a single and unusual pit lake-type, the clustering exercise therefore produced three distinct lake groups that could be further explored with numerical modelling (Müller *et al.*, 2010).

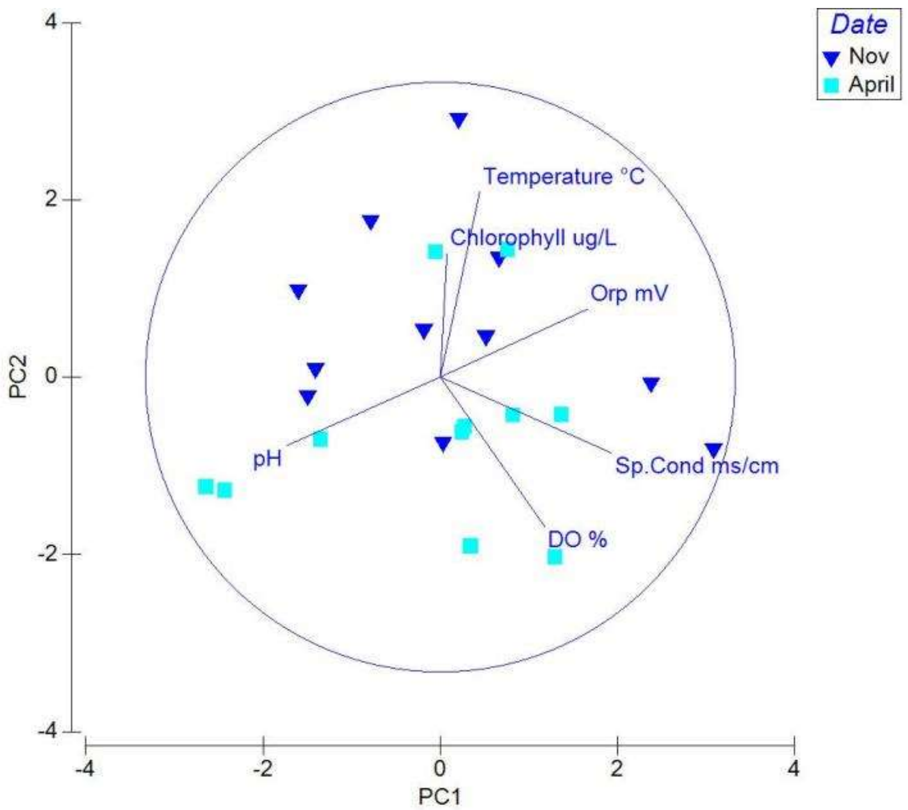

Figure 11. PCA of basic physico-chemistry differences between autumn (only April data for Blue Waters) and late spring (only November data for Centaur) for Collie pit lakes in 2009. PC1 = 36%, PC2 = 27%.

Table 1. SIMPER analysis showing basic physico-chemistry differences between autumn and spring water samples. 'Contribution %' is proportion of total dissimilarity between treatments which each variable contributed in a diminishing order. All data ln(x+1) transformed and normalised.

Variable	Mean Autumn	Mean Spring	Mean dissimilarity (%)	Dissimilarity SD%	Contribution %	Cumulative %
Temperature (°C)	20.1	22.1	2.3	1.0	19.9	19.9
DO (%)	96	92	2.1	0.7	18.1	38.0
EC (μg cm^{-1})	2.0	1.9	2.1	0.7	17.6	55.6
Chlorophyll (μg L^{-1})	0	1	2.0	0.3	17.3	72.9
pH	0.1	-0.4	1.7	0.7	14.2	87.1
ORP (mV)	0.0	0.3	1.5	0.6	12.9	100

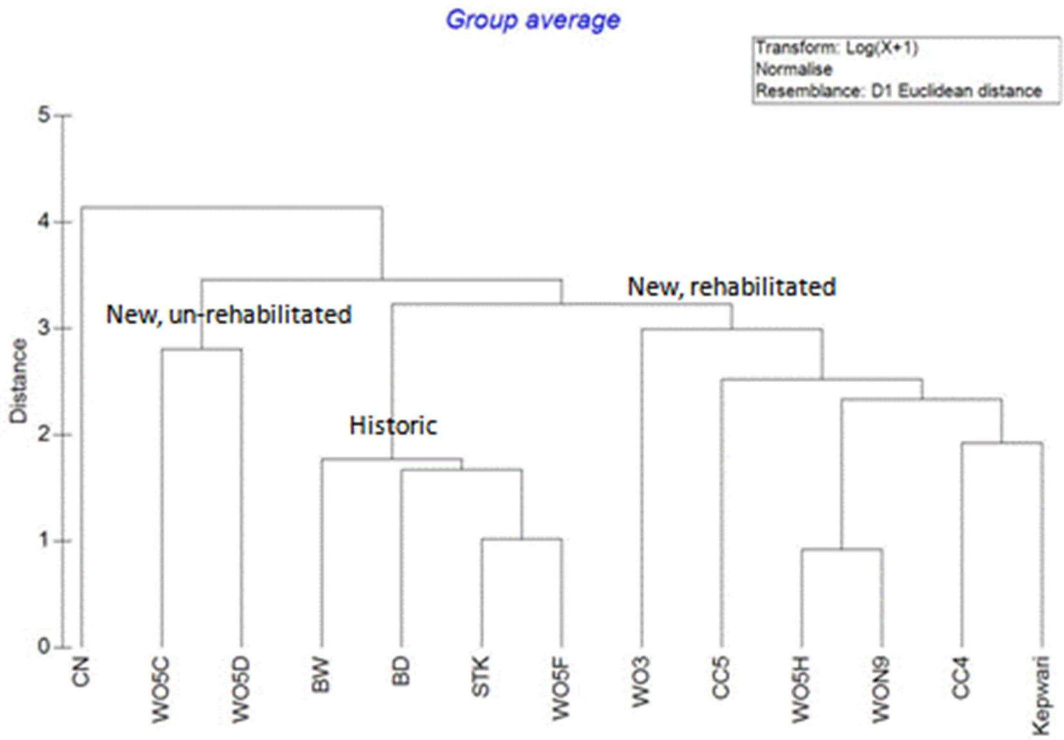

Figure 12. Cluster diagram of mean basic physico-chemistry differences between for individual Collie pit lakes for combined autumn (only April data for Blue Waters) and late spring (only November data for Centaur) in 2009.

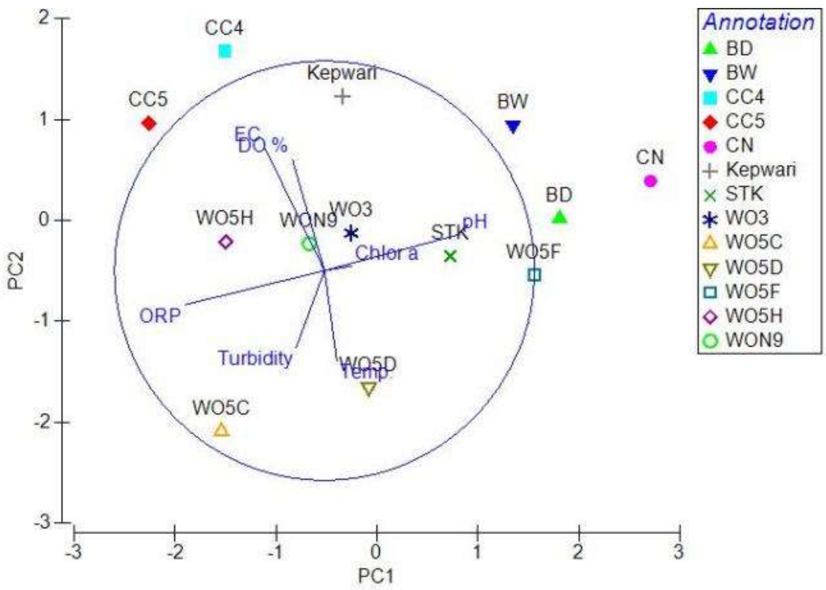

Figure 13. PCA of mean basic physico-chemistry differences between for individual Collie pit lakes for combined autumn (only April data for Blue Waters) and late spring (only November data for Centaur) in 2009.

Table 2. Summary of pit lake groups and their characteristics.

Group	Lakes	Characteristics
A	WO5C, WO5D	New lakes with newly rehabilitated catchments, low salinity
B	BW, BD, STK, WO5F	Historic or relatively large catchment lakes, low salinity
C	WO3, CC5, WO5H, WON9, CC4, Kepwari	New lakes with less more rehabilitation/less catchment acidity generation, high salinity

3.3.2 Conceptual modelling

Pit lakes fill with groundwater once dewatering stops and this is further supplemented with surface inflows and direct rainfall. Dominant hydrology across all Collie pit lakes is thought to fit a form of the "Flow Through" model of Commander *et al.* (1994). In this model, the pit lake in summer acts as a sink, and in winter acts as a recharge area, while net limited flow-thru occurs across the periods in total. Although it may still be fit for purpose of general understanding, this hydrology is, nevertheless, grossly simplified in the conceptual model as a mine pit cuts through a number of discrete groundwater lenses (saline, fresh, acidic, etc.).

Acidity appears to be arising in all Collie pit lake types through a number of sources (Table 3). Although sub-Bituminous Collie coals are low in sulfur (0.3–0.8%) (Le Blanc Smith, 1993), oxidation of sulfur as pyrites in coal in lake, groundwater and surface runoff will have a profound affect on the regional lake water which has little natural buffering capacity as a result of poorly buffered surrounding geologies (Lund & McCullough, 2008). Secondary mineralisation of iron and sulfur compounds and minerals to forms of Ferrihydrite ($Fe[OH]_3$), Goethite (FeO.OH), Gibbsite ($AL[OH]_3$), Jarosite ($KFe_3[SO_4]_2[OH]_6$) and Jurbanite ($Al[SO_4][OH]5H_2O$) are also all acidity-generating processes thought to be occurring in pit lake sediments (Salmon *et al.*, 2008). This low acidity buffering capacity means that small amounts of acidity result in low pH and also that lake pH very dependant on small surface and groundwater inputs.

All historic lakes appeared to have had some natural form of catchment restoration, albeit of a very different applied nature to the rehabilitation efforts of Premier around the Western mine pits (Table 3). The catchment vegetation of these older lakes was often dominated by wilding pines (*Pinus pinaster*) and exotic gums (*Eucalyptus* spp.) from the eastern states that may have carried from forestry plantations nearby.

The riparian vegetation of all pit lakes was very depauperate, although some amphibious vegetation (notably *Schoenoplectus validus*) was occasionally present around the margins of the historic lakes (Plate 2).

All lakes often become very turbid after rain, due to suspended solids. Particularly when combined with the large depth of many lakes, this may reduce the euphotic depth of many of the Collie pit lakes and consequently reduce the capacity for benthic primary production (Figure 14).

Plate 2. Typical 'bathtub ring' of depauperate riparian vegetation typical of Collie pit lakes, even examples with rehabilitated catchments such as WO3.

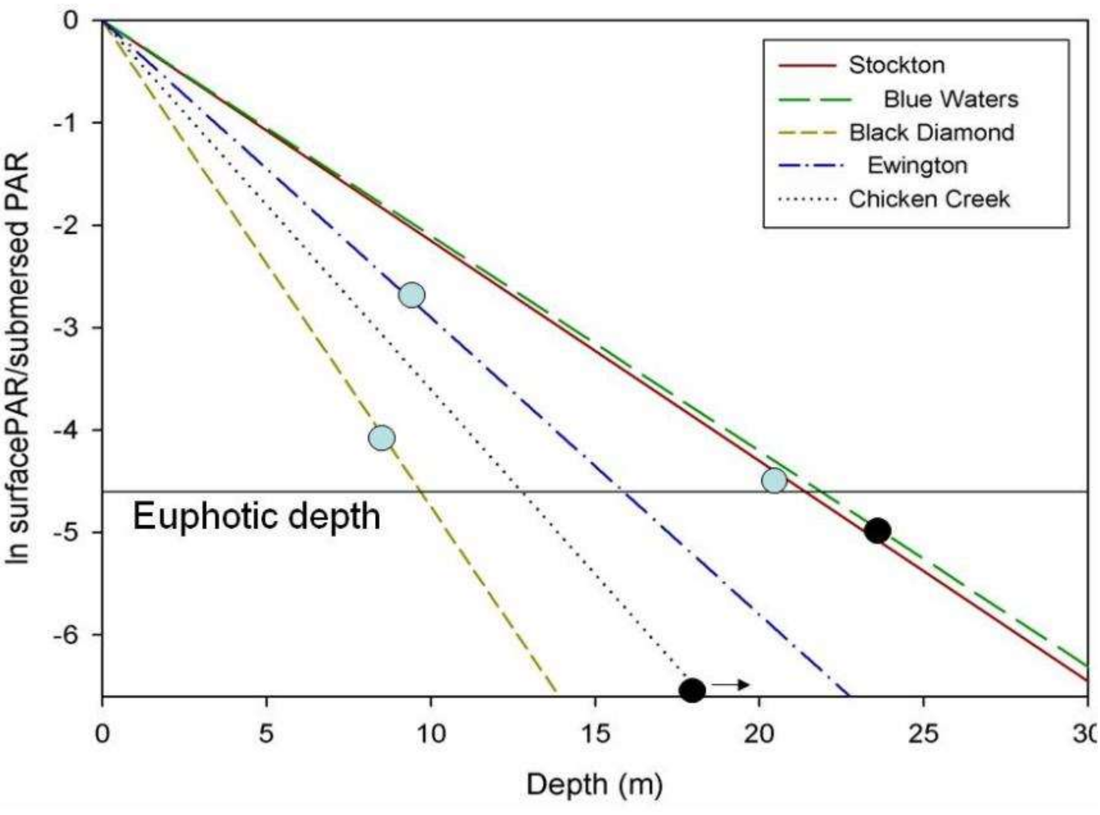

Figure 14. Euphotic depth and likely dominance of benthic primary production in some Collie pit lakes.

Table 3. Summary of Collie Lake District pit lake environment observations and their conceptualised water budgets (courtesy Tom Brooks). 2004-2005 only.

Sub basin	Void	In					Out				Characteristics						Comments
		Rain	**Catchment runoff**	**Stream/River**	**Ground water**	**Dewatering recharge**	**Evaporation**	**Stream/overflow**	**Ground water**	**Pipe discharge**	**Maximum depth (m)**	**pH**	**Total dissolved solids (mg L^{-1})**	**Mining complete?**	**Underground mines**	**Rehabilitation**	
Cardiff	Black Diamond A	✓	✓		✓		✓	✓	✓		15	5-6	600-800	1960s	✓	✓	Natural restoration >50 years.
Cardiff	Black Diamond B	✓	✓		✓		✓	✓	✓		?						
Cardiff	WON9	✓	✓		✓		✓		✓			3.7					
Cardiff	Stockton	✓	✓	✓	✓	✓	✓	✓	✓		30	4.5-6.5	500-600	1960s	✓	✓	pH 4.5 but up to 6.5 when water

Sub basin	Void	In					Out				Characteristics						Comments
		Rain	Catchment runoff	Stream/River	Ground water	Dewatering recharge	Evaporation	Stream/overflow	Ground water	Pipe discharge	Maximum depth (m)	pH	Total dissolved solids (mg L^{-1})	Mining complete?	Underground mines	Rehabilitation	
																	added to keep pH high. Natural restoration >50 years.
Cardiff	WO3	✓	✓		✓		✓		✓			4.2				✓	Rehabilitated <5 years
Cardiff	WO5B (Kepwari)	✓	✓	✓*	✓		✓	✓	✓		70	4.0-4.6	1,185-1,611	2004		✓	Rehabilitated <5 years. Rapid filled by Collie

Sub basin	Void	In					Out				Characteristics						Comments
		Rain	**Catchment runoff**	**Stream/River**	**Ground water**	**Dewatering recharge**	**Evaporation**	**Stream/overflow**	**Ground water**	**Pipe discharge**	**Maximum depth (m)**	**pH**	**Total dissolved solids (mg L^{-1})**	**Mining complete?**	**Underground mines**	**Rehabilitation**	
																	River South diversion 2005–2007.
Cardiff	WO5C	✓	✓		✓		✓		✓			3.4				✓	Rehabilitated <5 years
Cardiff	WO5D	✓	✓		✓		✓		✓			4.2				✓	Rehabilitated <5 years
Cardiff	WO5H	✓	✓	✓	✓		✓	✓	✓	✓	80	3-4	500-600	1990s	✓	✓	Rehabilitated <5

Sub basin	Void	In					Out				Characteristics						Comments
		Rain	**Catchment runoff**	**Stream/River**	**Ground water**	**Dewatering recharge**	**Evaporation**	**Stream/overflow**	**Ground water**	**Pipe discharge**	**Maximum depth (m)**	**pH**	**Total dissolved solids (mg L^{-1})**	**Mining complete?**	**Underground mines**	**Rehabilitation**	
																	years
Cardiff	WO5F	✓	✓		✓		✓		✓			5.7-5.9					
Premier	Centaur	✓	✓		✓		✓		✓			6.5-7.4	3000				
Premier	Chicken Creek 4	✓	✓		✓		✓		✓			2.6-5.7	1500-2000				Collie River East first flush diverted 2005–2007
Premier	Chicken Creek 5	✓	✓		✓		✓		✓			2.9	500-700				Planned for dewatering to allow

Sub basin	**Void**	**In**					**Out**				**Characteristics**						**Comments**
		Rain	**Catchment runoff**	**Stream/River**	**Ground water**	**Dewatering recharge**	**Evaporation**	**Stream/overflow**	**Ground water**	**Pipe discharge**	**Maximum depth (m)**	**pH**	**Total dissolved solids (mg L^{-1})**	**Mining complete?**	**Underground mines**	**Rehabilitation**	
																	Premier mining nearby
Premier	Ewington 1	✓	✓		✓		✓		✓			3.9-4.8	400-780				Remined in 2009
Premier	Blue Waters	✓	✓		✓		✓	✓	✓				642-973				Remined in 2009

3.3.3 Representative pit lake types

3.3.3.1 *Historic lakes*

The catchments of historic pit lakes were not rehabilitated and as a result are generally relatively small compared to newer pit lakes reducing surface water inputs. However, the acidity budget of historic lakes appears to be dominated by acidic inflows from catchments where high proportions of acidic over and inter-burden dumps were abandoned and will degrade these surface waters (Figure 15). Some historic lakes also have underground workings associated with them (Figure 6, Table 3), which may likely further increases acidity inflow through enhanced reactive geology interaction with pit lake and influx groundwaters.

In the historic pit lakes such as Black Diamond that do not have substantial acidic surface inflows, pH has not changed over 50 years. However, acidity has declined, as have Fe, Al and SO_4 concentrations. Secondary mineralisation and subsequent neutralisation of some acidity and eventual burial by kaolinite clay, may account for some of the loss of these ions but not for the decrease in acidity. Nevertheless, inputs of circum-neutral groundwater in shallower pit lake workings may explain this gradual loss of acidity in some e.g., Black Diamond, but not in others e.g., Blue Waters.

Evaporation rates may be reduced in historic lakes as wind fetch across the lake's surface is impeded both by the small catchment area, steep pit lakes sides and also by the presence of over-burden dumps. Direct precipitation to the lake is unlikely to be different from other lake types where net surface water gain during winter may lead to discharge to ground water as a source/through-flow lake whilst summer net surface water loss may then express during these months as groundwater sinks.

Contributions of organic matter and pit lake primary production may increase as pit lake catchments become established over long periods of time since abandonment. This stability facilitates allochthonous inputs and may also be reflected in greater rates of primary production. Although there is a minor increase in carbon, particularly in the sediments, there is still no real evidence of sulphate reduction being a dominant water quality control process in these lakes.

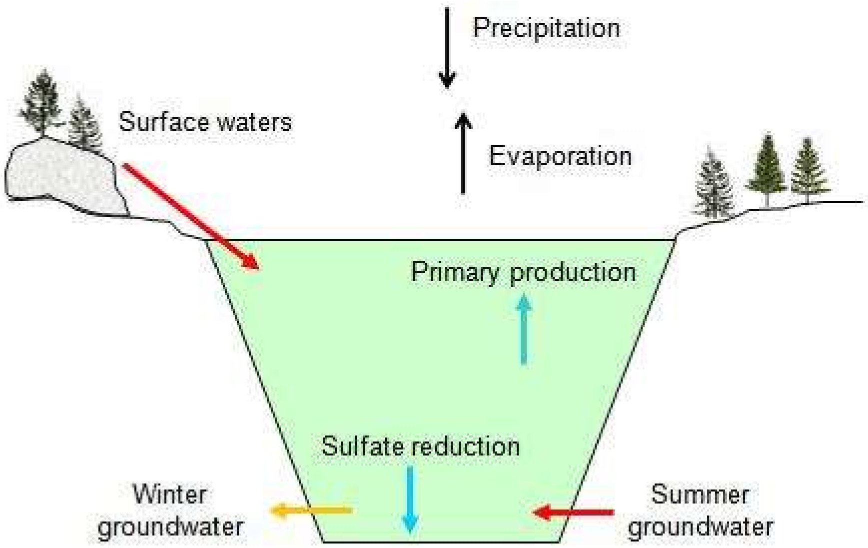

Figure 15. Conceptual model of fundamental bio-geo-chemical processes in Historic pit lakes.

Plate 3. Extensive un-rehabilitated workings and over-burden deposits in historic Blue Waters Lake catchment.

3.3.3.2 *New rehabilitated lakes*

Surface water inputs are likely to be greater in new rehabilitated lakes as a result of their greater catchment size relatively to pit lake size produced during high wall battering. However, evaporation rates may be higher as increased wind fetch leads to greater loss of surface waters relative to direct precipitation. The net result of this altered water budget may be high salinities resulting in these lakes over time. Although pit lake catchment soils may be layer to bury acid generating materials, erosion may exposed them leading to acidity efflux into the lake (Plate 5). As a result, significant net acidity may still be contributed to these lakes by their catchment.

New rehabilitated lakes may have relatively significant stores of carbon in their sediments from native catchment vegetation seeded during rehabilitation that became flooded during lake establishment. These elevated sediment carbon levels may facilitate sulfate reduction to a higher degree than in either historic or un-rehabilitated lakes, although these processes will still be limited by the small sulfate pool available.

Most importantly, new rehabilitated pit lakes all have higher salinity than the other lake types. Of these lakes, both Kepwari and Chicken Creek 4 have been directly filled with saline Collie River water and WO5H has a saline stream flowing into it. Chicken Creek 5 has possibly received some saline water from groundwater flow from the higher AHD level arising at Chicken Creek 4 during Collie River diversion, although it is unclear why salinity should be so high in WON9 and WO3.

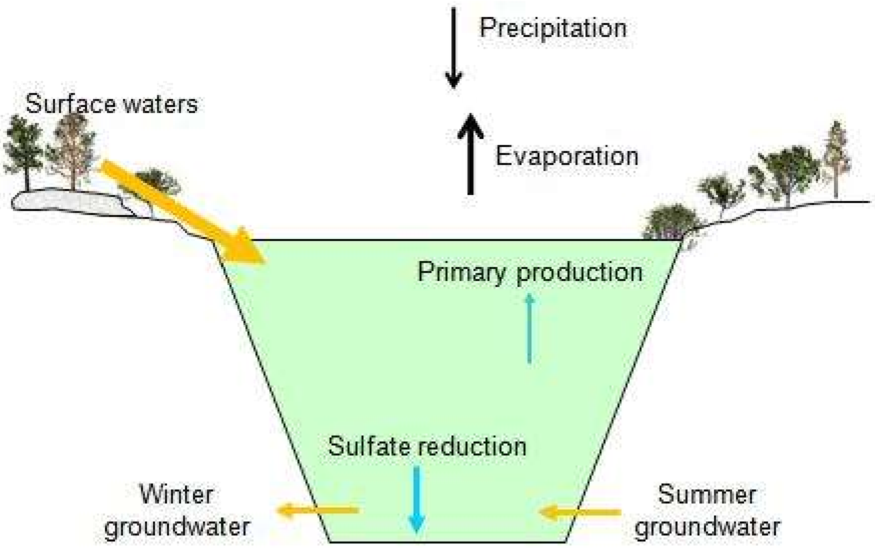

Figure 16. Conceptual model of fundamental bio-geo-chemical processes in new and rehabilitated pit lakes.

Plate 4. Catchment erosion and sedimentation in Lake Kepwari.

Plate 5. Soil and sub-soil erosion and weathering around Lake Kepwari showing exposed coal fragments.

3.3.3.3 *New, un-rehabilitated lakes*

New pit lakes that have not had or have only just recently had rehabilitation efforts made in their catchments will be affected by many of the same influences as those with more established rehabilitation (Figure 17). A further fundamental difference between this and other lake types is that bank erosion is likely to be much greater in lakes without plantings established in them (Plate 6). Directly related to this un-established catchment, un-rehabilitated lakes will not have carbon stores in their sediments to facilitate sulfate reduction and will therefore have less capacity for internal alkalinity-generating processes.

Fundamentally, however, these isolated lakes have not experienced saline diversions or indeed any surface water inputs other than those of their constrained catchments. As a result, their water quality has remained both more acidic (due to a lack of pH buffering from alkaline saline waters) and also fresher due to a lack of salt loading.

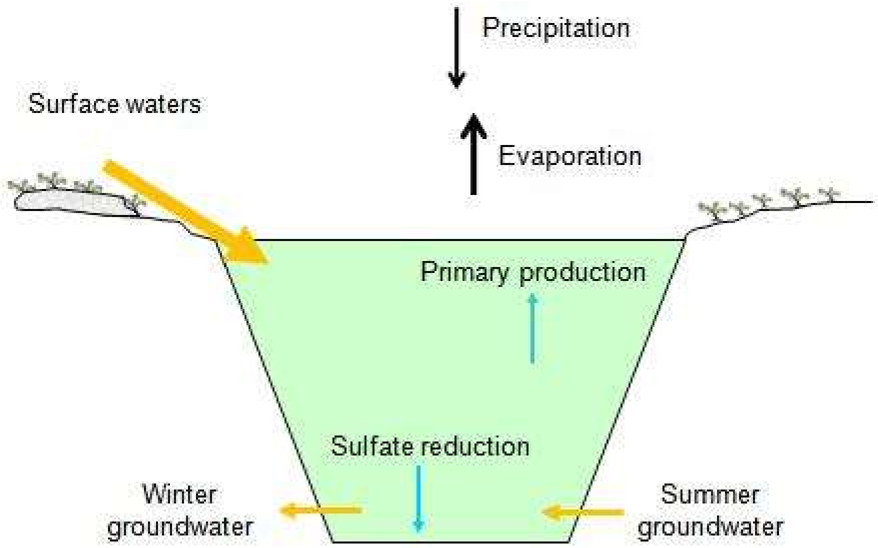

Figure 17. Conceptual model of fundamental bio-geo-chemical processes in new and un-rehabilitated pit lakes.

Plate 6. Lake WO5D catchment showing recent ripping and revegetation efforts (April 2009).

3.4 Discussion

Post-mining landscapes do not represent the same landscape functionality and structure as they held before; they are completely new landscapes (Haase *et al.*, 2009). However, one common desirable feature to all post-mining landscapes is that they be self-sustaining ecosystems, of desirable ecological value; for example, regional representation of biotic communities.

Algal primary producers play an important role in natural lakes, providing the dominant autochthonous energy sources that are the basis of lake-ecosystem food webs (Bott, 1996). Primary production contributes to the ecological value of an acid mine pit lake in many ways. Primary producers can facilitate sulphate production which increases alkalinity and pH in AMD impaired lakes (Lund & McCullough, 2009), chelate metals directly causing toxicity or sorbing phosphorus and overcome carbon limitation (Nixdorf & Kapfer, 1998). The presence of primary producers may also accelerate the development of the food chain. It is therefore necessary to investigate and determine what factors of acid mine lakes limit productivity (Koschorreck & Tittel, 2002).

However, there is a lack of understanding of the factors limiting primary productivity in acidic pit lakes. One possible environmental variable limiting primary productivity is acidity, or more specifically low pH. The presence of toxic metal ions in the water could also be another factor limiting primary productivity (Klapper *et al.*, 1998). However, the few ecological studies made on pit lakes highlight nutrient limitation restricting algal productivity and hence lake foodwebs (Thomas & John, 2006; Salmon *et al.*, 2008) (Gyure *et al.*, 1987). Previous authors have assumed that since availability of phosphorus (P), carbon (C) and nitrogen (N) tends to be low in these lakes they may also be limiting to primary productivity (Lund & McCullough, 2008, 2009). Studies on nutrient limitation in acidic pit lakes have determined that available nutrients are often limited in acidic pit lakes due to the high levels of Fe^{3+} hydroxides which bind with soluble fractions of phosphorus and quickly precipitate them out (Nixdorf *et al.*, 2001).

Although benthic algae productivity is often of similar magnitude per unit equivalent to phytoplankton productivity in many naturally occurring lakes scientists tend to focus their attention only on phytoplankton productivity in acidic pit lakes and a comprehensive study of benthic algae productivity in acidic pit lakes is lacking. Nonetheless, the benthos of many acid mine lakes may constitute a dominant part of the algal community and may play a significant energetic role (Koschorreck & Tittel, 2002).

Very little aquatic ecology is known about aquatic macroinvertebrate communities of pit lakes (Kumar *et al.*, in press). However, collectively, these studies show macroinvertebrate communities of limited diversity dominated by cosmopolitan and pollution tolerant taxa dominated by oligochaete worms, Chironomidae and other detritivorous insects and Dystiscid and Odonate predators and copepod zooplankters even in lakes of relatively good water quality (Proctor & Grigg, 2006). Biodiversity of macroinvertebrates in older pit lakes may be lower due to higher salinity, or lower as a result of higher nutrient concentrations. This finding suggests that, regardless of water quality, pit lakes will not have macroinvertebrate communities representative of natural water bodies, possibly due to reduced habitat diversity.

There is a gross dichotomy between relinquishment criteria and standards for terrestrial and aquatic communities. This difference in restoration expectations extends even to the edge of the pit lake, where riparian vegetation is seldom either representative of the region or self-sustaining. The absence of riparian vegetation around new pit lakes therefore appears to be unrelated to water quality and more likely a consequence of bank stability and appropriate habit suitability for seedling establishment to be successful. Pit lake riparian vegetation rehabilitation also appears to be more complex than original rehabilitation plans expected, with special requirements for nutrient and water retention required for the return of representative regional wetland species (van Etten *et al.*, 2009c). Finfish and large crustacea such as crayfish will also require a holistic environmental suite including habitat, food resource and water quality. Terrestrial mammal habitat requirements will include refugia such as burrows, fallen logs and rocky outcrops which form important shelter from predation (Foster, 1993). A holistic catchment strategy has already proved successful with other pit lakes of this broader region (van Etten *et al.*, 2009a, b; van Etten *et al.*, 2009c). This strategy involves vegetation planting and rehabilitation across more than one simple vegetation community type with particular regard for both where existing precedent for a riparian vegetation exists and for topography and depth to water requirements of plant species (Figure 18).

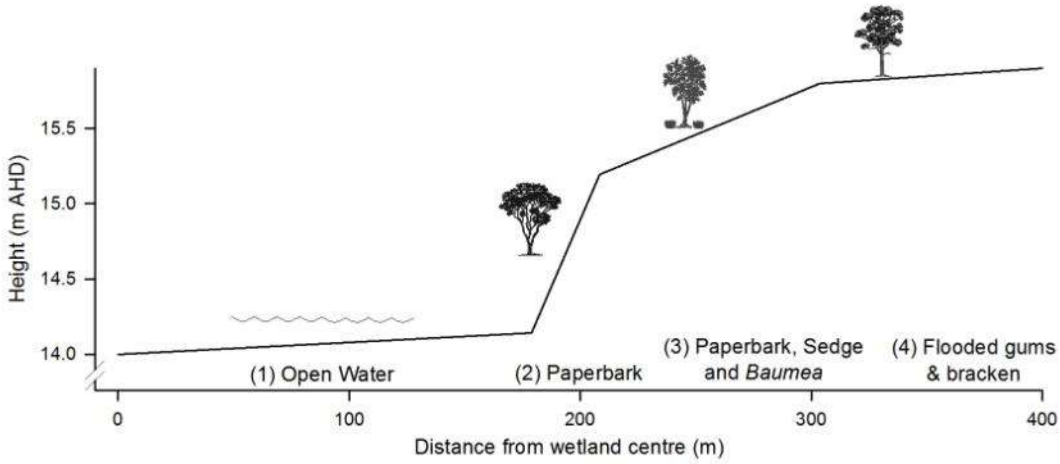

Figure 18. Suggested catchment restoration strategy including riparian seration considerations.

Analogous to restoration of terrestrial systems, a conceptual model illustrating both a natural evolution towards restoration as an Identifiable Desired State (c.f. Grant (2006)) and local stable states that prevent development along this evolutionary path appears to hold true. The current position of all of the Collie pit lakes appears to be as degraded local stable states or “Identifiable Degraded States”, many of which are below biological thresholds (Figure 20). As a result, water quality is largely stable as abiotic processes are the major determinator of water chemistry in acid mine lakes. A master variable for almost all these bio-geo-chemical processes appears to be pH and acidity. Rates of pyrite oxidation, ferrous iron oxidation, mineral dissolution, iron precipitation, iron hydroxide transformation, and iron and sulfate reduction are strongly pH dependent (Blodau *et al.*, 2000). Biotic remediation processes are weaker than current abiotic processes e.g., acid inputs across all of the pit lakes. For biological remediation by natural lake processes to occur or for passive strategies to be successful, these biotic need assistance, and not hindrance, from these simultaneous abiotic factors that buffer this transition.

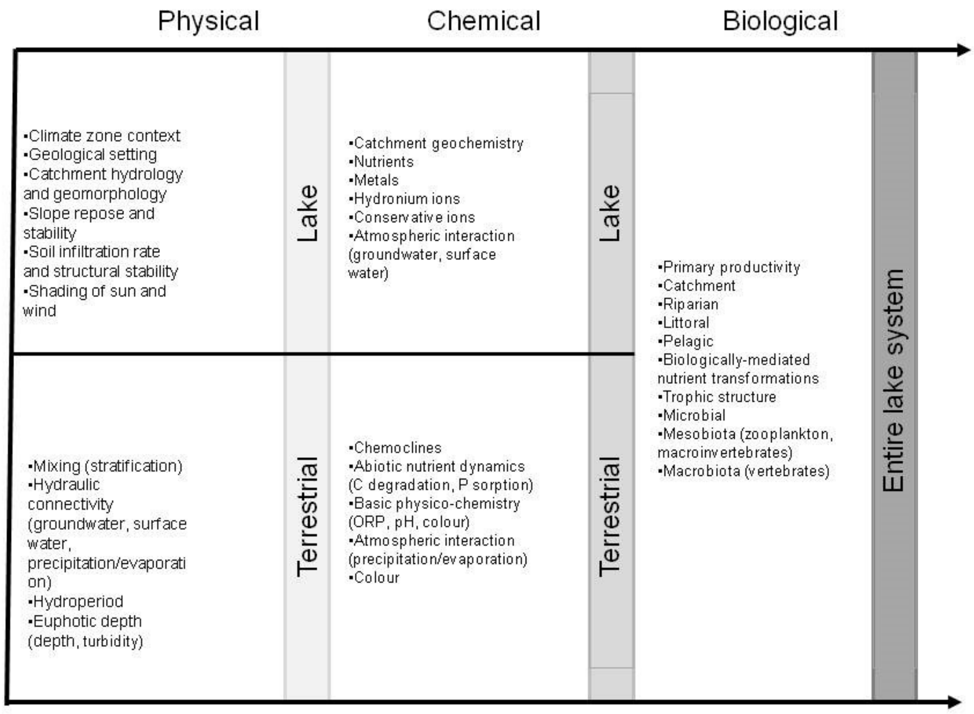

Figure 19. Pit lake and catchment ecological development stages and obstacles to their evolution (adapted from Whisenant, 1999).

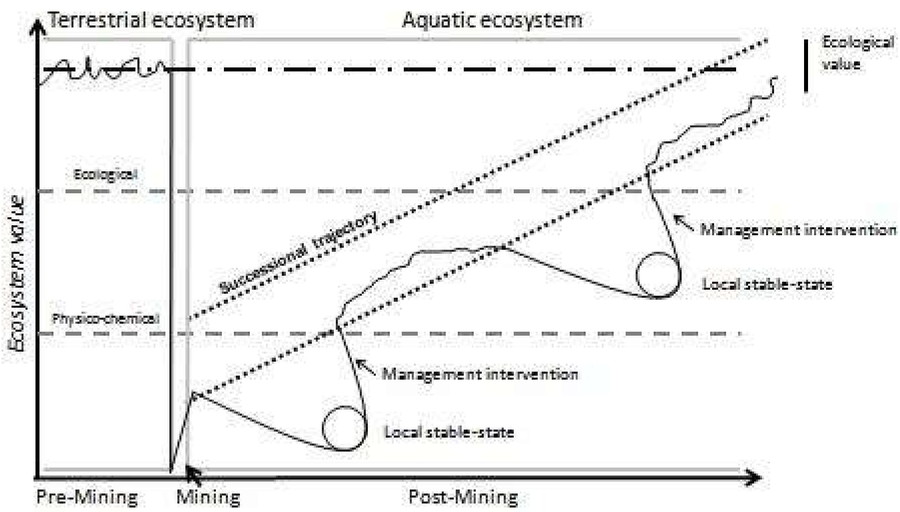

Figure 20. Hypothetical successional model of rehabilitation following mining showing state-and-transition concept of succession and identification of distinct thresholds (McCullough & Van Etten, submitted).

With domination of mine water research by physical and chemical sciences, environmental values (more directly described by ecological approaches) are frequently ignored by mine water funding bodies and researchers (McCullough *et al.*, 2009b). Such ecological approaches to mine water research opportunities may make significant contributions to the ecological sciences themselves (Kalin, 2009), but may also more clearly articulate targets for the long term sustainability of pit lake systems specifically (the "what are we actually setting water quality targets/remediating water quality for?" question). Such ecological versus physical/chemical-driven approaches recognise mine waters-affected water bodies such as pit lakes as more than a geochemical environment, with consequent further (and often simple) requirements for fundamental limnological processes also needing to be addressed if rehabilitation to a representative functional ecosystem is to be successful.

We hope that this research serves to move the field of both mining restoration forward by considering mine waters legacies in the context of their catchments, and vice versa, leading to realisation of more holistic environmental benefit. We also hope that the trans-disciplinary perspective offered by this study will translate into improved community and regulatory involvement in relinquishment planning, as well as providing an example to the mining industry of opportunities to cheaply and effectively achieve environmental sustainability targets.

4 ERA conceptual modelling

4.1 Introduction

Ecological Risk Assessment (ERA) evolved from ecotoxicological risk assessments that examined the risk posed by a toxicant (e.g. heavy metal, pesticide) on a target species. This approach was adopted and broadened in the Australian and New Zealand Water Quality Guidelines (ANZECC and ARMCANZ, 2001). The guidelines encouraged risk assessments for specific sites and toxicants (for example see Muschal & Warne, 2003). Ecological risk assessment has also been expanded to a more holistic level, covering multiple environmental stressors and ecological consequences (e.g. Hart *et al.*, 2003). Although ERA has become an increasing important management tool, much of the assessment remains qualitative. Qualitative assessments, while often considered the only possibility given poor data availability, are fraught with subjectivity, linguistic uncertainty and rarely adequate recognition of the degree of uncertainty (Burgman, 2001). A consequent emphasis on quantification of ERAs has led to a focus on the development of suitable models, (e.g. Bayesian modelling), to overcome some of these limitations (e.g. Hart *et al.*, 2003; Pollino, 2004; Webb & Chan, 2004).

Hart (2004) and Hart *et al.* (2001; 2003) proposed models of the ERA process that commence with a problem formulation, issue/hazard assessment followed by a risk assessment. Problem formulation deals with establishing the scope of the ERA and identification of the nature of the risks being discussed. In stakeholder groups problem formulation can be a significant part of the process, but is essential that group develops a common understanding of the process. Conceptual models are often developed so the group can gain a shared understanding of the processes involved in creating the risks. The risk assessment informs decision making which may trigger further more detailed investigations into assessment of the risk, or lead to risk management and monitoring. The whole process is iterative, with monitoring results feeding back into the problem formulation stage.

Ecological risk assessment for this task complements the human risk assessment (Task 2) by focusing on primarily the natural world. However a number of issues, particularly related to beneficial end uses straddle the boundary between human or ecological risk (Figure 21).

The aim of this project was to develop an ecological risk assessment of the Collie pit lakes to inform the development of relevant conceptual models of processes associated with the lakes.

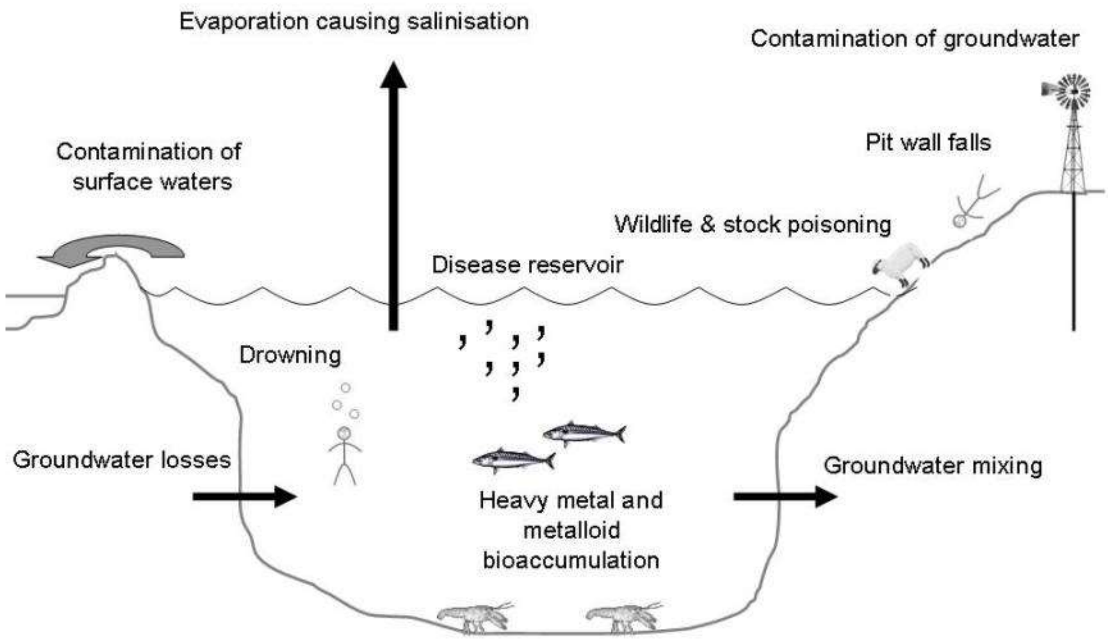

Figure 21. Some potential risks of pit lakes to the environment (after McCullough & Lund, 2006).

4.2 Methods

A Conceptual Modelling workshop was held as a two day event at the Collie Ridge Hotel and Function Centre in Collie, south-western Australia. The purpose of this project is to compile ecosystem information of the 15 pit lakes within the Collie Basin and assess current management strategies and end uses. The outcomes of this project were intended to support water resource planning and management in the Collie mine lakes.

The Workshop included a guided tour at mine lakes of different rehabilitation types, age and conditions in Collie. A select group of stakeholders from within Western

Australia were invited to the workshop (Table 4) to interact together to develop conceptual models of fundamental pit lake processes for assessing ecological risk to connected water bodies.

Table 4. ERA workshop participants.

Name	Organisation	Area of Expertise
Dr. Clint McCullough	MiWER (Edith Cowan University)	Aquatic Ecotoxicology
Assoc./Prof. Mark Lund	MiWER (Edith Cowan University)	Aquatic Ecology
Dr. Naresh Radhakrishnan	MiWER (Edith Cowan University)	Geochemistry and Microbiology
Tom Brooks	Department of Water	Hydrologist
Dr. S. Ursula Salmon	School of Earth and Environment, (University of Western Australia)	Geochemistry
Dr. Brian Barnett	Sinclair Knight Mertz	Hydrological Modeller
Sarah Bourke	Department of Water	Groundwater Hydrology
David Bills	Trans-Pacific Industries	Environmental Science
Travis Cattlin	Department of Water	Groundwater Hydrology
Assoc./Prof. Mark Tibbett	Centre for Land Rehabilitation, (University of Western Australia)	Soil Processes

The stakeholders included experts with a broad knowledge and experience of the pit lake research in diverse fields such as ecology, geochemistry, empirical modelling and hydrology. With the Collie Lakes District as a case-study, we expected new ideas and new perspectives on the environmental issues surrounding pit lakes to be developed. The approach proposed was based on ecological risk assessment with the major outcomes; identification of ecological risks, an assessment of the likelihood and consequences of each risk and development of conceptual models to expand our understanding of processes leading to ecological risks from pit lakes in the Collie district. The stakeholder meeting initially agreed upon the scope of the assessment, and then identified key risks and was facilitated by Assoc./Prof. Mark Lund. Risks were then determined based on stakeholders consensus into low, medium and high risk. Knowledge gaps were also highlighted by the process.

4.3 Scope

The scope of the ERA was considered to be confined by water inputs to the catchment of each lake for surface water and by the groundwater capture zone for the lake, and by the outputs which are the receiving systems, which include discharge to surface waters (Collie River and tributaries), wetlands and to groundwater dependent ecosystems. Another important consideration was the proposed end-use for the pit lake, which could impact on all of the above features. The scope of the study was also limited to primarily risks to non-human biota, as a human health risk assessment is being conducted in another part of the project. Only Collie lakes were considered during the workshop, although many of the issues raised would be applicable to other pit lakes.

4.4 Key Issues, processes (conceptual) and consequences

Initially a list of key issues related to likely risks were identified, the stakeholder group then developed a conceptual understanding of the most likely processes associated with the issues. The consequences of the issue were then identified as a precursor to risk assessment. These issues are detailed below:

4.4.1 Issue 1: Pit Lake waters contain toxic levels of metals.

Processes: Toxicity of lake waters will be influenced by a range of synergistic and antagonistic interactions between metals. For instance, Ca and Mg are known to reduce toxic effects of many metals. Although typically low in pit lakes, DOC complexation of metals could be important if the lake has been remediated with organic matter or is receiving surface water high n tannins e.g., from seasonal Creek flow such as Lake Centaur. Some metals such as Hg may also have their toxicity increased by methylation. Some metal species (particularly heavy metals) are also known to biomagnify and bioaccumulate up through the biota. High levels of certain metals such as Fe, Mn and Al can bind nutrients (particularly P) making it unavailable to primary producers. As pit lake waters discharge through groundwater, interactions with the soil will modify the concentrations of metals in the groundwater, low pH may encourage more dissolution of metals, while neutralisation and sorption could reduce metal concentrations.

Consequence: This will potentially limit in-lake biota (diversity and abundance), cause skin lesions (red spot) in vertebrates in the water, poison transient biota drinking or feeding of biota in the waters (livestock, pests and natives), reduce riparian development and contaminate receiving environments (surface and groundwater) causing similar problems.

4.4.2 Issue 2: Physical hazards in the catchment

Processes: Catchment shaping, bank instability and fluctuating water levels all create physical hazards in the catchment.

Consequences: Wild and domestic animals may fall from highwalls and become injured or drown. Erosion and bank instability will prevent riparian vegetation and catchment vegetation from becoming established. Erosion could result in smothering of aquatic plants but could also assist by burying secondary minerals, preventing re-oxidation of these. Erosion can also erode through soil profiles in the catchment to expose acidity producing soils that have previously been buried deep in the profile in order to prevent oxidation and acidity generation.

4.4.3 Issue 3: Salinisation

Processes: Lake surface area:volume ratio and catchment size and topography will affect water and hence salt balance. Where the balance favours more salts entering the pit lake system than leaving, then salinisation will occur.

Consequences: Limitation of beneficial enduses, especially if higher than surrounding natural systems e.g., stock water drinking guidelines. Potential for saline water discharge via groundwater that may contaminate downstream groundwater communities. Discharge of saline waters into surface receiving waters degrading these environments.

4.4.4 Issue 4: Stratification

Processes: Stratification can be caused by thermal or salinity differences in water density resulting in non mixing layers. Once the layers of water are separated then water chemistry within them can alter primarily in response to changes in oxygen concentration and ORP caused by chemical (COD) and biological (BOD) oxygen demands.

Consequences: If historically permanently stratified, and stratification does eventually break, then highly contaminated waters may reach surface and be discharged. For example, hazardous gases (CO_2, H_2S, CH_4 and N_2O) could be produced in the hypolimnion and specific conditions be released on mass into the atmosphere. In temporarily stratified lakes, on mixing there is potential for algal blooms and release of metals to surface waters and discharges. The hypolimnion may also accumulate contaminants that discharge via groundwater. Fro example, ammonia may increase to high levels in the hypolimnion due to anaerobic inhibition of nitrification (Hamersley *et al.*, 2009).

4.4.5 Issue 5: Disease and biotic toxins

Processes: With its typically low secondary production, the pit lake provides opportunities for toxic algal blooms, growth of disease vectors (e.g., mosquitoes), and protozoan disease such as avian botulism and *Salmonella*. *Salmonella* may also develop from human use of the lake or can be translocated to the lake by birds.

Consequences: Lakes may become a health hazard for people living near or coming into contact with the waters

4.4.6 Issue 6: Extreme low pH

Processes: Low pH is the result of oxidation of pyritic materials in the catchment or walls of the lake producing sulphuric acid which enter the lake via surface inflows or groundwater. Another important acidity generating process is ferrolysis of Fe^{2+} entering the lake via groundwater (Salmon *et al.*, 2008).

Consequences: Buffering as acidity (typically as Fe or Al) which makes remediation more difficult, as buffering has to be overcome prior to pH change. Where chemical neutralisation is used, the resulting flocs may result in smothering of benthic organisms and create a barrier to normal sediment/water interactions. Low pH reduces biota survival by increasing stress, often leading to reduced biodiversity (although abundance can still be high for tolerant species) (McCullough & Horwitz, 2010). Low pH may negatively impact on survival of riparian zone flora if flooding occurs infrequently. Soils coming into contact with acidity are likely to see death of soil biota and particularly plant symbionts which in term may reduce success of host plants. Corrosion of infrastructure interacting with the waters is considered likely (e.g., aluminium boats, pumps, concrete jetties).

4.4.7 Issue 7: Changes in groundwater

Processes: Ongoing abstraction from nearby mining may reduce the fill rate of the pit lake or reduce groundwater inputs into established lakes. The rate of groundwater rebound after dewatering stops will also be influenced not only by abstraction but also by surrounding geologies. The Collie pit lakes are thought to act as a preferential (low resistance) pathway for groundwater flow (Lund & McCullough, 2008), in areas of high evaporation this may be sufficient to make the pit lake a groundwater sink. The pull caused by evaporation may reduce local groundwater levels. In areas with multiple aquifers such as Collie, the pit lake effectively blends the water of these aquifers in the lake itself and on discharge. Changes caused by the lake exposing groundwater, including groundwater recharge from surface runoff or direct rainfall and evapo-concentration

Consequences: Changes in groundwater quality (salinity, metals, nutrients and pH) in discharge area. Reduced exploitability of groundwater in high evaporation areas, either in terms of quality or quantity.

4.4.8 Issue 8: Connection to underground workings

Processes: Underground workings are thought to allow increased connectivity to groundwater and potentially other pit lakes (Lund & McCullough, 2008). Oxidation of materials in old workings can contaminate the pit lake.

Consequences: Reductions in water quality and greater inter-seasonal variation in pH, difficult to remediate the lake without closing connections to underground passages.

4.4.9 Issue 9: River flow-thru

Process: Changes in water quality in riverine flow through systems (caused by loss of volume (evaporative loss), absorption and/or release of contaminants and buffering of flows (timing, frequency and intensity of flood events).

Consequences: Changes in riverine water quality (both positive e.g., nutrient additions and negative e.g., increased salinity), changes in hydrologic regime downstream e.g., flows too stable which might impact on riverine processes such as timing of biotic responses to season and flow change.

4.4.10 Issue 10: Lake morphology

Processes: The shape of the pit lake is determined by the original void shape and modified by any backfilling and shaping (including area: depth ratio). The shape will influence the amount of material that is available for oxidation upon filling. The quality and arrangement of backfill can further influence acidity production following oxidation. Orientation of the lakes largest dimensions compared to prevailing winds will influence the fetch and therefore wind induced mixing.

Consequences: The shape will influence the areas available for biological activity, both in lake and riparian. Shape may help or hinder human use (for swimming, water skiing), in turn these may conflict with environmental outcomes. The bathymetry of the lake can influence the timing, duration and extent of stratification. Wind mixing can also be enhanced or reduced through the lake orientation and area: depth ratio. The degree of acidity producing materials exposed directly or contained within backfill can impact on overall water quality.

4.4.11 Issue 11: In lake storage

Processes: Pit lakes are often seen as the ideal storage facility for reactive ores, burdens and tailings. Backfill may blend together a range of overburdens.

Consequences: If these reactive materials become exposed to oxidation then they may release contaminants into the lake water impacting on water quality. Mixing of backfill will make it difficult to predict groundwater flows and potential sources of contamination.

4.4.12 Issue 12: Overburden dumps

Processes: The shape, location and inevitable failure of covers (if used) of over burden dumps in the catchment can influence wind flow and the microclimate around the lake, provide a source a contaminants and soil (erosion). Acid mine drainage may also leach out of overburden dumps.

Consequences: Contaminants can reduce lake water quality. Soils washing in can smother aquatic plants or benthic algae, but can also bury secondary minerals. Changes in wind flow and microclimates can influence lake mixing and stratification. Dumps can affect the aesthetics of the pit lake.

4.4.13 Issue 13: Catchment morphology

Processes: The size of the catchment relative to the lake volume will have a profound effect on the lake water budget and hence water quality. Many pit lakes are created in areas where there were no natural drainage lines, hence the catchment is artificial, in other areas, a natural catchment may overly the artificial catchment. This can create a diverse landscape of engineered and natural landforms that have no counterparts in the surrounding region. The landuse cover, slope and soil type will be important in determining water runoff rates and potential for erosion of the catchment and carriage of contaminants to the lake. The riparian zone will be an important buffer between the catchment and lake and could reduce transport of contaminants and soils in overland and subsurface flows.

Consequences: Rates of erosion and sedimentation can be impacted, as will the transport of contaminants. The hydrology of the lake (in terms of water budget) will be impacted.

4.5 Conceptual Models

To further develop the mechanisms illuminated by the discussions of issues and the processes that drive them was the development of conceptual models. These models can be split into two: acidity/alkalinity cycles, and lake development over time.

4.5.1 Conceptual model of acidity/alkalinity cycles in Collie pit lakes

The processes by which pyrite is oxidized in the presence of bacteria, water and oxygen to form sulphuric acid are well understood (Mielke *et al.*, 2003). The acidity then dissolves metals from materials which it passes through. This typically results in Collie in waters that are of low pH (3-4), with moderate levels of metals particularly Fe and Al (which is typically buffering). Although Collie coals and overburdens do not generate large quantities of acidity compared to many coal types, the lack of buffering in the local geology ensures that this is sufficient to create acidic pit lakes. Other important mechanisms for acidity generation include ferrolysis which is the oxidation and hydrolysis of Fe^{2+} which can occur in significant quantities in Collie groundwater (Salmon *et al.*, 2008). Peine et al. (2000) found that in German pit lakes that acidification of the lakes was maintained by the establishment of an acidity driven iron cycle. This cycle was dependant on the formation of the mineral Schwertmannite, constant input of Fe^{2+} and no sulfate-reducing bacteria (SRB) activity below pH of 5.5. There appears to be no evidence at this stage in Collie that Schwertmannite forms.

The acidity budget of the pit lake will depend on the balance between incoming acidity, acidity generated within the lake (e.g. secondary mineral formation), evaporation (increasing concentration), dilution by less acidic sources (surface runoff or rainfall), neutralisation by internally generated alkalinity (primary production), incoming sources of alkalinity (groundwater, rainfall and surface runoff), losses into the groundwater and into the sediment (sink). All these processes are shown in Figure 22.

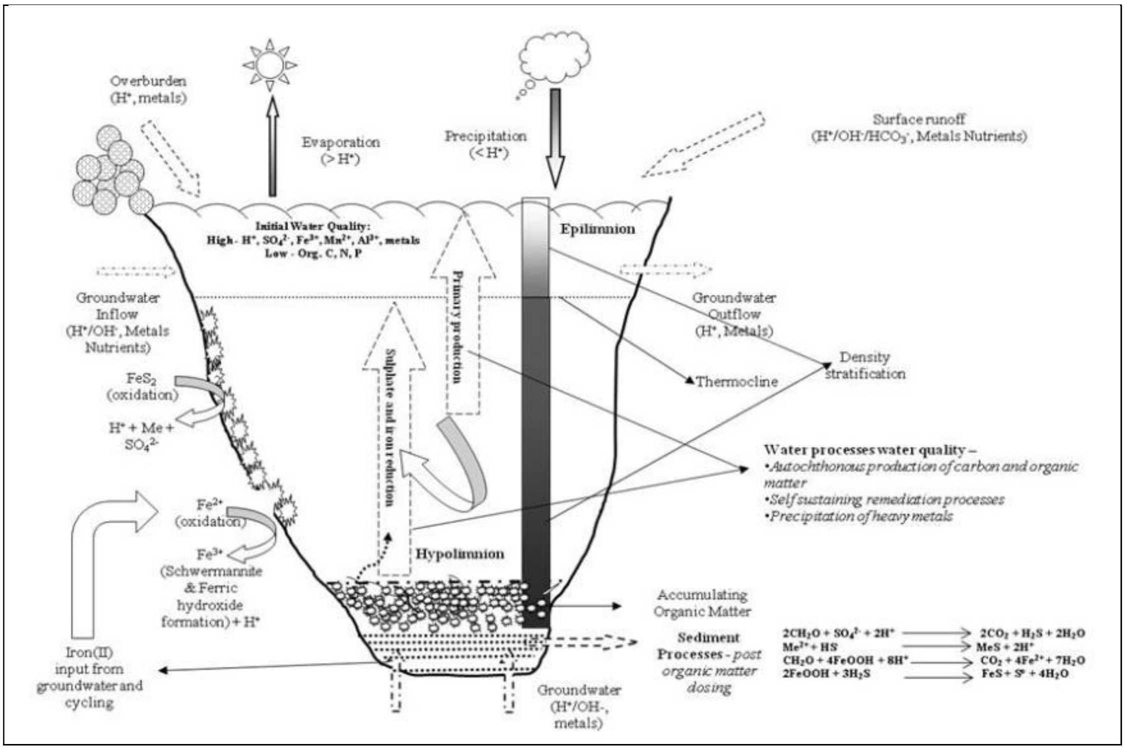

Figure 22. Conceptual model showing key acidity and alkalinity generating pathways in Collie pit lakes (after Kumar *et al.* (in prep), with equations from Frommichen *et al.* (2004)).

4.5.2 Conceptual model of lake development over time

Most pit lakes will eventually move from being chemistry dominated to biological systems simply through the long term accumulation of organic matter which will allow biological processes to commence. The timeframe for this change in Collie may be in the order of 50-100 years or substantially greater. Rehabilitation of the catchment will tend to increase the rate at which organic matter accumulates. The historic Collie pit lakes (Stockton, Blue Waters, Ewington, Centaur, Black Diamond) and the Chicken Creek lakes represent non rehabilitated lakes, while the majority of those from the Cardiff sub-basin have extensively rehabilitated catchments. Table 5 shows a conceptual understanding of the processes that develop and change over time in rehabilitated and non rehabilitated pit lakes in Collie, with a particularly focus on the acidity and alkalinity generating pathways.

Table 5. Conceptual model showing the development of pit lakes, highlighting the impact of key water sources on internal processes and both acidity and alkalinity generating pathways, split into lakes that received no rehabilitation and those that did.

Timeline	Water Sources	Internal Processes		Acidity Pathways		Alkalinity Pathways	
		No Rehab	Rehab	No Rehab	Rehab	No Rehab	Rehab
Filling to battering	Groundwater	Ferrolysis of Fe^{2+}; oxidation of pit walls		Dependant on groundwater quality of each aquifer. Faster fills reduces time pit walls exposed to oxygen and water which promotes acidity generation. Relies on creation of an anoxic barrier – unknown if occurs and anoxia only likely during temporary summer stratification. Nature of backfill also very important.			
	Direct rainfall	Neutralisation and dilution		Rainfall circum-neutral and adds some alkalinity, carbon (as carbonic acid) and dilutes AMD matrix			
	Significant stream flows into pit lake	Neutralisation, salinisation (dependant on source), nutrient, biota inputs, chelation of metals. Less dense summer inflows (i.e., less saline) forms a surface layer (as seen in Stockton)					
	Direct runoff from catchment	Neutralisation and dilution; oxidation of sulfidic materials in catchment		Pyritic oxidation in exposed acidity producing soils	Layering of materials and vegetation cover minimises this source	Very limited and dependant on soils in catchment	Inputs of carbon from catchment, some alkalinity from soils due to layering
Filling above battering	Groundwater	Ferrolysis of Fe^{2+}; oxidation of pit walls		Dependant on groundwater quality of each aquifer. Faster fills reduces time pit walls exposed to oxygen and water which promotes acidity generation. Relies on creation of an anoxic barrier – unknown if occurs and anoxia only likely during temporary summer stratification. Nature of backfill also very important.			

Timeline	Water Sources	Internal Processes		Acidity Pathways		Alkalinity Pathways	
		No Rehab	Rehab	No Rehab	Rehab	No Rehab	Rehab
	Direct Rainfall	Neutralisation and dilution		Rainfall circum-neutral and adds some alkalinity, carbon (as carbonic acid) and dilutes AMD matrix			
	Significant stream flows into pit lake	Neutralisation, salinisation (dependant on source), nutrient, biota inputs, chelation of metals. Inflows in summer that are not dense (i.e. saline) will form a surface layer (as has been seen in Stockton)					
	Direct runoff from catchment	Neutralisation and dilution; oxidation of sulfidic materials in catchment		Pyritic oxidation in exposed acidity producing soils	Layering of materials and vegetation cover will minimise this source	Very limited and dependant on soils in catchment	Inputs of carbon from catchment, some alkalinity from soils due to layering
5 years after filling	Groundwater (inflow)	Ferrolysis of Fe^{2+}		Dependant on groundwater quality of each aquifer. Faster fills reduces time pit walls exposed to oxygen and water which promotes acidity generation. Relies on creation of an anoxic barrier – unknown if occurs and anoxia only likely during temporary summer stratification. Nature of backfill also very important.			
	Groundwater (outflow)	Removal of acidity and metals		Some lakes will be flow through, some will be sinks in summer and supercharge in wet winters			
	Direct Rainfall	Neutralisation and dilution		Rainfall circum-neutral and adds some alkalinity, carbon (as carbonic acid) and dilutes AMD matrix			

Timeline	Water Sources	Internal Processes		Acidity Pathways		Alkalinity Pathways	
		No Rehab	Rehab	No Rehab	Rehab	No Rehab	Rehab
	Direct runoff from catchment	Neutralisation and dilution; oxidation of sulfidic materials in catchment		Pyritic oxidation in exposed acidity producing soils	Erosion in weak areas will expose some acidity producing soils	Very limited and dependant on soils in catchment	Inputs of carbon from catchment, some alkalinity from soils due to layering
	Stream flows into pit lake	Flows volumes limited to loss of water by discharge (groundwater, evaporation and surface outflows)		Neutralisation, salinisation (dependant on source), nutrient, biota inputs, chelation of metals. Inflows in summer that are not dense (i.e. saline) will form a surface layer (as has been seen in Stockton)			
	Surface Outflow	Loss of metals and acidity		Potential negative impacts on downstream receiving environments			
	Water Body	Frequent sedimentation, burying secondary minerals. Secondary mineralisation results in acidification	Secondary mineralisation results in acidification				
50 years after filling	Groundwater (inflow)	Ferrolysis of Fe^{2+} (significance dependant on source), potential for neutralisation and dilution		During stratification, groundwater inputs may contribute to differences in the bottom waters from surface waters			
	Groundwater (outflow)	Removal of acidity and metals		Some lakes will be flow through, some will be sinks in summer and supercharge in wet winters			

Timeline	Water Sources	Internal Processes		Acidity Pathways		Alkalinity Pathways	
		No Rehab	Rehab	No Rehab	Rehab	No Rehab	Rehab
	Direct Rainfall	Neutralisation and dilution		Rainfall circum-neutral and adds some alkalinity, carbon (as carbonic acid) and dilutes			
	Direct runoff from catchment	Neutralisation and dilution; oxidation of sulfidic materials in catchment; salt inputs		In most cases, this source is now minimal and acidity (not pH) starts to reduce in the pit lakes		Very limited and dependant on soils in catchment	Inputs of carbon from catchment, some alkalinity from soils due to layering
	Stream flows into pit lake	Flows volumes limited to loss of water by discharge (groundwater, evaporation and surface outflows)		Neutralisation, salinisation (dependant on source), nutrient, biota inputs, chelation of metals. Inflows in summer that are not dense (i.e. saline) will form a surface layer (as has been seen in Stockton)			
	Surface Outflow	Loss of metals and acidity		Potential negative impacts on downstream receiving environments			
	Water Body	Frequent sedimentation, burying secondary minerals. Secondary mineralisation now minimal unless surface sources significant	Unless secondary minerals become covered with sediment, potential for them to buffer changes in lake			Limited biological alkalinity production	Sources of nutrients and carbon from rehab are likely to promote biological alkalinity generation through denitrification, SRB activity and primary production

Timeline	Water Sources	Internal Processes		Acidity Pathways		Alkalinity Pathways	
		No Rehab	Rehab	No Rehab	Rehab	No Rehab	Rehab
100 years after filling	Groundwater (inflow)	Ferrolysis of Fe^{2+} (significance dependant on source), potential for neutralisation and dilution		During stratification, groundwater inputs may contribute to differences in the bottom waters from surface waters. Potential for monimolimnion. Fe cycling may buffer pH changes			
	Groundwater (outflow)	Removal of acidity and metals		Some lakes will be flow through, some will be sinks in summer and supercharge in wet winters			
	Direct Rainfall	Neutralisation and dilution		Rainfall is circum-neutral and adds some alkalinity, carbon (as carbonic acid) and dilutes			
	Direct runoff from catchment	Neutralisation and dilution; oxidation of sulfidic materials in catchment; salt inputs		In most cases, this source is now minimal and acidity (not pH) starts to reduce in the pit lakes		Very limited and dependant on soils in catchment	Inputs of carbon from catchment, some alkalinity from soils due to layering
	Stream flows into pit lake	Flows volumes limited to loss of water by discharge (groundwater, evaporation and surface outflows)		Neutralisation, salinisation (dependant on source), nutrient, biota inputs, chelation of metals. Inflows in summer that are not dense (i.e. saline) will form a surface layer (as has been seen in Stockton)			
	Surface Outflow	Loss of metals and acidity		Potential negative impacts on downstream receiving environments			

Timeline	Water Sources	Internal Processes		Acidity Pathways		Alkalinity Pathways	
		No Rehab	Rehab	No Rehab	Rehab	No Rehab	Rehab
	Water Body	Frequent sedimentation, burying secondary minerals. Secondary mineralisation now minimal unless surface sources significant	Unless secondary minerals become covered with sediment, potential for them to buffer changes in lake	pH increasing as acidity has dropped, secondary mineralisation has removed most Fe and Al from water		Limited biological alkalinity production	Sources of nutrients and carbon from rehab are likely to promote biological alkalinity generation through denitrification, SRB activity and primary production

4.6 Risk Assessment

The stakeholder meeting identified from all the issues raised the following key risks for Collie pit lakes:

- Contamination (pH, salinity, metals, nutrients) of groundwater
- Contamination of surface waters (pH, salinity, metals, nutrients, algal toxins)
- Instability of highwalls
- Falling off highwalls
- Gas release
- Algal blooms
- Disease risk to animals
- Damage to infrastructure
- Changes to ecohydrology of groundwater dependant ecosystems around the lake
- Changes to ecohydrology of surface flows to dependant ecosystems in flow thru systems
- Changes in availability of water to downstream users (groundwater and surface)
- Loss of aesthetics associated with overburden

Risk is commonly defined in terms of the likelihood of it occurring (unlikely through to certain), consequence (low to catastrophic). As knowledge of a number of pit lake issues is still poor, this factor is usefully included in the risk assessment, as a low knowledge may indicate that the likelihood or consequence of a risk are under appreciated essentially increasing the risk from a management perspective. The stakeholder group provided an initial assessment on the state of knowledge and the consequences of the risks identified, to this the authors have added likelihood to produce an overall risk score. The risk assessment for Collie pit lakes is shown in Table 6.

Table 6. Risk assessment for risks identified for Collie Pit Lakes, based on likelihood (1 – 5, where 1 is unlikely and 5 is certain), consequence (1-5, where 1 is inconsequential and 5 is catastrophic), knowledge (1-3, where 1 is high and 3 is low) and the risk rating is the sum of likelihood and consequence, multiplied by data confidence. Minimum risk rating = 2, maximum risk rating = 30.

Risk	Likelihood	Consequence	Confidence	Risk Rating
Contamination of discharge groundwater – pH	4	2	Low (3)	18
Contamination of discharge groundwater – salinity	2	4	Low (3)	24
Contamination of discharge groundwater – nutrients	2	2	Low (3)	12
Contamination of discharge groundwater – metals	3	4	Low (3)	21
Contamination of surface water discharge – pH	4 (in WO5H, Stockton, Black Diamond A, Kepwari, Centaur) 1 (in others)	3	Low (3)	21 and 12
Contamination of surface water discharge – salinity	2 (in WO5H, Stockton, Black Diamond A, Kepwari, Centaur) 1 (in others)	4	Low (3)	18 and 15
Contamination of surface water discharge – nutrients	1 (in WO5H, Stockton, Black Diamond A, Kepwari, Centaur) 1 (in others)	2	Low (3)	9 and 9
Contamination of surface water discharge – metals	4 (in WO5H, Stockton, Black Diamond A, Kepwari, Centaur) 1 (in others)	4	Low (3)	24 and 15

Risk	Likelihood	Consequence	Confidence	Risk Rating
Contamination of surface water discharge –algae	2 (in WO5H, Stockton, Black Diamond A, Kepwari, Centaur) 1 (in others)	3	Low (3)	15 and 12
Instability of highwalls	2	3	Medium (2)	10
Falling off highwalls	2	5	Medium (2)	14
Gas Release (primarily following remediation)	1	4	Low (2)	15
Algal blooms in the lake	3	3	Low (3)	18
Disease risk	2	4	Low (3)	18
Damage to infrastructure	3	4	High (1)	12
Changes to ecohydrology of surrounding groundwater dependant ecosystems around the lake	3	4	Medium (2)	14
Changes to ecohydrology of surface flows to dependant ecosystems in flow thru systems	4 (in WO5H, Stockton, Black Diamond A, Kepwari, Centaur)	3	Low (3)	21
Changes in availability of water to downstream users (groundwater and surface)	3	3	Medium (2)	12
Loss of aesthetics associated with overburden	2	2	High (1)	4

In Table 6, it can be clearly seen that knowledge of most of the risks is relatively low, even where knowledge is medium or high this is typically not direct knowledge in Collie but application of knowledge from similar areas elsewhere. The highest rated risks clearly relate to discharges out of the pit lake either as surface waters or in groundwater where knowledge of water quality is poor, consequences are generally high and likelihood is also relatively high. Not many risks were identified for the lake itself, as without clearly defined proposed end uses the risks cannot be clearly identified.

5 Conclusions

5.1 Pit lake hydrochemistry

Conceptual models were constructed as diagrammatic representations highlighting the nature of relationships between parameters and processes. Empirical and conceptual modelling of Collie pit lake hydrochemistry and lake system environments identified three major lake types; historic, new rehabilitated and new un-rehabilitated. Differences between pit lakes appeared to be predominantly due to higher pH and lower ORP in historic pit lakes, high salinity in rehabilitated pit lakes and lower salinity and pH in un-rehabilitated pit lakes. Key bio-geo-chemical processes within the lakes requiring further research were S, Fe and nutrient cycling. Trace elements and their interaction with algae such as for trace nutrients or metal toxicants are also unknown.

Groundwater around pit lakes is also particularly poorly understood. This lack of knowledge generally extends from inputs (quantity and quality) to the quality of discharge. Some aquifer tests to determine k values would aid in modelling. Similarly, although the importance of connection to underground workings is thought important for Stockton and WO3 Lake but not so in other Collie lakes, this hypothesised importance needs to be quantified.

5.2 ERA modelling

5.2.1 Environmental

The identification of issues and the formulation of a conceptual understanding of the underlying processes revealed a set of important knowledge gaps.

- In particular, little is known of the ecology of the lakes, in terms of fish, macro- and micro-invertebrates, microbes, algae, aquatic plants and riparian vegetation. Our knowledge improves in the catchment, where there is a reasonable body of literature on terrestrial revegetation and successional processes that is probably applicable to most of the catchment.

- Understanding of the approaches to remediation of pit lakes is still in its infancy worldwide and particularly limited to the Collie pit lakes with their uniquely low level of contamination and high water quality expectations.
- Human health issues relating to both short-term contact recreation health effects and long-term bioaccumulation health effects are largely unquantified. Although the former will be partially addressed by the study in Task 2 (Hinwood *et al.*, 2010) the risk of bioaccumulation in pit lake fisheries remain unquantified.

Other environmental risk knowledge gaps that were considered of low immediate importance are;

- Metal toxicity,
- Bioaccumulation and biomagnification of metals within pit lake biota,
- Poisoning of terrestrial visitors (e.g. stock, pests, migratory birds and native species) to the lake,
- Movement of metals into regional groundwater reserves,
- Anaerobic or other forms of metals being released from sediments,
- Loss of burrowing habitat of native vertebrate wildlife above and below the waterline.

5.2.2 Human health

Exposure assessment is the study of the distribution and determinant of substances of factors affecting human health (Nieuwenhuijsen, 2003). An exposure assessment considered chemical, biological and physical substances and their interaction with the population to produce a conceptual model of potential exposure pathways. This conceptual health risk model identified not only the chemical, biological and physical substances which could impact on health but also the physical characteristics of the pit lakes (Figure 23).

A literature review was then undertaken to identify potential health impacts associated with recreation use of the Collie pit lakes. A review of the water data was used to identify the potential chemical, biological and physical pollutants. Potential exposure routes were identified from the types of recreational activities people were likely to undertake at the lakes.

A conceptual model consisting of pollutant source, exposure pathways, and exposure routes indicated the likely dose received by an individual. These parameters along with exposure time and frequency can now be used to ascertain the level of exposure, and in turn, determine the potential health impacts. A comparison can now be made between the results of the exposure assessment and health guidelines to ascertain if there was a risk of potential health effects from recreational activities at the pit lakes (Hinwood *et al.*, 2010).

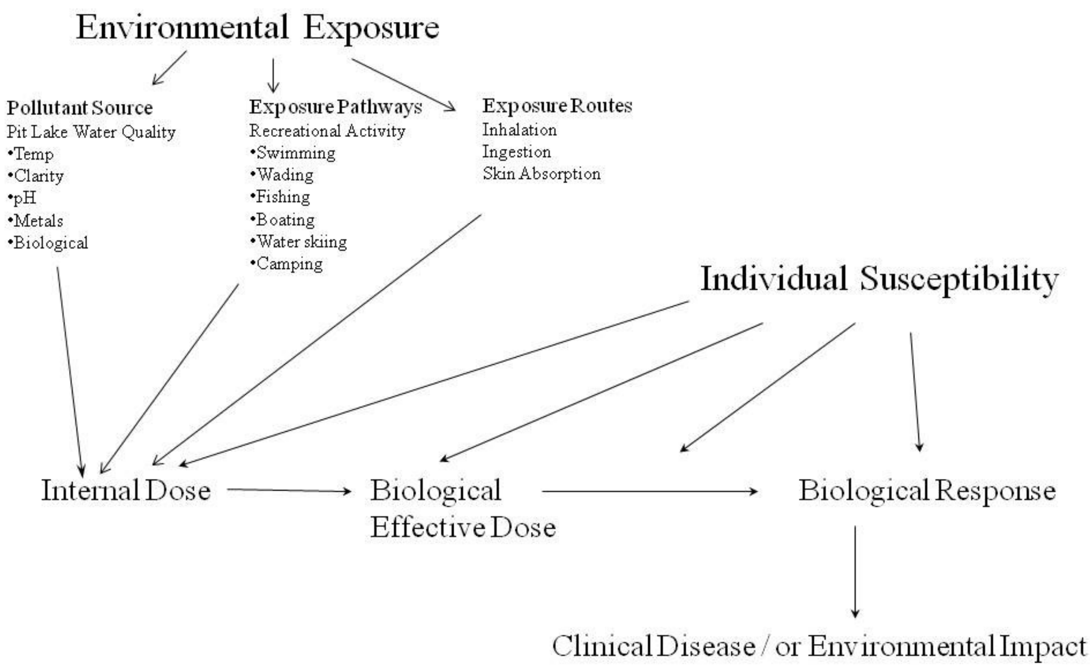

Figure 23. Environmental exposure ricks to human health from Collie pit lakes (after Helen Tanner).

The physical characteristics of the pit lakes were identified as having the potential to impact on health as steepness of highwall (risk of individuals falling off), however, it is not possible to undertake an exposure risk assessment on the health impacts of the physical characteristics.

The most recent water quality data used in the risk assessment and identified that mercury was elevated at Black Diamond, arsenic was elevated at Stockton Lake and Lake Kepwari showed elevated levels of aluminium, iron and manganese. Results from the exposure assessment found that the risk of potential health effects from exposure to arsenic, aluminium, iron and manganese was low. However the risk of health effects from exposure to mercury at Black Diamond is of concern particularly in regards to exposure of children. Thirty eight percent of survey respondents who visited the lakes reporting experiencing health effects, with the most common effect being sore eyes (Hinwood *et al.*, 2010). Although it has been indentified in conceptual modelling as an area of concern, there was insufficient water data to undertake a risk assessment on the health effects from exposure to biological hazards such as pathogenic aquatic biota and aquatic-based vectors.

6 Recommendations

- 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 under a drying climate expected by climate change predictions, it is necessary to continue monitoring of pit lake water quality and its aquatic biota. The risk assessment and manage 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 implemented (this will form Task 3 of the programme).
- The Collie Region’s groundwater is thought to be the main recharge and discharge source of pit lakes. As the geographic and hydrological characteristic, the water qualities of pit lakes are controlled by groundwater. 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 evolve to become dominated by biological rather than chemical processes; the consequence of this is unknown. A detailed monitoring program to monitor changes in biological communities is needed and are considered in Task 3.
- 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.
    - Little is known about which remediation approaches may be successfully employed to treat water quality issues in Collie pit lakes. Research is required to develop a range of cost-effective approaches.
    - The role of riparian vegetation in facilitating aquatic, terrestrial and amphibious habitat quality for pit lake environments is very poorly understood. A study involving assessment of historic and rehabilitated pit lake riparian communities and any reference communities e.g., even water dams, should be made to better understand this fundamental lake community feature.
- The relative contributions to the pit lake acidity budgets from surface and groundwaters across the different pit lake types are still not well understood.
    - NAG/NAP testing and characterisation of pit lake soils and sub-soils may help better explain these sources of continuing incoming acidity as well as assist in predictions of future acidity budgets and water qualities.
- The Ecological Risk Assessment has clearly highlighted the paucity of knowledge of how pit lakes function and their impacts on the surrounding waters. Although some of this knowledge can be inferred from other localities, there is also relatively little work conducted on pit lakes across the world.

- Research is needed to determine the ecological impact of discharges from pit lakes into the surrounding environment. A logical extension of this, is that approaches need to be investigated that can mitigate discharge impacts if they are then shown to be significant.

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