

**Division of Science and Engineering  
Department of Environmental Biology**

**Limnology and biota of Lake Yindarlgooda – an inland salt lake in  
Western Australia under stress**

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**This thesis is presented for the Degree of  
Doctor of Philosophy  
of  
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## **Declaration**

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: .....

Date: .....

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## Abstract

Inland salt lakes of the arid and semi-arid zones of Western Australia are unique systems. An unpredictable rainfall pattern and a transient water regime ensure these lakes remain dry for much of the year. Lake Yindarlgooda in the Eastern Goldfields of Western Australia is a typical inland salt lake that has been subjected to additional stresses. This thesis is the outcome of investigations conducted on the lake from 2001 to 2003. Emphasis is on the limnology and biota of the lake, including an adjacent wetland, and impacts on the aquatic ecosystems caused predominantly by mining.

Lake Yindarlgooda is a large, shallow hypersaline lake situated on the Yindarlgooda Palaeoriver. It is sodium chloride dominated and has naturally high background levels of nickel. Sites impacted by the leaching of hypersaline decant water from a leach residue storage facility (LRSF) were differentiated from control sites using multivariate statistics. Salinity was found to be a major determinant in the structure of the biological communities in the lake systems.

Different biotic communities with low taxonomic diversity were recorded in Lake Yindarlgooda and Swan Refuge, a nearby hyposaline clay pan. The benthic microbial communities were dominated by halotolerant diatoms, notably *Amphora coffeaeformis*, *Navicula incertata* and *Hantzschia baltica*. Variation in the diatom assemblages between the playa sites and the clay pan were noted, influenced by habitat type and salinity. Within Lake Yindarlgooda, the diatom assemblages in the control and impact sites were found to be similar. A narrow salinity spectrum dictated the taxa present. Many of the benthic diatoms collected during the dry phase were encysted, having entered dormancy.

The invertebrate fauna in Lake Yindarlgooda and Swan Refuge belonged to the Crustacea. A larger percentage of hyposaline invertebrate taxa were recorded from Swan Refuge, while those in Lake Yindarlgooda were typically halotolerant species. The Ostracoda showed the greatest diversity and their abundance was higher in the southern control sites while the Anostracan, *Parartemia* sp., dominated the northern impact sites of the playa.

The riparian zone of Lake Yindarlgooda supported a diverse plant community, dominated by the Chenopodiaceae. The marginal vegetation communities along the

shores of Lake Yindarlgooda were found to be similar, indicating habitat homeogeneity. Within the riparian zone both biological and physical soil crusts occupied large areas not inhabited by vascular plants. The biological soil crust identified was composed of an association between the filamentous cyanobacterium *Microcoleus* sp. and a moss species (Musci). Both biological and physical soil crusts were found to have functional roles in stabilising the surrounding low dunes. The soil crusts in the northern control sites were badly degraded as a result of trampling by livestock, while those in the southern control sites were protected and were intact.

Only one *Parartemia* species was found to inhabit Lake Yindarlgooda, *Parartemia* n. sp. d. It was collected in salinities ranging from 50 to 140 g L<sup>-1</sup>. The population appeared to be oviparous, recruitment mostly from resting eggs. The male to female ratios varied between sites, as did the number of juveniles compared to the adults. The northern impact sites had a more mature *Parartemia* population than the southern control sites and appeared to have undergone a second recruitment. Examination of the surface sediment found a well established *Parartemia* “egg bank” in the northern impact sites with egg numbers much higher than in the southern control sites.

The ultrastructure of the *Parartemia* resting egg was identical to that of *Artemia*. Differences in the external features and internal structure of the resting egg of *Parartemia* n. sp. d and *Parartemia* n. sp. g from Lake Miranda, another saline lake, were identified. This study showed morphological variation of the egg within *Parartemia*, a finding not previously recorded.

Rehydration trials on the *Parartemia* egg bank indicated that the increase in sediment salinity from the LRSF had a negative effect on the hatching of the resting eggs. In salinities above 60 mS cm<sup>-1</sup> hatching was less successful. The conditions provided in the trials were similar to those in Lake Yindarlgooda. The hatching technique was repeated on sediment from Lake Miranda with similar results. These trials were considered a valuable monitoring tool in the assessment of impacts on the biota of temporary lakes in the absence of water.

This study demonstrated that in the absence of water the egg and spore/seed bank can be used as a proxy for monitoring temporary lakes. It was also found to be valuable in understanding the distribution and diversity of the biotic communities in Lake

Yindarlgooda. This study provides the first integrated reference information on a Western Australian inland salt lake against which any future impact may be assessed.

## **Chapter 1.0. Introduction**

### **1.1 Scope and structure of the thesis**

The focus of this study is on the limnology and the biota of Lake Yindarlgooda, an inland salt lake in Western Australia's semi-arid zone. For over 100 years, the lake and the surrounding area has been subjected to pressures from both mining activities and pastoralism. This study was designed to investigate the possible impacts on the ecology of the lake from mining and to provide reference data for future studies. By adopting an integrated approach, the relationship between the different biotic communities such as the riparian vegetation, the aquatic invertebrates and algae, and the use by waterbirds could be explored. The role each of these functional components played in maintaining the integrity of the system was assessed. The impact on the ecology of the lake from the release of the hypersaline decant water onto the lake could then be determined. Lake Yindarlgooda was found to be an example of an extreme environment with high salinities and the absence of surface water for much of the year due to an unpredictable rainfall pattern.

This thesis is organised into ten chapters and the layout is as follows: Chapter 1.0 provides background to the study, incorporating a literature review on inland salt lakes. In Chapter 2.0, descriptions of each of the study sites are given. The sites are classified as control and impact in Lake Yindarlgooda. The chapter includes a brief history of the leach residue storage facility (LRSF), as it represents the mining impact, as well as a description of the geology of the Yilgarn Craton.

Chapters 3.0 and 4.0 are the baseline studies of Lake Yindarlgooda and the adjacent wetlands, recorded for the first time, investigating both the wet and dry phases. Chapter 3.0 describes the physical and chemical limnology of the lake. The differentiation between control and impact sites according to the influences from the LRSF, are verified. The biotic communities, including waterbirds, are presented in Chapter 4.0, including the resting egg and seed bank in the lake. The dominant biotic groups are identified and differences in community structure between the control and impacts sites investigated. The dominant biotic groups are then examined further in the following chapters.

In Chapter 5.0, the riparian zones of Lake Yindarlgooda and Swan Refuge, a peripheral wetland, are described. Biological soil crusts are identified from sites around Lake Yindarlgooda and their role within the riparian zone examined, for the first time in a Western Australian inland salt lake. This chapter identifies the different habitats in Lake Yindarlgooda, recognising the lake as having habitat homogeneity.

In Chapter 6.0, the diatom communities in Lake Yindarlgooda and Swan Refuge, as one of the dominant biotic groups, are studied in more detail. Differences in the community structure between the control and impact sites in Lake Yindarlgooda are discussed and the effects of increased salinity examined.

Chapter 7.0 is the first of three on the dominant aquatic invertebrate in Lake Yindarlgooda the endemic brine shrimp *Parartemia*. This chapter examines the morphology of this species, including the resting egg. Comparisons are made with the resting egg of a *Parartemia* species from another salt lake, Lake Miranda, and with the egg of *Artemia*, for the first time. This information is then incorporated in the hatching trials of Chapter 9.0.

Chapter 8.0 describes the ecology of the *Parartemia* species from Lake Yindarlgooda, indicating their salinity ranges from the field collections. The resting egg bank is examined, providing background information for the hatching trials presented in Chapter 9.0.

Chapter 9.0, this is the final chapter on the *Parartemia* and examines the effects of increased salinity on the hatching of the *Parartemia* eggs from the sediment. The hatching methods adopted for this study are tested on a *Parartemia* species from Lake Miranda and a protocol is provided. The role of the egg shell in the protection of the embryo is discussed. This chapter identifies the LRSF as having a direct impact on the biota and therefore the ecology of Lake Yindarlgooda.

The concluding chapter, Chapter 10.0, brings together all the findings in the previous sections. The ecology of the lake is discussed and conclusions drawn together from this study. The impact caused by the release of hypersaline water from the LRSF on the system as a whole is reviewed. Recommendations for future studies are detailed in this chapter.

## 1.2 Australian inland salt lakes

An estimated one third of the total world land mass is either arid or semi-arid. Salt lakes are abundant in these regions (Williams 1998a) and a common feature on every continent (Hammer 1986). Australia is the driest inhabited continent in the world with the lowest average rainfall, the exception being Antarctic, and the lowest runoff from its catchments (McMahon *et al.* 1982). The most characteristic feature of Australia's physical environment is the extent and severity of seasonal aridity with 75% of the continent in the semi-arid zone (Bowler 1976). Salt lakes are a salient feature of the interior of western, and southern Australia, as well as western and north western Victoria (Arakel *et al.* 1990). Over 80% of wetlands in Australia are saline, occupying an area in excess of 100 000 km<sup>2</sup> (Timms 2005).

Within Australia, four main types of salt lakes have been recognised: large playas, small pans, crater lakes and coastal lakes (De Deckker 1988). For the formation of a salt lake, a suitable geomorphological depression is required allowing for the collection of water and lakes are normally of aeolian, tectonic, or volcanic origin (Hutchinson 1957). Aeolian deflation is recognised as a major force in lake geomorphology in arid lands (Timms 1992, 2006; Harper and Gilkes 2004). Larger lakes (playas) have more irregular outlines due to the decreasing influence of water as aridity increases (Bowler 1976). The playas of the Salinaland of Western Australia are such an example.

The balance between the input of water (precipitation) and the output (evaporation) is determined by the hydrological cycle and the relative aridity dictates the persistence of the surface water. For salt lakes to form, the annual evaporation rates must exceed precipitation (Hammer 1986). For semi-arid regions precipitation is between 250 and 500 mm per annum (Brendonck and Williams 2000). Excessive evaporation rates lead to the concentration of salts resulting in saline sediments. Permanent salt lakes, though rare, can be large, Lake Corangamite in eastern Australia being an example (Timms 2004a). Within the arid to semi-arid regions, rainfall is unpredictable and episodic, and lakes remain dry for much of the year. These systems can be further divided into intermittent, temporary salt lakes where water retention is predictable; and episodic, temporary salt lakes which inundate unpredictably (Williams 1998a).

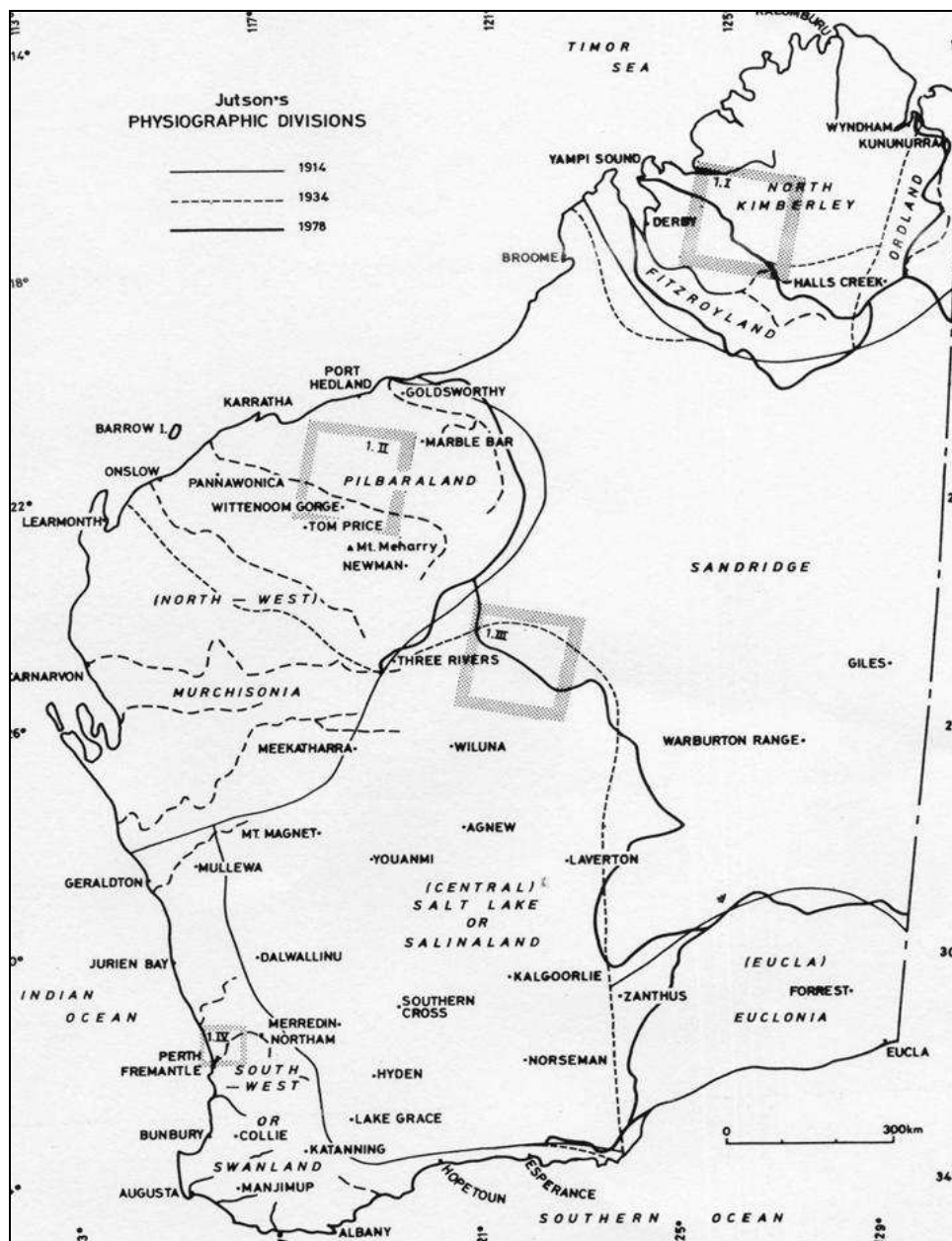
Drainage within these zones is predominantly endorheic (internal) and the systems are closed. Inland, or athalassic, salt lakes have had no connection to the sea during the geologically Recent times (Hammer 1986). The term was first coined by Bayly (1967) and originally used to describe both fresh and saline systems. The salts of athalassic lakes have mostly been derived from geological weathering and/or from the sea via the atmosphere (Bayly and Williams 1966).

### **1.2.1 Western Australian salt lakes**

Development of aridity in Australia dates from the Late Tertiary following a period when subtropical humid environments extended to the southmost continental margins. The Salinaland, or Salt Lake Division, (Gentilli 1979b) in Western Australia is evidence of this (Harper and Gilkes 2004; Bowler 1976). During the Tertiary, an extensive river system flowed in the interior of the Australian continent. A change to a more arid climate in the late Tertiary resulted in the partial blocking of the rivers that led to the formation of the present salt lakes (Gentilli 1979) with the palaeochannels now the remnants of that once vast river system (Figure 1.1).

The Australian landmass is divided into 3 geotectonic units - the Western Shield, Central Basins and Eastern Australian Highlands. The Yilgarn Craton comprises the largest area of the Western Shield and consists of Archaean granites, gneisses and greenstones. The Salinaland, covers the greater part of the Yilgarn Craton and is characterised by a landscape of low relief with broad valleys, low-angled valley side slopes with sluggish drainage (Harper and Gilkes 2004). It is an area of internal drainage, each salt lake acting as a sump or basin for the accumulation of salts and sediment. High evaporation rates ( $> 2000 \text{ mm yr}^{-1}$ ) and low precipitation ( $< 200\text{--}350 \text{ mm yr}^{-1}$ ) is experienced by this region resulting in short water retention periods and the gradual increase in salinity toward the end of each hydrocycle.





**Figure 1.1:** Jutson's physiographic divisions showing the Salinaland or Salt Lake Division. Six distinct areas are recognised in WA according to their geomorphology as well as vegetation and surface drainage. The Salt Lake Division is the only division with internal drainage. (map from Gentilli (1979a)).

### 1.2.2 Chemical and physical features of Western Australian salt lakes

Hutchinson (1957) defined the salinity of inland waters as the concentration of all the ionic constituents present. In general Western Australian salt lakes are NaCl dominated and follow an ionic sequence of  $\text{Na} > \text{Mg} > \text{Ca} > \text{K}$  and  $\text{Cl} > \text{SO}_4 > \text{HCO}_3$ , (Geddes *et al.* 1981) which is similar to sea water. The majority of saline lakes in the

world are NaCl dominated (Hammer 1986), this also holds true for Australia (Williams 1966; Hart and McKelvie 1986).

Williams (1967) classified all water bodies with a concentration of total dissolved solids greater than  $3 \text{ g L}^{-1}$  as saline, a value widely accepted in Australia (Williams 1998b; Timms 2005). Because the salinity ranges recorded from salt lakes is large, from 5 to  $500 \text{ g L}^{-1}$  (Williams 1998a), a further division of hyposaline ( $3\text{-}20 \text{ g L}^{-1}$ ), mesohaline ( $20\text{-}50 \text{ g L}^{-1}$ ) and hypersaline ( $> 50 \text{ g L}^{-1}$ ) was proposed by Hammer (1986).

Salinity can be expressed in a variety of ways with the two most accepted being the concentration of total dissolved solids (TDS), or as the specific electrical conductance contributed by each ion in the water. Within Australia, the ionic composition of the water is more or less homogeneous (Williams and Buckney 1976; Williams 1986). At salinities below  $70 \text{ g L}^{-1}$  the relationship between conductivity and TDS is linear and strongly correlated (Williams 1986).

The pH in salt lakes can vary from acidic (3.0) to highly alkaline (11) (Williams 1998b). There are a few Australian acidic saline lakes (Conte and Geddes 1988), the majority being alkaline ( $> 7.0$ ) (Williams and Buckney 1976; Arakel *et al.* 1990; Radke *et al.* 2002). Various factors affect the pH of inland waters and, as a general rule, pH and alkalinity (the buffering capacity of water) are positively correlated with pH increasing as salinity increases (Williams 1998a).

The shallow nature of Western Australian salt lakes is attributable to their aeolian origin. Depth strongly influences the optical properties, temperature and ultimately the oxygen levels in lakes. Optical properties of salt lakes are influenced by allochthonous input and primary productivity (Hammer 1986). The strong wind action often associated with these systems cause considerable fluctuations (Williams 1998c) and stratification is non-existent. The ambient temperature is reflected in the surface water, resulting in wide fluctuations of water temperature within a short time (Marchant and Williams 1977).

The solubility of gas is dependant on pressure, temperature and salinity. In general, solubility is inversely proportional to increases in temperature and salinity. Concentrations of dissolved oxygen (DO) decrease significantly at higher salinities and temperatures, Sherwood *et al.* (1992) recording DO concentrations of  $14 \text{ mg L}^{-1}$

in salinities of  $< 3 \text{ g L}^{-1}$ , dropping to  $2 \text{ mg L}^{-1}$  in salinities of  $260 \text{ g L}^{-1}$ . The strong winds characteristic of the Australian interior, prevent hypoxia and the shallow nature of these water bodies allows for constant mixing of the water column.

Climate is one of the strongest parameters influencing inland salt lakes in the Western Australian arid zone. With the exception of salinity, the hydrological cycle ultimately dictates the biotic community of inland salt lakes (Williams 1998b), considered as the most important environmental determinant (Williams and Kokkinn 1988). Because of the transient nature of the water regime, salt lakes can appear as barren landscapes for extended periods. Fortunately, research has unveiled a unique biotic community associated with these inland wetlands.

### **1.3 The biota of inland salt lakes**

In biological terms, salt lakes are often described as extreme habitats of low biodiversity, inversely proportional to increased salinity (Bowler 1976). Large episodic salt lakes support fewer species than the equivalent hypersaline lakes that are regularly filled (Timms 2001a). They are, however, areas of high productivity, albeit periodic, referred to as “boom and bust” systems (Jenkins *et al.* 2005). A wide variety of taxa exists in these lakes including many of those with representative of fresh waters (Brendonck and Williams 2000).

#### **1.3.1 Bacteria**

Bacteria are the earliest and simplest forms of life on earth. Their association in the formation of stromatolites has been well documented (Walter 1976). The benthic microbial communities (BMCs) of salt lakes are dominated by photosynthetic prokaryotes (Bauld 1986). They occupy some of the most extreme environments where other organisms have failed. The structural differentiation found in the halophilic bacteria has resulted in the formation of a separate group, the Archaea (Post 1981) dominant in hypersaline environments (Borowitzka 1981). At least six genera of halobacteria are now recognised, often responsible for the red colouration of brines (Oren 2001, 2002).

The contribution of photosynthetic bacteria to the primary production of salt lakes is a vital one, particularly in environments where they are the only biota present (Borowitzka 1981). Their contribution can exceed that of eukaryotes in lakes around the globe (Hammer 1981) such as in the Great Salt Lake in the USA (Post 1981).

### 1.3.2 Algae

True phytoplankton are generally absent in temporary salt lakes, the exception being the halophilic flagellated chlorophyte, *Dunaliella*, and one or two species of dinoflagellates and diatoms (e.g. *Chaetoceros* species). The fluctuating water levels, high light intensity and salinities of these lakes restrict much of the biota to the surface sediment (Borowitzka 1981) where they exist as BMCs (Bauld 1981, 1986). Microbial mats are communities that colonise benthic surfaces and form cohesive structures, the best examples being the stromatolites (Walter 1976). The BMCs provide a sheltered environment from the extreme conditions experienced within these environments. Many produce large quantities of mucilage as a barrier to desiccation and ultra violet radiation with high salinities inducing mucilage production (Burke and Knott 1989).

Although the cyanobacteria predominate the BMCs, such as in Lake Lefroy (John 1999; Handley 2003), many eukaryotic algae such as diatoms (Bacillariophyta) are present and occasionally dominate (Bauld 1981). Such an example is Lake Carey, an inland salt lake in Western Australia, where 22 out of 30 algal species were diatoms (Chaplin *et al.* 1999).

### 1.3.3 Macrophytes

The episodic nature and the high salinities of salt lakes restrict the presence of macrophytes. The term macrophyte is used to describe all macroscopic plants, attached or free floating, vascular or non, that occur in the aquatic environment (Hammer 1986). The more tolerant species are termed halophytes and are typically of the Potamogetonaceae, *Ruppia* and *Lepilaena* species being the most common in Australian arid zone wetlands (Brock 1981, 1997; Williams 1998a, 1998b).

The halobiont Charophyte *Lamprothamnium* is common in many Australian salt lakes (Garcia 1999). It is able to withstand salinities up to 150 g L<sup>-1</sup> (Porter 2007) as well as extended and unpredictable periods of desiccation. Charophytes regenerate from propagules with their fertilised eggs (oospores) forming a dormant spore bank in the sediment (Casanova and Brock 1996). These spore or seed banks are vital in the regeneration of the wetland after drying events with the delayed germination proving to be a survival mechanism in an unpredictable environment (Brock 1998).

Not all macrophytes germinate at the same time in these systems, an important adaptation to the unpredictable water retention.

The halophyte meadows in these shallow lakes provide an important resource, even if temporary, for many life forms. *Ruppia* has shown to be an important component of the food web in estuarine and saline ecosystems (Nichols 2005) and forming part of the diet of Black Swans (Congdon and McComb 1981; Bayly 1993). Macrophytes also provide shelter and the relationship between aquatic invertebrates and Charophytes has been found to be mutually beneficial (van den Berg and Coops 1999).

### **1.3.4 Aquatic invertebrates**

The aquatic fauna of inland salt lakes are predominantly invertebrates, the more conspicuous being the crustaceans, yet many species of protozoa and Rotifera are also frequently encountered (Shiel and Koste 1986; Williams 1998a, 1998b). The diversity of the aquatic fauna in Western Australian salt lakes is higher than that found in the eastern states. Displaying a high level of endemism (Halse 2002), Western Australia is considered the evolutionary centre for much of the Australian endemic salt lake fauna (Geddes *et al.* 1981). These lakes have not only displayed regional and localised endemism (Halse and McRae 2001), but also exhibit remarkable species radiation within a short time (Remigio *et al.* 2001).

The dominant invertebrates of these temporary salt lakes are the Ostracoda (De Deckker 1983; Halse 2002) and the endemic brine shrimp, *Parartemia* (Williams 1998b). In Western Australia, 152 species of ostracods have been recorded from inland waters (Halse 2002). Research by Remigio *et al.* (2001) found *Parartemia* to be the most diverse genus of the halophilic crustaceans in Australia. Recent taxonomic revision by Savage (2004) suggests that there may now be three genera in the one family Parartemiidae with *Parartemia* retaining three species, another genus with three species and a third with 11 currently recognised species. This again reinforces the large species diversity within a relatively small geographic region, the majority of the species of the Parartemiidae located within Western Australia (Savage and Knott 2004; Timms 2004b).

The aquatic invertebrates of temporary inland waters have strategies that ensure their survival when water is absent. These involve a lifecycle synchronised with the

physicochemical conditions of the lake, the ability to withstand high variations in salinity and temperature, and to withstand desiccation (Geddes 1976). Many have adopted cryptobiosis as part of their lifecycle, producing desiccation resistant eggs that ensure long-term dormancy and viability. This has proved to be a highly adaptive survival technique (De Stasio 1989). It has been noted that Australia has a characteristic fauna associated with the sediments of these lakes that are not opportunistic organisms derived from the surrounding areas (Brendonck and Williams 2000). They have, in effect, evolved to a life based on the hydrocycle of these systems, many unable to complete their lifecycles if they do not experience a period of desiccation.

### **1.3.5 Waterbirds**

In recent years, the major filling events resulting from cyclones in the northwest of Australia have triggered spectacular feeding and breeding activities of colonial waterbirds, initiating an increased interest in the conservation of inland salt lakes. Species such as the Banded Stilt (*Cladorhynchus leucocephala*), Red-necked Avocet (*Rescurvirostra novaehollandiae*), Black-winged Stilt (*Himantopus himantopus leucocephalus*), Gull-billed Tern (*Sterna nilotica macrotarsa*) and the Whiskered Tern (*Sterna hybrida javanica*) have all been recorded after such events (Serventy and Whittell 1976; Burbridge and Fuller 1982; Dunlop 1990; Johnstone and Storr 1998). Nomadic shorebirds such as the threatened Hooded Plover (*Thinornis rubricollis*) have also been recorded on Western Australian salt lakes near Kalgoorlie following an above-average rainfall (Chapman and Lane 1997) and at Lake Gore (Weston and Elgar 2000). Records from inland wetlands during these periods suggest the return movement of the shorebirds to these systems (Newbey 1996, Singer 1999), signifying their importance.

The high concentration of waterbirds in these wetlands for short periods is based on the high productivity of these lakes. Salt lakes provide a much needed habitat for many of the waders as the southwest of Australia has limited coastal tidal flats (Lane 1987).

### **1.4 Riparian zones**

Riparian zones are the interfaces between terrestrial and aquatic systems (Gregory *et al.* 1991). They are important functionally, preventing erosion, providing habitats

and contributing allochthonous organic material to aquatic systems (Schindler and Scheuerell 2002).

#### **1.4.1 Vegetation**

Greater varieties of salt tolerant plants are found along the periphery, or riparian zone, of lakes that are inundated periodically. These are predominantly small bushes belonging to the Chenopodiaceae family, *Halosarcia* being the most common genus (Williams 1998a), collectively known as samphires. A high diversity of samphires is displayed in Australia, unlike other countries, with five genera and 19 species in the Goldfields area alone (Davey 2001; Datson 2002).

These halobionts are an important component of the arid zone wetlands with some species, such as *Halosarcia indica* and *H. pergranulata*, tolerant of elevated salinities (English 2001). They are soil stabilisers, used in the rehabilitation of saline areas, and provide shelter and breeding sites for many waterbirds (Datson 2002).

#### **1.4.2 Microbiotic soil crusts**

The climatic conditions of arid and semi-arid regions of the world limit the establishment of dense vegetation. Large open spaces are common between vascular plants and often covered by a hard crust. These crusts are a complex microbial community occupied by a number of specialised organisms. Termed microbiotic, or cryptogamic soil crusts, they result from an association between soil particles and cyanobacteria, algae, microfungi, lichens, and bryophytes (Belnap *et al.* 2003a). They inhabit the top of the soil and the first few millimetres below. The crusts have low moisture requirements and their upward growth enables them to take advantage of the dry, sparse regions of the arid zones.

Their ability to stabilise soil (Belnap 2003), retain moisture (Eldridge and Greene 1994; Belnap *et al.* 2003b, Eldridge and Greene 1994) and add nutrients to a system (Eldridge 2003) has led to their use as a biological indicator. The presence of these crusts is generally associated with a stable landscape (Belnap *et al.* 2003a).

The majority of the research thus far on microbiotic crusts has been performed on those from desert region of the world (Johansen *et al.* 2001; Dor and Danin 2001; Belnap *et al.* 2003a). Microbiotic crusts are common within the riparian zone of many salt lakes in the Australian semi-arid zone (Hacker 1987; Ullman and Budel 2003; Barrett 2006) and are critical to the maintenance of the integrity of an already

fragile system. Anthropogenic impacts such as pastoralism (Warren and Eldridge 2003) has led to the degradation of many of these crusts.

### **1.5 Importance of salt lakes**

Salt lakes form an important component of the Australian continent. Economically they are a valuable source of minerals. The eastern Yilgarn Craton is one of the most intensely mineralised terranes and contains world-class gold and nickel sulphide deposits as well as massive base metal deposits (Barley *et al.* 2004). Salt lakes are a prominent feature of this area and act as drainage sumps for the surrounding area, receiving minerals as a result of the various weathering processes (Mann 1982; Morgan 1993).

Salt lakes are an important source of evaporative minerals, in particular sodium chloride (Williams 1998a). They are major sources of other minerals such as lithium, borax and uranium (Williams 1993). The harvesting of their biological components such as carotenoids from microalgae (Borowitzka and Hallegraeff 2007) and *Artemia* resting eggs ('cysts') (Dhont and Sorgeloos 2002) have become the basis of multimillion dollar industries globally. Other industries include fisheries where a large portion of the world's caviar are sourced from fish caught in the Caspian Sea (Williams 1993).

Salt lakes are of interest scientifically. Inland salt lakes are closed systems with a simplistic habitat structure, and low biodiversity, making them ideal for ecological studies. They are the loci for palaeolimnological studies contributing to information on climate change (Gell 1997; Fritz *et al.* 1999) and for the exploration of mineral and oil deposits (De Deckker 1988). The adaptations of their biota to the extremes of nature have provided physiologists with perfect model organism, in particular the brine shrimp *Artemia* (Clegg *et al.* 2000a; Clegg *et al.* 2000b). In a global context inland salt lakes are vital to the survival of migratory and nomadic birds, providing a refuge for many species (Roshier *et al.* 2001). Larger permanent lakes, such as Lake Corangamite in eastern Australia, are recognised for their high value and are home to a number of endangered species (Timms 2004a).

The increase in our understanding of these systems has been brought about in part to their exploitation. Their importance has been acknowledged in Australia by government bodies such as The Department of Environment and Heritage (Ball *et al.*



2001), and internationally by organisations such as the United Nations Environment Programme (Williams 1998a). While there has been an increase in interest and understanding of the ecological processes and the unique biota of the inland salt lakes, this has unfortunately been a result of anthropogenic impacts on the salt lakes (Williams 2001).

### **1.6 Stresses on salt lakes**

Already many wetlands in arid zones are already experiencing the impact of climate change (Roshier *et al.* 2001) particularly in relation to the issue of extended dry periods, or drought (Humphries and Baldwin 2003). The third assessment by the Intergovernmental Panel on Climate Change (IPCC) concluded that the region of Australasia may face an overall reduction in average run-off and drought-prone areas were one of the four regions of most concern (Basher *et al.* 2001).

The wetlands in arid and semi-arid zones of Australia face intensifying pressure for their water resources (Jenkins *et al.* 2005). The extraction of surface water and groundwater for human uses such as agriculture, drinking water and industry result in the reduction and alteration of flow patterns (Ball *et al.* 2001). It has been estimated that by 2022 the hypersaline groundwater in the palaeochannels of the Eastern Goldfields will be exhausted due to over extraction by the mining industry (Turner *et al.* 1996). The active diversion of inflow to many inland waters in Australia has caused a gradual increase in their salinity. Lake Corangamite, Australia's largest permanent salt lake is an example. Water diversion has occurred since European settlement in the 1840s. Gradually the salinity of the lake has increased and a large portion of the aquatic biota has been lost (Timms 2004a).

Other pressures resulting from activities in the catchments include land clearing, resulting in dryland salinity, increased soil erosion and eutrophication of water bodies (Ball *et al.* 2001). Secondary salinisation is recognised as one of the biggest threats to ecosystems both fresh and saline, particularly in Western Australia (Williams 2001; Cale *et al.* 2004) where it accounts for more than 70% of Australia's salinity problem (NLWRA 2001). While the biota in natural salt lakes have evolved and adapted to an extreme environment, changes within these systems can result in the surpassing of certain critical thresholds. Often, once these thresholds have been exceeded, restoration of the original conditions are difficult (Williams 1998c).

The impact of mining on salt lakes is apparent. Many of the large playas are depositories for the disposal of hypersaline groundwater resulting from processing and extraction of minerals. Not only is this extra salt load detrimental to the aquatic biota, there is often an increase in heavy metals associated with the discharge. The groundwater is extracted from the ancient palaeorivers and because of the processes of geochemical weathering as they move through the interior, these waters are naturally high in heavy metals (Mann 1982). Many playas are actively mined and causeways that allow access of heavy machinery across them modify the surface hydrology and impede the movement of the aquatic biota.

Of recent concern has been the invasion of “weed” species, such as *Artemia*, into the more permanent hypersaline water bodies of the Wheatbelt (Geddes and Williams 1987). Movement further inland toward the Salinaland has been recorded (McMasters *et al.* 2007) and the ecological impact of such a migration is unknown.

The lack of adequate management practices, and a poor understanding of their ecology, has resulted in the degradation of many of these salt lakes, although the conservation values of these systems are recognised (Timms 2005). It has been acknowledged that baseline, or background data, for the inland salt lakes is severely lacking resulting in their mismanagement (Jasper 1999; John 2003; Smith 2003). Lake Yindarlgooda, the focus of this study, is an inland salt lake subjected to various stresses yet no baseline data on the limnology or biota are available.

### **1.7 Lake Yindarlgooda**

Lake Yindarlgooda is situated 30 km east of Kalgoorlie and approximately 630 km east of Perth, the capital of Western Australia. It forms part of the Yindarlgooda Palaeoriver within the eastern division of the Yilgarn Craton. It is a large, shallow temporary playa, interspersed by numerous small, vegetated islands, typical of many playas in the arid to semi-arid zone of Western Australia. Normally, the lake fills with the onset of winter rainfall in late May to August, though will flood after summer cyclonic events in the north of the state.

The vegetation of the area is predominantly eucalypt woodlands, with a halotolerant shrub understorey on more calcareous soils, typical of the Coolgardie Botanical District (Beard 1979). Lake Yindarlgooda has a clay lake bed, interbedded with halite. The lake is surrounded by kopi dunes, the area gently undulating with occasional low hills and is generally subdued.

Lake Yindarlgooda is located on the Yilgarn Craton and consists of Archean granites, gneisses and greenstone (Anand and Paine 2002). The eastern Yilgarn Craton is rich in mineral deposits, especially gold and nickel (Barley *et al.* 2004). Nickel is mined from the Bulong deposit in the Bulong Domain located within the Kurnalpi Terrane, and processed on site. Hypersaline water extracted from the Yindarlgooda Palaeoriver is used in this process and the slurry deposited in storage facilities built near the lake. A second facility was required to store the excess water produced after the first was found to be too small. As part of the environmental compliance regulations, a study of the impacts from the storage facility on the biota of Lake Yindarlgooda was required and this study was initiated.

Prior to this study, a vegetation report on the immediate area of construction (Mattiske 2000) and some historical water samples collected as part of their annual monitoring reports, were the only available data on this lake. Information on the limnology of the lake, its aquatic biota and the ecological functioning of the lake was non-existent and the impacts of the mining activities could not be determined.

### **1.8 Objectives**

The principal objective of this study was to investigate the limnology and aquatic ecology of Lake Yindarlgooda with special emphasis on the biota, adopting an integrated approach. With this information, the impacts such as the extension of the hypersaline storage facility onto the lake could be assessed. The objectives of this study are:

- To investigate the limnology of Lake Yindarlgooda,
- To determine the biotic communities of Lake Yindarlgooda and how they respond to a changing environment,
- To assess the role of the riparian vegetation in Lake Yindarlgooda and,
- To investigate the effects of the main impacts from the leach residue storage facility (LRSF) on the dominant aquatic biota in Lake Yindarlgooda.

## **Chapter 2.0. Site descriptions: Lake Yindarlgooda and Lake Miranda**

### **2.1 Introduction**

This chapter describes the study area of Lake Yindarlgooda, including the geology and geomorphology of the Yilgarn Craton. The sites are designated as “control”, “impact” or “wetland” sites. Impact sites are affected by the leachate from the leach residue storage facility (LRSF) in the form of decant hypersaline water, either directly discharged onto the lake at some time, or as seepage from the facility’s walls onto the lake. Control sites are those not affected by the LRSF due to their distance from the facility. The two peripheral wetlands, Swan Refuge and Lake Penny, were classified as wetland sites, separating them from the playa sites. A description of Lake Miranda in the Northern Goldfields is included. Lake Miranda is the habitat of a second *Parartemia* species, which has been included as a comparison in the *Parartemia* component of this study (Chapters 7.0-9.0). Both lakes are located within the Goldfields region of Western Australia.

#### **2.1.1 The Yilgarn Craton: Geology and Geomorphology**

The Australian landmass is divided into three geotectonic units, namely the Western Shield, the Central Basin and the Eastern Australian Highlands. The Archaean Yilgarn Craton is the largest of two sections of the Western Shield (Pilgrim 1979) comprising an area of approximately 657 000 km<sup>2</sup> (Anand and Paine 2002), having stabilized before 2.4 Ga (Cassidy *et al.* 2006). It is located on the central part of the Western Shield and is composed of Archaean rocks, predominantly granitoids (approximately 70%), that are crossed by north-northwest trending belts of greenstones (30%) (Anand and Paine 2002).

Dominant landforms of the Yilgarn Craton include sandplains, plateaux, breakaways, colluvial and alluvial plains, north-northwest striking ridges (greenstones), granitic hills and rises with extensive debris fans, large salt lakes and dunes along broad valleys (Anand and Paine 2002). Much of the area is characterised by a landscape of low, undulating relief with broad flat-floored valleys, with greater relief towards the coast (Harper and Gilkes 2004). Extensive alluviation of the valley floors occurred as a result of the absence of an active external river system, eventually forming the salt lakes (Pilgrim 1979). The salt lakes are the dominant feature of Jutson’s Salt

Lake Division which cover the greater part of the Yilgarn Craton. The lakes vary in shape and size and many interconnect, representing the remnants of the palaeoriver systems that flowed during the Tertiary (Morgan 1993). The change in climate, becoming more arid during the Miocene, resulted in the clogging up of the inland drainages with sediments, surface flow now non-existent, the exception being major flooding events.

### **2.1.2 Climate**

The large size of the Yilgarn Craton has resulted in a number of different climatic regimes throughout the area which have contributed to the formation of different landforms and the resultant regolith, both fluvial and aeolian depositions (Glassford and Semeniuk 1995).

Generally, the area is classified as having a semi-arid to Mediterranean climate, with wide variation in the annual rainfall from 150 to 1400 mm, and annual evaporation potential of 2500 - 4100 mm. Droughts and floods are features of this region. The decrease in reliability of rainfall from the southwest to the northeast follows the increase in temperature and subsequently evaporation pattern.

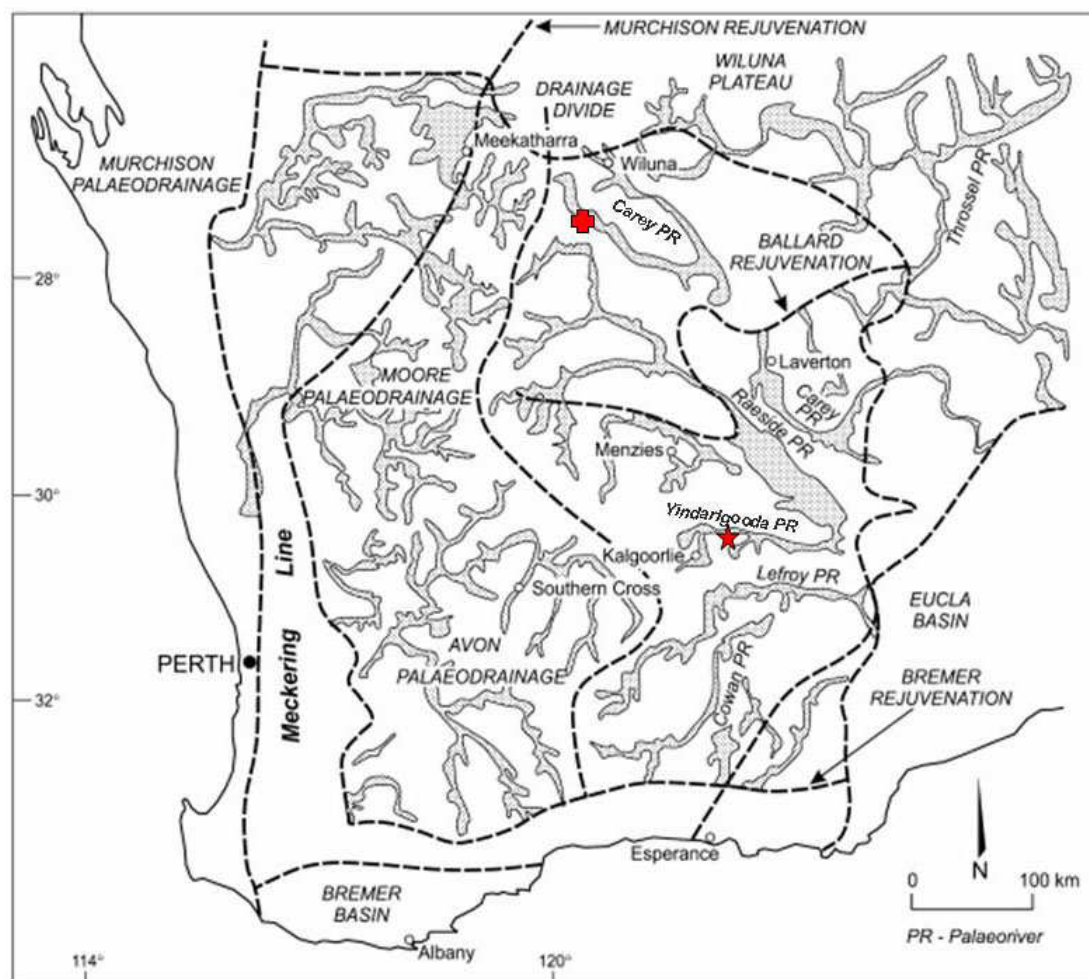
Morgan (1993) describes the climate of three regions of the Yilgarn Craton, following the divisions by van der Graaff *et al.* (1977), as being distinct and influencing the hydrochemical processes of the palaeorivers. The southwestern region is described as temperate, rainfall falling mostly during the winter months and a prolonged saturation of the soil. The southeastern, or Eucla, region is a low rainfall area, precipitation evenly distributed throughout the year. Internal run-off as a result is negligible with a poor transfer of water through the soil profile, the majority lost via evapotranspiration and evaporation. The northeastern region of the Craton is semi-arid, rainfall unpredictable and not restricted to any particular month. Cyclonic events cause sheet runoff and the duration of flow is short-lived.

### **2.1.3 Drainage**

Drainage in the Yilgarn Craton is inherited from an ancient river system radiating from a broad drainage divide that bisects the Craton (Figure 2.1). In southwestern Western Australia, the drainage follows two main directions, west-southwest and north-northeast (Anand and Paine 2002). The palaeodrainage in the Yilgarn Craton

is well preserved and forms part of the extensive palaeodrainage system of the Australian continent (Morgan 1993).

Clarke (2005) proposed the recognition of three major drainage divisions underlain by the Yilgarn Craton following that of van der Graaff *et al.* (1977). These are an eastern drainage division associated with the Eucla Basin; a western, associated with the Perth and Carnarvon Basins; and a northern, which is associated with the Pilbara region and Canning Basin.



**Figure 2.1:** Palaeodrainage systems of the Yilgarn Craton with associated palaeorivers. The major drainage divide is shown bisecting the Craton. Drainage divisions are the northern (associated with the Canning Basin/Wiluna Plateau); western (associated with the Perth and Carnarvon Basin on the western side of the Drainage Divide); and the eastern associated with the Eucla Basin. Lake Yindarlgooda (★) and Lake Miranda (✚) are indicated on the map. (modified after Morgan 1993 and Anand and Paine 2002).

#### 2.1.4 Palaeorivers

Palaeorivers (palaeochannels) are the remnants of ancient flowing rivers, those in the Yilgarn Craton having developed in the Late Cretaceous (Morgan 1993). Drainage incisions along the palaeovalleys resulted in the formation of channels during the Early-Middle Tertiary. Subsequent weathering resulted in the filling of the channels with sediments deposited under fluvial, lacustrine, estuarine and marine environments of the Middle to Late Eocene. The onset of aridity resulted in the deposition of colluvial, alluvial and aeolian sediments overlying the early regoliths, filling the channels and ceasing surface flow (Anand and Paine 2002). The salt lakes are the deflated remnants of the palaeorivers and act as a basin for the accumulation of sediment and salts, many connected to the local and regional groundwater systems (Salama 1997).

Groundwater quality and quantity in the palaeorivers relate to the geomorphic and climatic regimes of the Yilgarn Craton and to the geochemical interactions with the surrounding rock. The effective rainfall recharge in the north results in less saline or fresh groundwater increasing northward where precipitation is mostly in the summer, compared to the southern regions where the groundwater is more saline with winter precipitation (Anand and Paine 2002).

The palaeorivers of the northern Yilgarn Craton (above 30 °S latitude) have developed separate geochemical systems associated with the formation of each salt lake along the palaeoriver. The groundwater near the intake is alkaline and rich in bicarbonates. Salinity and alkalinity increase along the flow path as the water interacts with the sediment and the water becomes chloride dominated. South of latitude 29 °S calcrete formations wane and there is minimal alteration of common ionic ratios with increasing salinity due to low reactivity with sediment. The groundwater is mostly acidic and much of the deposition of elements occurs on the surface of the lake bed rather than in the aquifers, with the reduction of sulphur in extensive anoxic conditions a feature (Morgan 1993). This reaction of groundwater and sediments is highly significant, as it has resulted in a range of valuable mineral deposits. Ultimately, the biological facies of a salt lake are linked to the sedimentary ones (De Deckker 1988).

## 2.2 Lake Yindarlgooda

Lake Yindarlgooda is located approximately 30 km east of the city of Kalgoorlie in the Goldfields region of Western Australia, 600 km east of Perth, within the latitudes 30° 30' and 31° 00'S and longitudes 121° 30' and 122° 00'E (Ahmat 1995). It is located in the Bulong Domain, within the Kurnalpi Terrane, one of three making up the Eastern Goldfields Super Terrane of the Yilgarn Craton (Anand and Paine 2002). The Bulong rock assemblages comprise mafic to ultramafic volcanic and intrusive rocks (Ahmat 1995).

The lake has an area of 419.55 km<sup>2</sup> with a catchment of 3864.93 km<sup>2</sup> (Turner 1999), the lake acting as a compensating basin for the drainage from the surrounding undulating plateaux. The topography is subdued and characterised by low, rounded hills that grade gently into wide alluvial valleys. The majority of the area is at 320 m above sea level, with a few individual hills (Ahmat 1995). Surface drainage is characterised by short isolated creek lines ( $\leq 10$  km) and diffuse ephemeral drainage lines which can be several hundred square kilometres (WAM 1992). Lake Yindarlgooda is underlain by the Yindarlgooda Palaeoriver with alluvium-covered palaeochannels and is situated within the eastern drainage division according to Clarke (2005). The playa and surrounding clay pans are saline, surrounded by kopi (CaSO<sub>4</sub>) dunes of aeolian origin. The water bodies consist of clay, silt and sand, interbedded with evaporite minerals such as gypsum and halite.

Climate is classified as semi-arid with an average rainfall of 257 mm a<sup>-1</sup> and evaporation rate of 2 641 mm a<sup>-1</sup> (Kinhill 1996). Rainfall distribution varies from light winter rainfalls to patchy heavier summer-autumn falls. Flooding occurs in the summer months from cyclonic events in the northwest of the state. The average summer temperature is above 35 °C and winters are cool with the occasional frost.

Lake Yindarlgooda is situated within the Coolgardie Botanical District of the South Western Interzone (Beard 1979). The area is characterised by open eucalypt woodlands, mostly of Salmon Gums, gimlet and mallee interspersed with saltbush (*Atriplex*) and bluebush (*Kochia*). Native pines (*Callitris*) are common on the kopi dunes. Halophytic shrublands dominated by *Halosarcia*, *Atriplex* and *Cratystylis* species surround the playa and the clay pans (Brearley 2002).



Land use around Lake Yindarlgooda is mining and pastoralism. The area has been intensely prospected for nickel and contains a number of mining leases. The majority of the area is pastoral, under the lease of Hampton Hill Station, a sheep station run by the Jones family for over 100 years. Situated near the lake was the town of Bulong, a once thriving gold mining centre at the turn of the 20<sup>th</sup> Century.

### **2.3 Bulong Nickel Laterite Project**

In 1970, Australian Selection Pty Ltd identified nickel enriched laterites in the Bulong area and between 1978 and 1982 Western Mining Corporation carried out substantial drilling and test work. The technology of the time restricted the development of the nickel laterite until 1987 when the tenement was purchased by Resolute Resources Limited. Tests conducted indicated that 90% of the contained nickel and cobalt could be recovered. The Bulong Nickel Laterite Project was acquired by Preston Resources in 1998 and the first metal from the on-site processing plant was produced in March 1999 (L. Cahill, Bulong Nickel, *pers. comm.* 2002). The mine operates open-cut nickel-cobalt ore with a processing plant for the ore producing up to 9 600 tonnes of nickel and 1000 tonnes of cobalt metal per annum.

The residue from the processing plant (slurry) is deposited in the leach residue storage facility (LRSF). The LRSF was constructed on the shore of Lake Yindarlgooda, some 7 km east of the processing plant, and was considered the most attractive option from an environmental aspect (Kinhill 1996). The LRSF consists of a 36 Ha tailings dam and two evaporation ponds LRSF1 (16 Ha) and LRSF2 (50 Ha). This study focuses on the impacts of the LRSF on the limnology and biota of Lake Yindarlgooda and the surrounding environment.

### **2.4 Selection of Lake Yindarlgooda study sites**

The study sites were selected using a topographical map and chosen to represent the different habitats around the lake. These included two wetlands, a clay pan and a small saline lake. Anthropogenic impacts from leach residue storage facility (LRSF) on the ecology of the lake were analysed in this study. Sites chosen near the LRSF were under the direct influence of the evaporation pond. This was as a result of direct discharge of the hypersaline water onto the lake from 2000 to 2001, or as constant seepage from the facility's walls. These sites were classed as "impact".

Sites regarded as free from the influence of the LRSF were classed as “control”. The two adjacent wetlands, Swan Refuge and Lake Penny were classed as “wetland” sites.

Accessibility to the sites in both wet and dry conditions was an important criterion. In total, 12 sites were selected (Figure 2.2; Table 2.1), ten sites from the lake proper (playa sites) and two adjacent wetlands, Swan Refuge and Lake Penny to the north. Three control sites were selected on the southern shores of the lake, sites 1–3. They were buffered from the effects of the LRSF by a number of islands. Two control sites located on the northern shores, sites 6 and 7, were approximately 20 km from the LRSF.

Site EP1 was directly influenced by the constant seepage of leachate from the LRSF walls. Site EP2 was affected by the direct discharge water, released during construction of the extension of the second LRSF. To the west of EP1, approximately 500 m, was Site 5. Site 4 was north of EP2. Both Site 4 and Site 5 were not under direct influence from the LRSF leachate and the extent of the impact was investigated at these two sites.

Swan Refuge was a small gypsum clay pan located in the southern floodplains of Lake Yindarlgooda near Site 3. Lake Penny, a small saline lake, located to the north of Lake Yindarlgooda. Both wetland sites were included as reference sites, in particular as refugia for the waterbirds visiting Lake Yindarlgooda.



**Figure 2.2:** Location of the study sites in Lake Yindarlgooda for 2001 to 2002. ● = playa control sites, ● = playa impact sites, ● = wetland sites. Yellow dots indicate mineral deposits (mine sites). Base map from [www.australianminesatlas.gov.au](http://www.australianminesatlas.gov.au)

**Table 2.1:** Coordinates and classification of the sampling sites for Lake Yindarlgooda, including the two peripheral wetlands, Swan Refuge and Lake Penny. Sites classified as control, impact or wetland. (March 2001–September 2002).

Site	GPS Coordinates	Classification
Site 1	S30°48.820' E121°52.116'	Control
Site 2	S30°46.972' E121°56.810'	Control
Site 3	S30°42.341' E122°06.801'	Control
Site 4	S30°42.131' E121°53.618'	Impact
Site 5	S30°43.206' E121°52.316'	Impact
Site 6	S30°34.482' E122°05.659'	Control
Site 7	S30°36.289' E122°11.976'	Control
Site EP1	S30°42.616' E121°52.709'	Impact
Site EP2	S30°42.197' E121°53.618'	Impact
Swan Refuge	S30°43.271' E122°07.776'	Wetland
Lake Penny	S30°32.010' E121°53.181'	Wetland

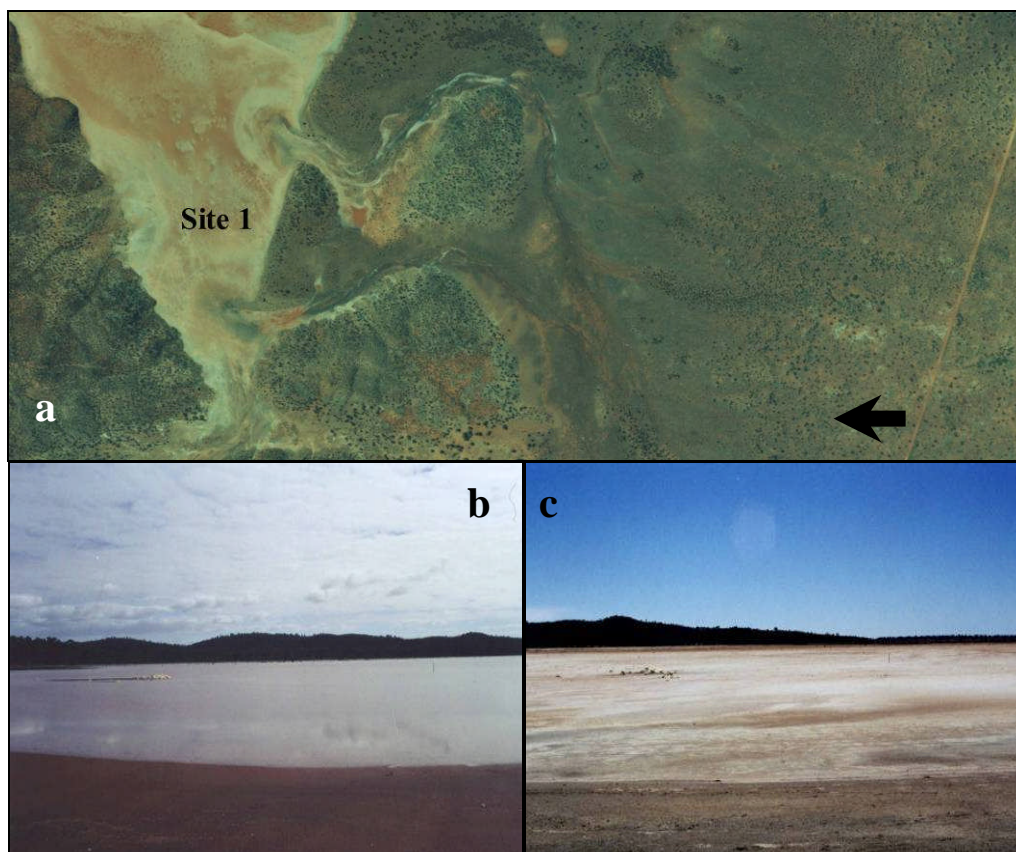
## 2.5 Description of study sites

### 2.5.1 Control sites

#### *Site 1* (Figure 2.3 a-c)

Located within a narrow embayment (Figure 2.3a) and buffered by islands in the southwestern section of Lake Yindarlgooda, this site represented the western point of the playa study sites (Figure 2.2). The site showed no signs of livestock or feral animal disturbance. No other recent mining activities were apparent at this site and the data obtained were considered a good indication of the background levels for Lake Yindarlgooda. Some historical data collected from Bulong Nickel in 2000 near to this site were available.

The surrounding relief was of sparsely vegetated low dunes of quartz sand, gradually sloping down to a flat heavy clay beach, the margins fringed by a samphire community. A fine dark crust, intermingled with quartz pebbles covered the surface of the sand, extending from the dunes down to the water's edge. The average water depth was 4 cm, at the time of sampling in March 2001 (Figure 2.3b). Sediment and water samples were collected near a laterite outcrop 20 - 30 m from the shoreline. The surface of the lake bed was clay. During subsequent field trips, when the lake was dry, a fine halite crust was observed on the surface (Figure 2.3c).

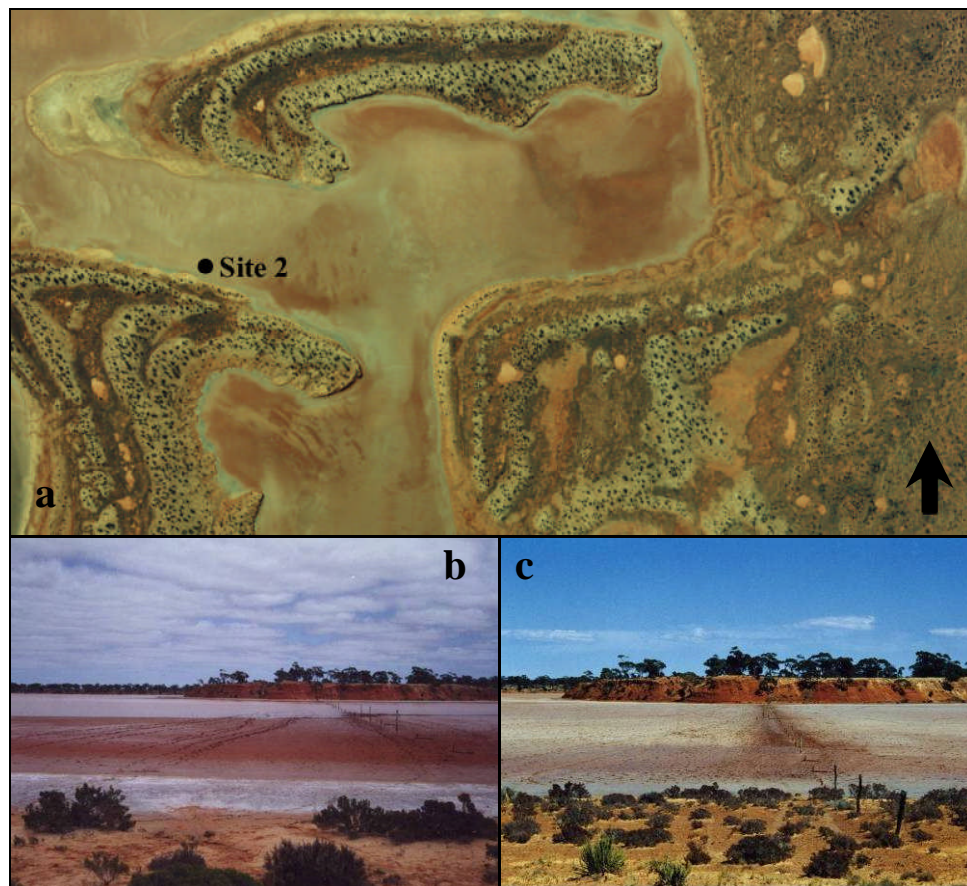


**Figure 2.3:** Site 1. (a) Aerial photograph, arrow points north. (b) March 2001. (c) September 2001. Halite crust seen covering the surface of the lake. Photo taken from the shore, facing north.

*Site 2* (Figure 2.4 a-c)

Approximately 13 km northeast from Site 1, Site 2 was located in the southwestern section of Lake Yindarlgooda (Figure 2.2). The low kopi dunes were covered in a fine, light brown crust in between the sparse vegetation. The area showed no evidence of disturbance by livestock or feral animals. Kangaroos regularly visited the area and accessed the island along the fence line traversing the lake (Figure 2.4c). The area did not appear to have been affected by previous mining activity.

The average water depth was 2 cm, at the time of sampling in March 2001. Samples were collected along a boundary fence 50 m from the shoreline where the surface water commenced (Figure 2.4b). Observations made during subsequent field trips noted a halite crust covering the surface of the dry lake bed (Figure 2.4c).

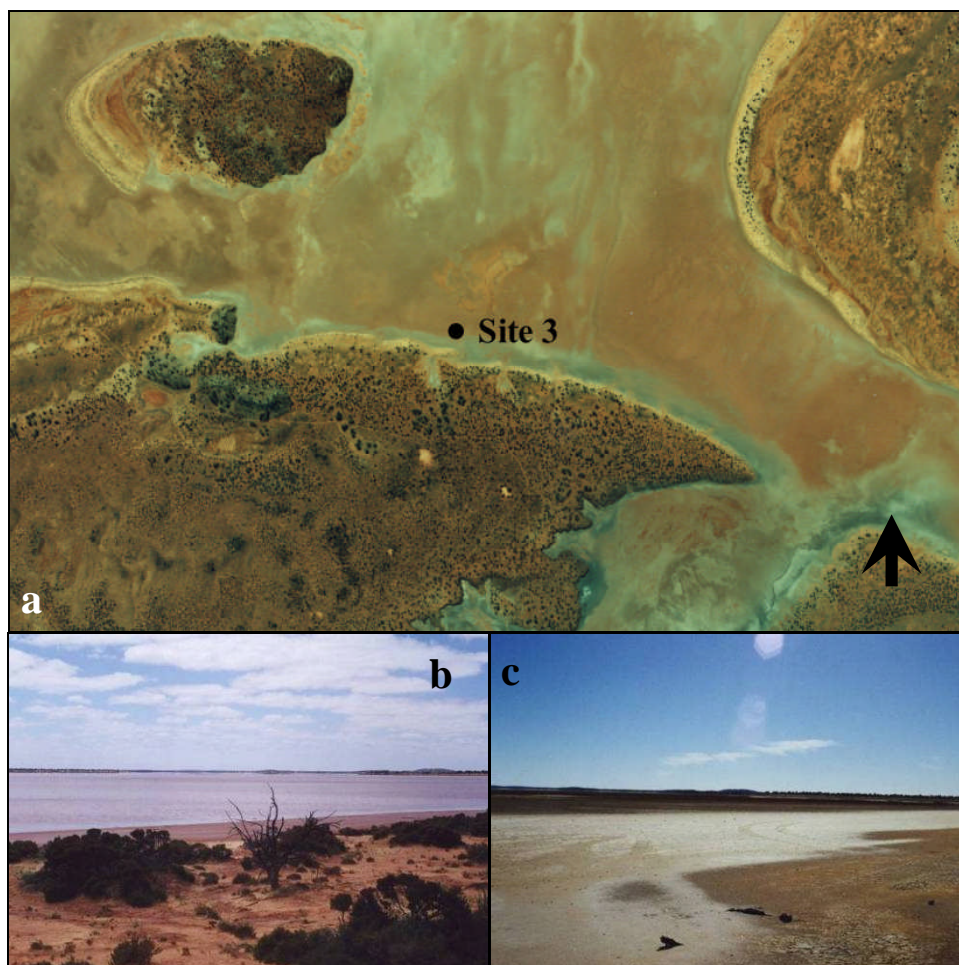


**Figure 2.4:** Site 2. (a) Aerial photograph, arrow points north. (b) March 2001. (c) September 2002. Photo taken 30 m from shoreline facing east.

#### Site 3 (Figure 2.5 a-c)

Site 3 was located 20 km east from Site 2 along the middle, southern section of Lake Yindarlgooda. The site was buffered from the LRSF by a number of islands in the centre of the playa. The low-rise kopi dunes contained sparse populations of dunna-dunna (*Lawrencia helmsii*) interspersed by biological soil crusts. No evidence of livestock disturbance was observed at this site. The lake margin was characterised by the non vegetated flat beach with a sparse samphire zone.

The average water depth was 7 cm, in March 2001 and samples were collected 10 – 20 m from the shoreline (Figure 2.5b). Black Swans were observed in the open water during the March 2001 field trip. A fine halite crust covered the hard clay surface when the lake was dry (Figure 2.5c).



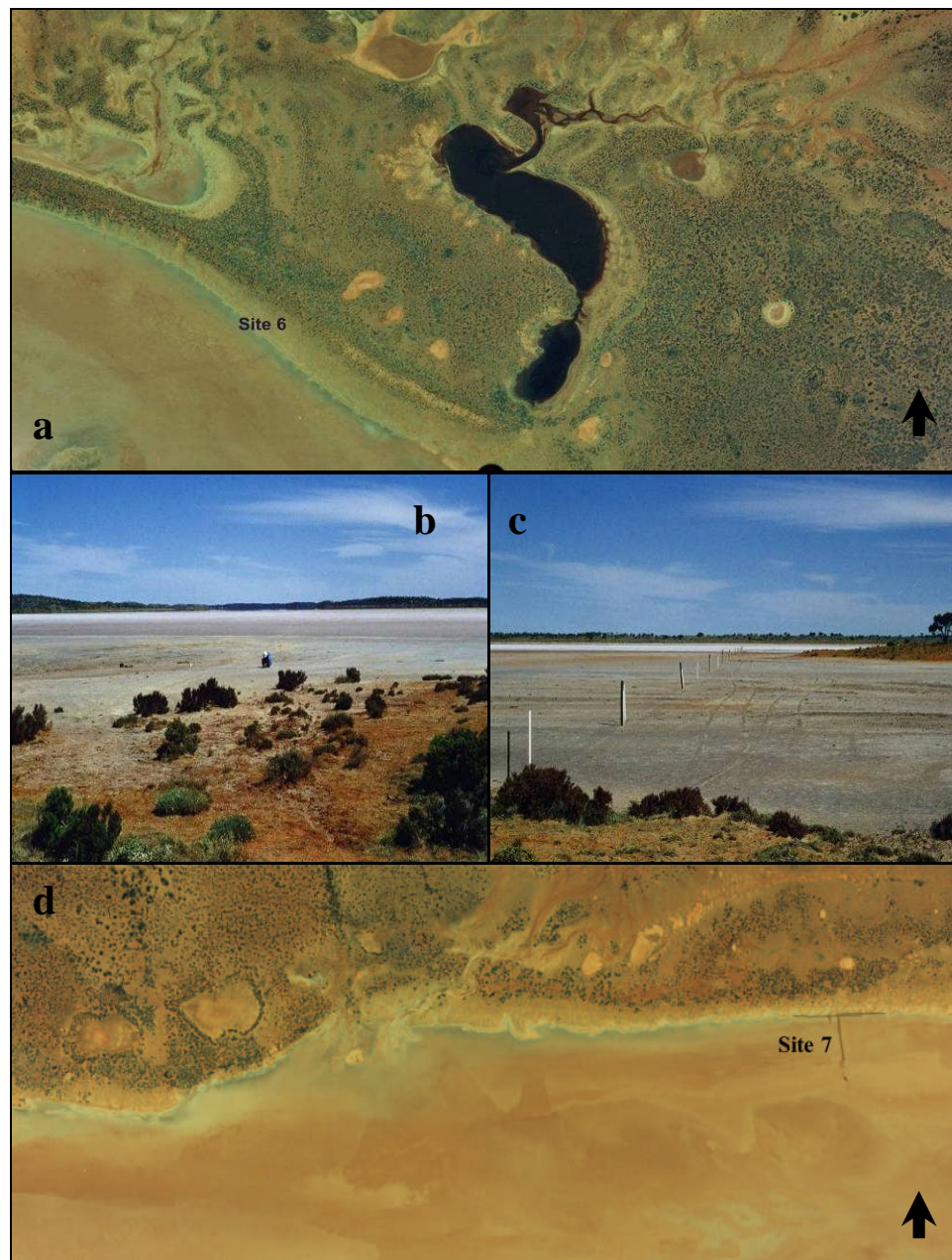
**Figure 2.5:** Site 3. (a) Aerial photograph, arrow pointing north. (b) March 2001. (c) September 2001. Photos taken facing NE from shore.

*Site 6* (Figure 2.6 a & b)

Site 6 was located along the far northern section of Lake Yindarlgooda and exposed to the open body of Lake Yindarlgooda. This site was not sampled in March 2001 because of the lack of water. The shoreline was relatively flat, fringed by sparse vegetation on a low kopi dune. Signs of disturbance by livestock were evident. Sediment samples were collected 20 m from the shoreline during September 2001. The surface sediment of the lake bed was covered in a fine halite crust (Figure 2.6b).

*Site 7* (Figure 2.6c & d)

Site 7 was 11 km east of Site 6, situated within a narrow arm of the northern section of the lake, the distance to the opposite shore was approximately 1 km. The peripheral vegetation was similar to that of Site 6 and a light halite crust covered the sediment surface. Light vehicle tracks can be seen in Figure 2.6d.



**Figure 2.6:** Sites 6 and 7, northern control sites. (a) Site 6, aerial photograph, arrow points north. Body of water to the northeast of the site is Coffee Swamp, dry at the time of sampling. (b) Site 6 September 2001. (c) Site 7, September 2001. (d) Aerial photograph arrow points north.

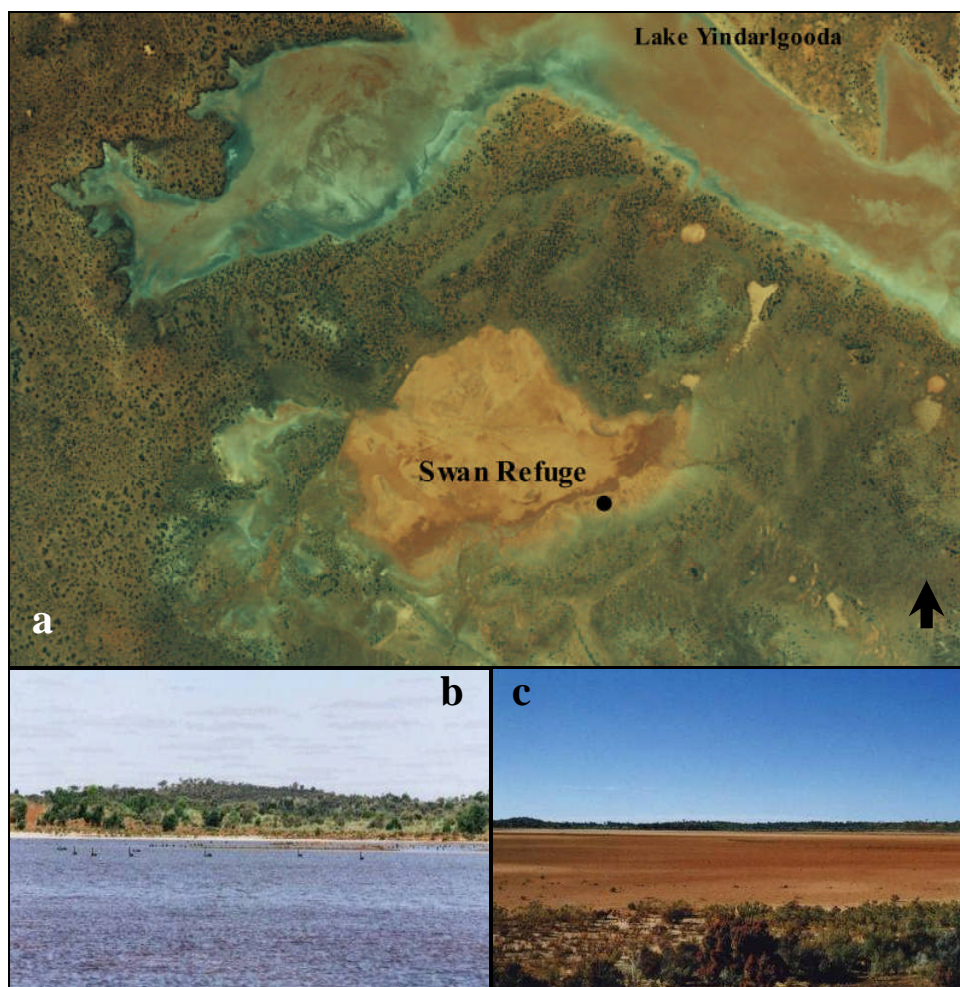
### 2.5.2 Wetland sites

*Swan Refuge* (Figure 2.7 a-c)

Swan Refuge, a clay pan, was located approximately 5 km south-east of Site 3. Located on the southern floodplain of Lake Yindarlgooda, it formed part of a mosaic of temporary wetlands. The depth of the water 2 m from the shore was 29 cm when



sampled in March 2001. The periphery of the lake consisted of dense samphire bushes and low shrubland (Figure 2.7a), providing suitable habitats for a diverse waterbird population (Figure 2.7b). The lake sediment was clay with an extensive meadow of dried *Ruppia* sp, visible during subsequent trips. Numerous exposed sand bars along the western edge formed roosting sites for many birds. Subsequent sampling events recorded a hard clay base with no signs of a salt crust (Figure 2.7c).

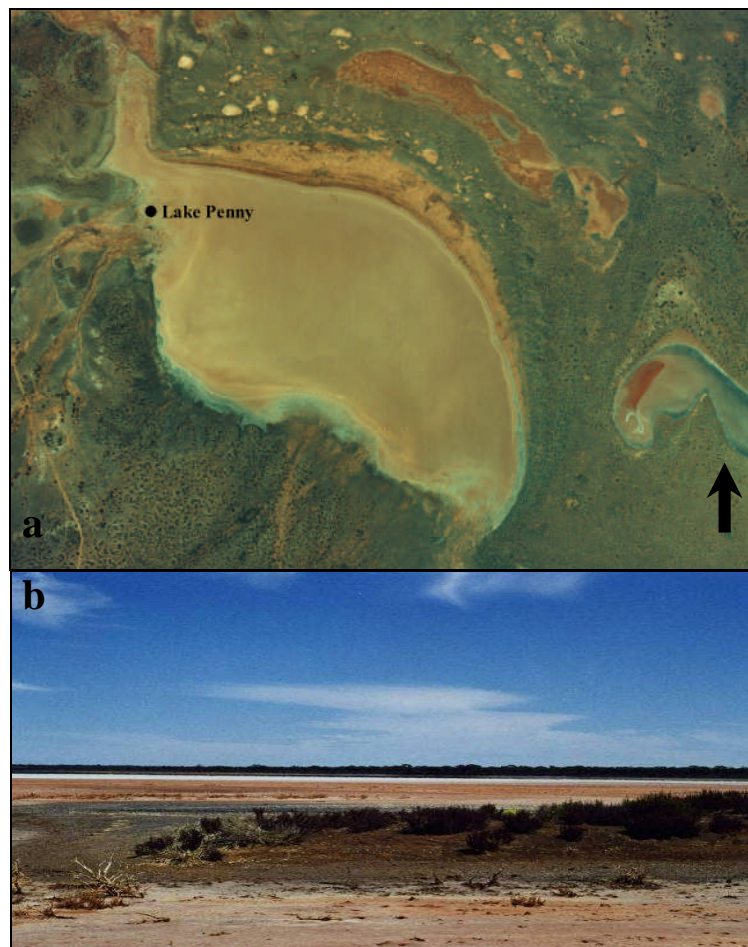


**Figure 2.7:** Swan Refuge. (a) Aerial photograph, dot indicates sampling site. (b) March 2001. Large numbers of Black Swans can be seen in the water. (c) September 2001. Figures a & c were taken from the south eastern shoreline of the wetland. Arrow points north.

*Lake Penny* (Figure 2.8 a-c)

Lake Penny is a small saline lake. It is located to the north of Lake Yindarlgooda, approximately 20 km north from the BNLP site. An initial visit by C. Vivian (Bulong Nickel) noted large numbers of Banded Stilts, during March 2001 when the

lake was full. Numerous tributaries can be seen feeding into Lake Penny (Figure 2.8a) and observations in September 2001 indicated there was substantial surface flow when wet. The area appeared productive with extensive dried *Ruppia* mats observed in September. Small, vegetated sandbanks had abandoned swan nests, again indicting the productivity of the lake when wet. Sediment samples were collected 40–50 m from the margins near *Ruppia* mats. The surface sediment was clay, a halite crust observed toward the centre of the lake and there were patches of dried mats present.



**Figure 2.8:** Lake Penny. **(a)** Aerial photograph, dot indicates sampling point. Arrow points north. **(b)** September 2001. In the foreground of the photo is a vegetated sandbank where Black Swan nests were found. Photo was taken from the northern tributary as indicated in the aerial photograph.

### 2.5.3 Impact sites

#### *Site 4* (Figure 2.9a, Figure 2.10 a & b)

This site was located on the northern section of Lake Yindarlgooda and just north of EP2 and the eastern wall of the LRSF (Figure 2.9a). The lake sediment was of sandy clay with large quartz pebbles throughout. The distant shoreline had characteristic flat beach zones, ideal for foraging by waders. The water depth recorded in March 2001 was 7 cm and samples were collected 20 m from the shoreline. A fine halite crust had developed during the subsequent field trips and the lake sediment was compact (Figure 10b).

#### *Site 5* (Figure 2.9b, Figure 2.10 c & d)

Site 5 was situated in an embayment sheltered by steep, unvegetated rocky cliffs and a large rocky island toward the centre of the lake. It was located to the west of EP1 and the western wall of the facility (Figure 2.9b). The water depth was 5 cm at the time of collection, approximately 100 m from the margin of the playa (Figure 2.10c). During subsequent field trips a speckled halite crust overlay soft, clay sediment in the embayment, while on the other side of the island the crust was much thicker (Figure 2.10d).

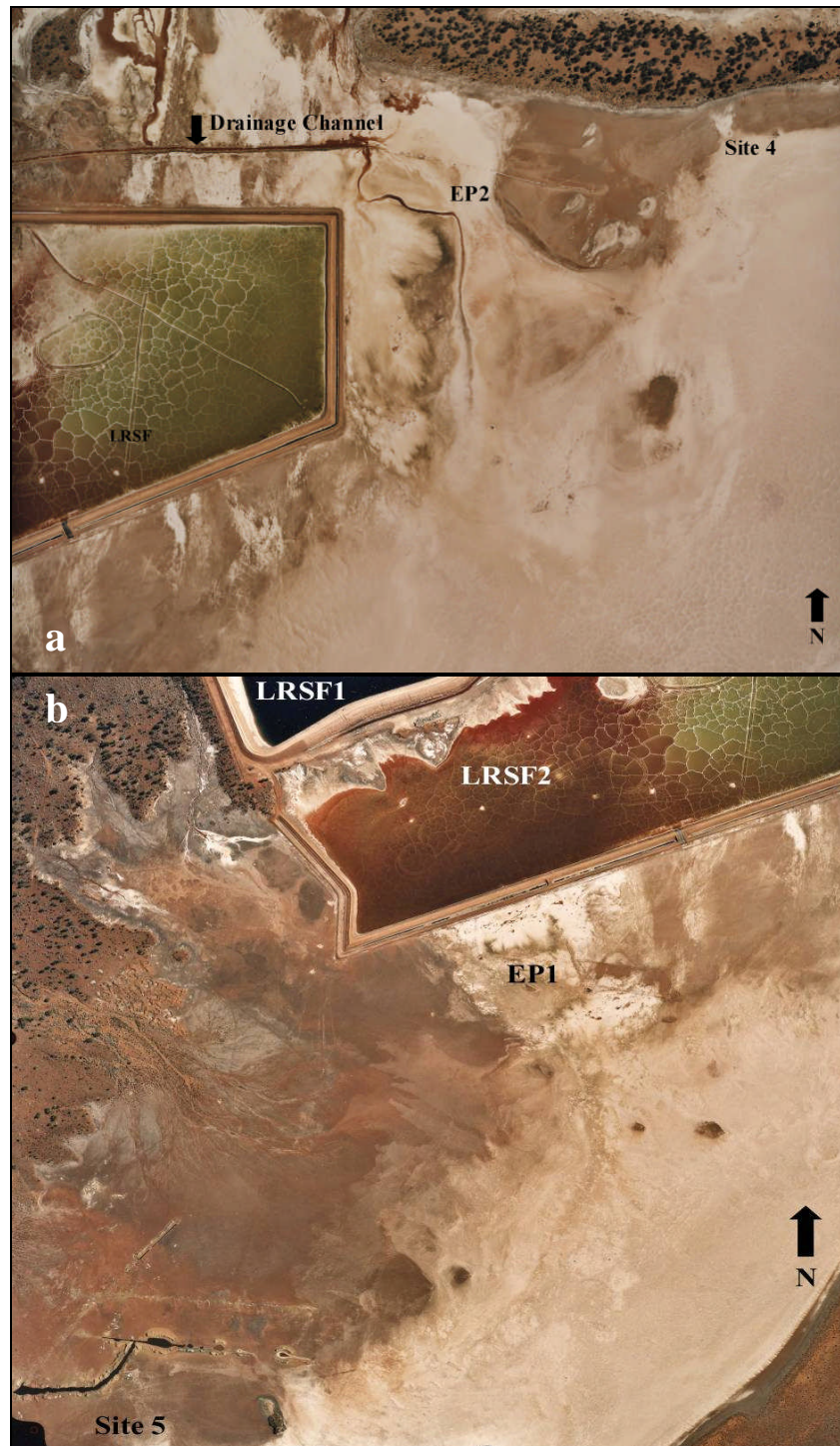
#### *Site EP1 - Evaporation Pond 1* (Figure 2.9b, Figure 2.11 a & b)

Site EP1 was directly under the influence of the seepage from the LRSF. Samples were collected next to a laterite outcrop, 50 m from the outer LRSF wall (Figure 2.9b). Fringing vegetation was absent as the LRSF was constructed on the lake bed. Surface water was present during all field trips. During the March 2001 a depth of 4 cm was recorded. During subsequent field trips the surface of the lake at this site was covered in water no more than 2 cm, and the sediment sticky. A thick salt crust had developed by September 2001.

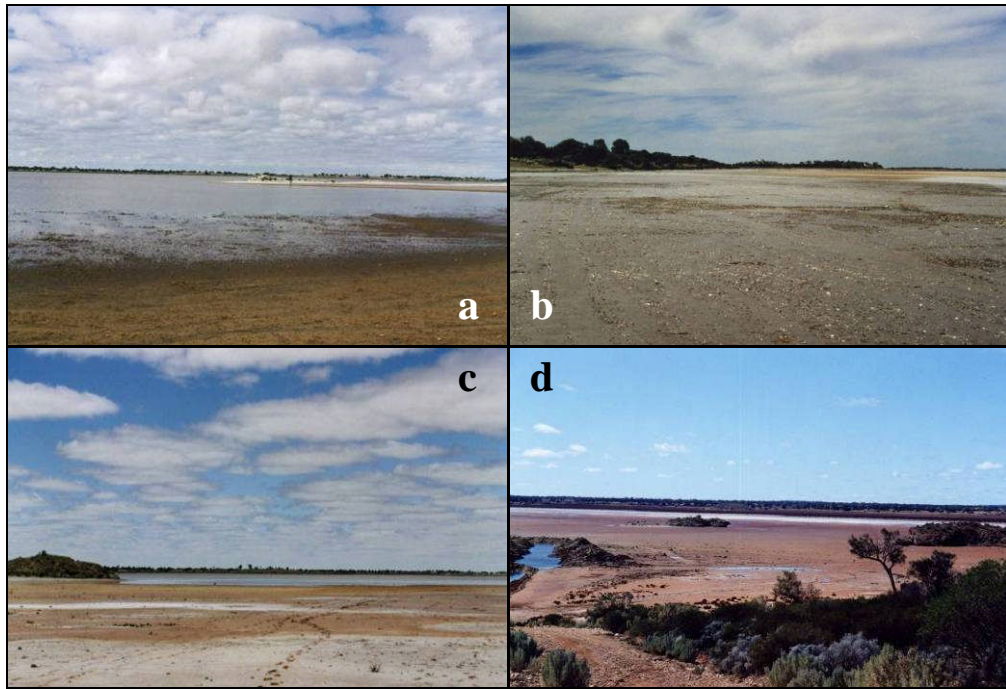
#### *Site EP2 - Evaporation Pond 2* (Figure 2.9a, Figure 2.11 c & d)

Site EP2 was to the north of site EP1 near a channel where hypersaline decant water from the EP had been discharged. The water level at this site was minimal (<1 cm) and construction of the channels had disrupted the sediment (Figure 2.9a). Dead shrubs were observed at this site in March 2001 (Figure 2.11c) and by September

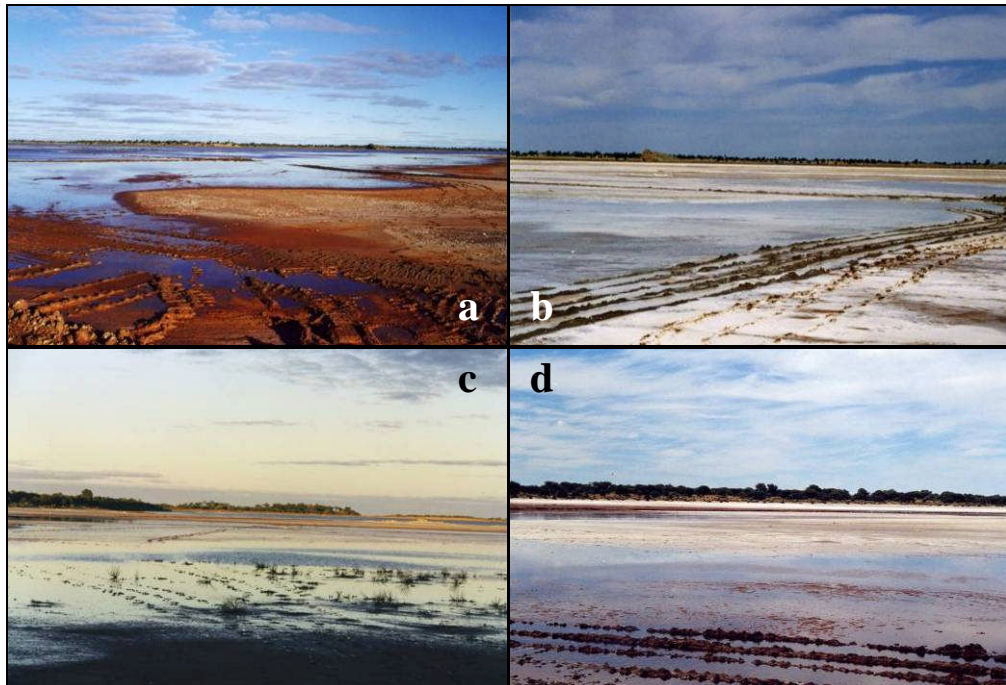
2002 a thick, hard salt crust (5 cm) had formed. The sediment was waterlogged and sticky.



**Figure 2.9:** Leach residue storage facilities (LRSF) and the impact sites. **(a)** EP2 and Site 4. Discharge drainage channel shown in the aerial photograph, surrounded by a thick salt crust. **(b)** Aerial photo of EP1 and Site 5. The thick salt crust directly in front of the LRSF can be seen in the photograph. (Photos courtesy of Bulong Nickel 2002).



**Figure 2.10:** Sites 4 and 5. (a) Site 4, March 2001, (photo taken facing southwest). (b) Site 4, September 2001. Image taken from shore facing east. (c) Site 5, March 2001, facing south, away from margins. (d) Site 5, September. Photo taken from the top of the hill facing south.



**Figure 2.11:** Sites EP1 and EP2 (a) EP1, March 2001. (b) EP1, September 2001. Both EP1 photos face toward centre of lake. (c) EP2, March 2001. (d) EP2, September 2001. Both photos for EP2 face east from the LRSF. In both (b) and (d) thick salt crust are visible and sites retained surface water.

## 2.6 Lake Miranda

Lake Miranda is located approximately 400 km north of Lake Yindarlgooda and 800 km northeast of Perth. It is underlain by the Carey Paleoriver, above the Ballard Rejuvenation line. It is situated within the Sandstone-Sir Samuel Study Area between latitudes 27° 00'S and 28° 00'S and longitudes 118° 30'E and 120° 45'E and falls within the Kalgoorlie Terrane (Anand and Paine 2002). The lake is approximately 200 km<sup>2</sup> with a number of low islands intersecting the playa. The lake bed consisted of alluvial and colluvial sediments overlying dense clay. Drainage is internal, the catchment of low relief totally 1 400 km<sup>2</sup>, mostly of surface sheet flow.

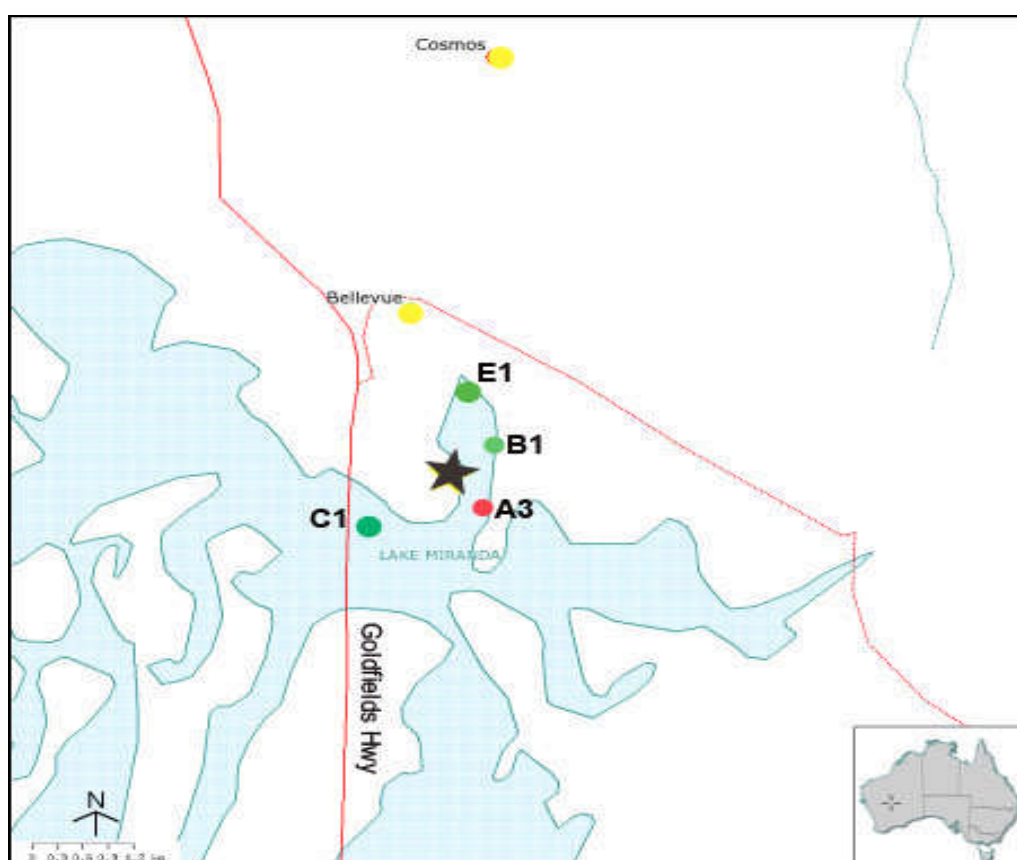
The climate is semi-arid to arid with hot summers and cool to mild winters, with an average rainfall of 215 mm a<sup>-1</sup> and the potential evaporation of 2 500 – 3 500 mm a<sup>-1</sup>. Rainfall is unreliable and the area subject to both drought and flash flooding. The early months of the year are normally the wettest. Daytime temperature averages above 36 °C in January (Bunting and Williams 1976).

The area surrounding Lake Miranda is generally flat, and undulating, consisting of low halophyte shrublands dominated by *Halosarcia*, *Maireana* and *Cratystylis* species on the poorly drained sub-saline soils and clays, with mulga (*Acacia aneura*) woodlands on the sandier soils and loams (Hall and McKenzie 1994). Sparsely settled, the mining town of Leinster is the main population centre. Apart from mining, pastoral leases supporting a sheep grazing industry cover the Sandstone-Sir Samuel Study Area. The felling of timber for use in the mining industry in the past along with pastoralism has degraded a large portion of the land (Hall and Milewski 1994).

### 2.6.1 Selection of sample sites

Samples were received from Lake Miranda as part of a program monitoring the discharge of hypersaline mine water on to the lake and the subsequent impacts on the surrounding environment. The samples were incorporated in the *Parartemia* research component of this study. The sites have been referred to as collection sites rather than study sites as only the *Parartemia* population was examined.

Samples were collected by Fiona Taukulis and Erin Thomas from Lake Miranda in 2001 and 2003. Sites B1, C1 and E1 were classified as control sites with no influence from the discharge water. Site A3, an impact site, was in the path of the discharge, opposite the tailings storage facility (Figure 2.12; Table 2.2). Classification of the sites was at time of collection. Descriptions of the sites were obtained from John *et al.* (2002). Higher than average rainfall in early 2001, as a result of cyclonic events in the northwest of Australia, filled large sections of Lake Miranda.



**Figure 2.12:** Location of collection sites at Lake Miranda (2000–2003). ★ = Bellevue storage tailings facility (BSTF) shown. Sites B1, C1 and E1 were classified as control (●) sites at time of collection, site A3 impacted (●) from the hypersaline discharge from the BSTF.

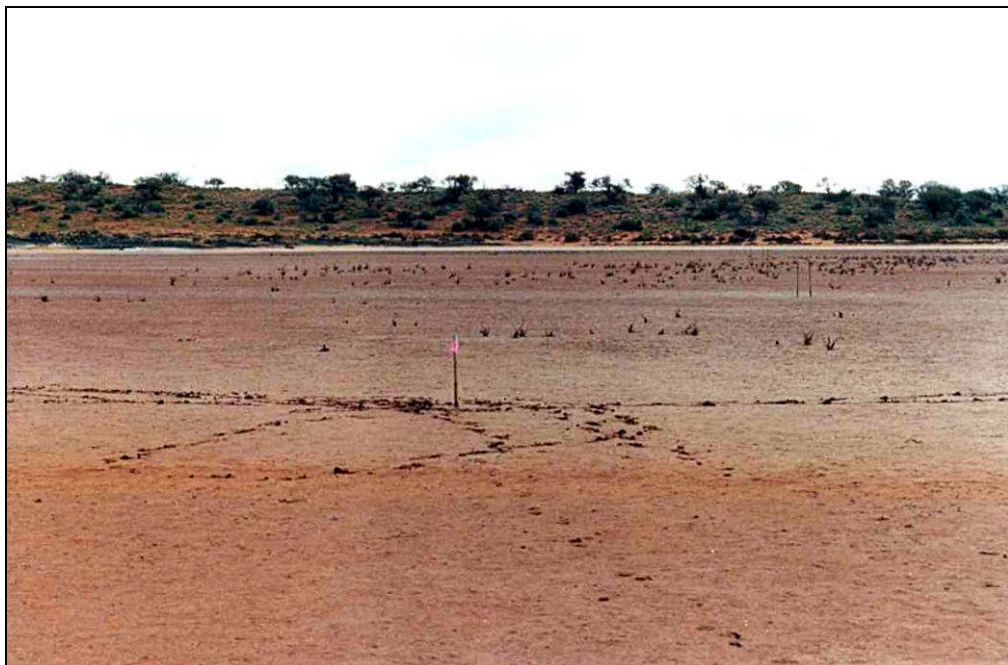
**Table 2.2:** Collection sites for Lake Miranda. Sites classified as control or impact at the time of collection.

Sites	GPS Coordinates	Classification
A3	S27° 39' 16 E120° 34' 00	Impact
B1	S27° 39' 05 E120° 33' 58	Control
C1	S27° 39' 05 E120°34' 07	Control
E1	S27° 39' 39 E120° 33' 32	Control

### 2.6.2 Description of collection sites

#### *Site A3- Impact site* (Figure 2.13)

This site was classified as an impact site as it was located near the dewatering discharge point from the BSTF. The area was within a floodplain, which was dry for the majority of the year, only filling after substantial rainfall. It was sparsely vegetated with *Halosarcia* and *Atriplex* species on the floodplain. During the summer months a halite crust appeared on the surface of the lake,



**Figure 2.13:** Site A3, Lake Miranda. This was an impact site located east of the BSTF. Photo taken during April 2003.



*Site B1 -Control Site (Figure 2.14)*

Site B1 was located within a channel in the northern section of Lake Miranda. The channel flowed into the playa proper opposite the BSTF near site A3. With the exceptions of the summer months, the site maintained surface water. The area was a flat-floored floodplain of sandy soil and clay, covered by a sparse population of samphires and *Atriplex*. The area was considered a control site at the time of sampling.



**Figure 2.14:** Site B1, Lake Miranda. Located within a small channel, draining to the main playa near A3. Photo taken during April 2003.

*Site C1 - Control Site (Figure 2.15)*

Located within a shallow basin in the southwestern arm of Lake Miranda, site C1 was adjacent to the Leinster-Waroona Highway (Figure 2.12). The site was classified as a control site at time of collection, readily filling with water. Flow was south-southwest and this site may have been a collection point. A halite crust had developed when the lake was dry and this site supported *Lamprothamnium* groves, interspersed amongst samphires when inundated.



**Figure 2.15:** Site C1. Control site located adjacent to the Leinster-Waroona Highway. Photo taken in April 2003.

*Site E1- Control Site (Figure 2.16)*

Located within the north western section the lake, E1 was classified as a control site at the time of collection. The site was just below an inflow area and easily filled with water at the onset of the hydrocycle. It was similar to C1, though the floodplains were devoid of vegetation. During the dry months, a halite crust formed on the surface, which was readily broken revealing an “anoxic” subsurface sediment.



**Figure 2.16:** Site E1, April 2003. The site was located in the north western section of Lake Miranda at an inflow point. The site was classified as control at the time of collection. Photo taken in April 2003.

## **Chapter 3.0. Baseline study of Lake Yindarlgooda, Swan Refuge and Lake Penny: the physicochemical limnology**

### **Abstract**

A baseline study of Lake Yindarlgooda and two surrounding wetlands, Swan Refuge and Lake Penny, was performed in March 2001 after a significant rainfall caused by cyclonic events in the north of Western Australia. The aim of this study was to investigate and describe the physical and chemical limnological features of the lake, none of which had previously been identified.

Lake Yindarlgooda displayed characteristics typical of many large playas in the Salinaland of Western Australia. It was classified as a temporary, shallow, hypersaline salt lake (playa) which only partially filled in 2001. The lake was NaCl dominated, a thin halite crust covering the surface of the lake when dry. Two wetlands adjacent to the lake, Swan Refuge, a clay pan, and Lake Penny, a saline lake to the north, followed a similar pattern of ionic dominance. Salinity was identified as one of the main factors separating the control, impact and wetland sites. Other factors were nickel, arsenic and pH, all indicating a direct influence on the chemical limnology of the lake from the LRSF.

### **3.1 Introduction**

This chapter investigates the physical and chemical limnology of Lake Yindarlgooda and two adjacent wetlands, Lake Penny and Swan Refuge, at the start of the hydroperiod in 2001 and continuing through to September 2002, when the area was in drought. Once salt lakes were accepted as significant both economically and scientifically, Williams (1986) proposed that limnology be redefined as the study of inland waters, fresh or saline. The chemistry of inland waters are primarily geologically influenced, receiving soluble salts and nutrients from the sediment or via the weathering of the drainage area (Cole 1975).

Salinity may be defined as the concentration of total ions (Hutchinson 1957) and refers to the eight major ions: Na, Mg, Ca, K, Cl, SO<sub>4</sub> and HCO<sub>3</sub>, CO<sub>3</sub> (Hammer 1986). It is best expressed as mass (g L<sup>-1</sup>) but several surrogate measurements involving density, electrical conductivity and total dissolved solids (TDS) are commonly adopted. The most widely used of these is conductivity, measured in

electrical conductivity (EC) units, and is dependent on the ionic composition, total ion concentration and temperature of the water. In regions where the ionic composition of the lake is homogeneous, there is a high correlation between salinity and specific conductance, conductivity thus providing a good indication of the salinity of the water (Williams 1998a). Changes in the concentration and proportion of the major ions are mostly due to evapoconcentration and the influx or ingress of water (Hart and McKelvie 1986).

The effects of the drying and refilling of temporary wetlands is dependant on a number of factors. The sediment properties, the type of drawdown, the severity of drying, and the conditions of refilling, such as the source of water and degree of sediment disturbance, all play a role in changes to the water quality (McComb and Qui 1998). The water regime, or hydrological cycle, plays a critical role in the availability of nutrients and occurs in two phases. The first is drawdown where the sediment is exposed and the lake dewatered, and the second is the reflooding of the exposed, dried sediments (McComb and Qui 1998). The desiccation of sediments have been found to affect the release of nutrients such as phosphorous (Mitchell and Baldwin 1998) and nitrogen (Qui and McComb 1996). Decreases in inputs of dissolved organic carbon, nitrogen and phosphorous, particularly during droughts, can lead to carbon limitation which in turn cause changes in the ecological roles functioning within these systems (Humphries and Baldwin 2003).

Sediments represent both the largest source and sink of nutrients in many aquatic systems (Mitchell and Baldwin 1998). They are the final repository for many contaminants (Batley *et al.* 2003), such as heavy metals which can then circulate to the biotic compartments. The physical and chemical characteristics of a lake have ecological implications for the aquatic biota in the lakes (Hammer 1986). An understanding of the abiotic components that regulate the biotic component of an aquatic system is required in order to achieve management that is meaningful (Wetzel 1983).

### **Objectives**

The objectives of this chapter are:

- To investigate the abiotic limnology of Lake Yindarlgooda and two adjacent wetlands, Lake Penny and Swan Refuge, for the first time,

- To use the data collected from this study and available historical data to identify any difference between the designated control and impact sites,
- To identify the dominant factors separating the impact sites in Lake Yindarlgooda.

## 3.2 Methods

Sampling of the study sites was conducted from March 2001 until mid September 2002 over four field trips. The initial field trip was in March 2001 following a cyclone event in northern Western Australia in February 2001. The heavy summer rains only partially filled Lake Yindarlgooda. Surface water and sediment samples were collected from the lake and the two adjacent wetlands. Wet samples were collected in March 2001 and dry sediment samples were collected for the following three sampling periods for chemical and biological analyses. In May 2002 only the impact sites, 4 and 5, EP1 and EP2 could be sampled. All the sites were sampled for the other three trips and included the control sites 1-3, 6 and 7 and the two adjacent wetlands. Sites were designated as impact, control and wetland in Chapter 2.0.

### 3.2.1 Physicochemical parameters

The physicochemical parameters of water depth, temperature, pH, electrical conductivity ( $EC = \text{mS cm}^{-1}$ ) and salinity ( $\text{g L}^{-1}$ ) were measured *in situ* during March 2001. Measurements were taken within 20 m of the shoreline using a handheld TPS WP-81 meter. Water samples were collected for analyses in 1 L containers and sediment samples in sterilised glass jars. All analyses were conducted by Analabs Pty Ltd Environmental Service (SGS Groups, NATA accredited), Welshpool Western Australia. Samples were kept cool until transport to the SGS Laboratories within 24 hrs of collection. The chemical and nutrient parameters tested are shown in Table 3.1.

**Table 3.1:** Suite of chemical and nutrient analyses for water and sediment samples collected from Lake Yindarlgooda, Swan Refuge and Lake Penny (2001 – 2002).

<b>Water Samples</b>	<b>Sediment Samples</b>
Total Dissolved Solids (TDS)	Total Carbon (TOC)
Na, K, Ca, Mg, Cl, CO <sub>3</sub> , HCO <sub>3</sub> , SO <sub>4</sub>	Total Soluble Salt (TSS)
NH <sub>3</sub> -N , NO <sub>3</sub> -N, NO <sub>2</sub> -N, Total N, NO <sub>3</sub>	Ni, As
TKN, PO <sub>4</sub> , Total P,	
Total C, TOC	
SiO <sub>2</sub> , Chl <i>a</i> , Chl <i>c</i>	
Fe(soluble), Ni, As	

### 3.2.2 Treatment of data

The relationship between the control, impact and wetland study sites according to their abiotic (environmental) parameters was examined using multivariate techniques. A principal component analysis (PCA) of the environmental parameters and the sites was performed using PRIMER (Clarke and Gorlet 2006) to determine the main factors differentiating the sites. Data were transformed using  $\log(x + 1)$  and then normalised to account for the differences in units. Parameters that displayed collinearity were removed from the ordination plot. Sites that displayed the greatest dissimilarity were separated by distance on the ordination plot. Sites were coded into control, impact and wetland. Analyses were performed for each of the sampling periods for water and sediment samples. A final PCA was performed on all sediment data for the three dry sampling periods September 2001, May 2002 and September 2002 to examine differences between sampling periods.

## 3.3 Results

### 3.3.1 Physical limnology

#### 3.3.1.1 Rainfall and hydrology

From January 2001 to October 2002, 445 mm of rainfall was recorded from the Bulong Operation weather station (32° 42'0"S 121° 52'0"E) for Lake Yindarlgooda. Approximately 40% of the total rainfall fell in February 2001 (Figure 3.1). The average rainfall for the Kalgoorlie-Boulder region was 269.8 mm a<sup>-1</sup> with an evaporation rate of 2562.3 mm a<sup>-1</sup> (BOM 2002). During June, August and September 2002 data were not recorded from Bulong Operations weather station due

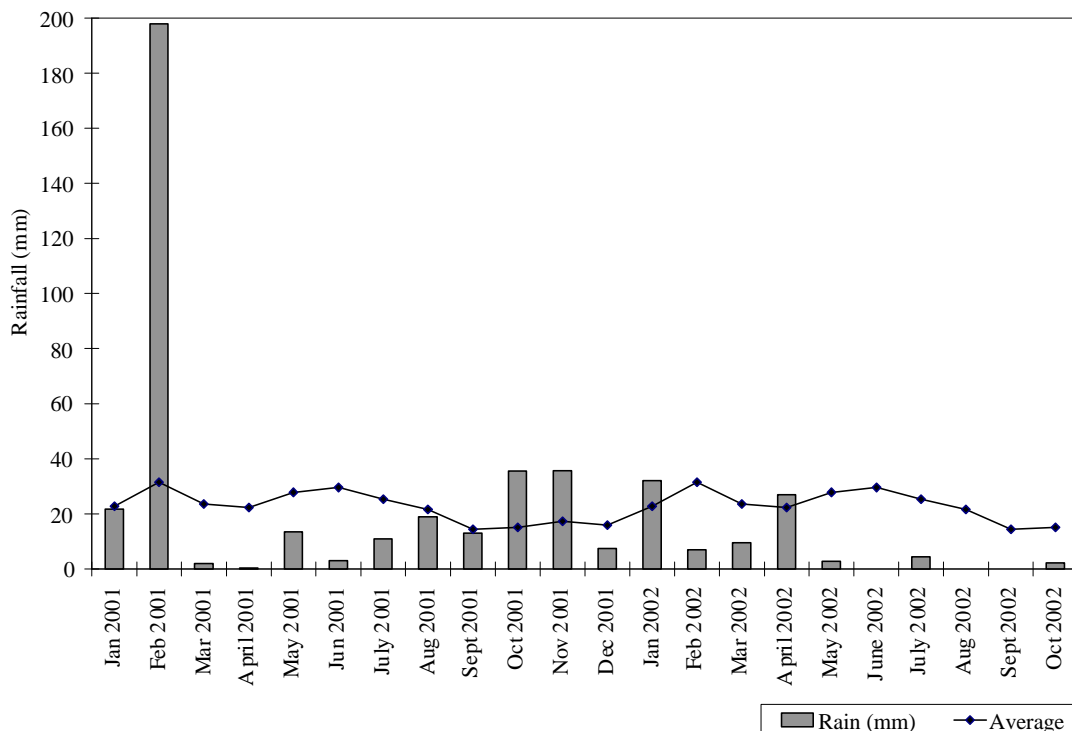
to mechanical error. A total of 84.9 mm was recorded from January 2002 to October 2002, which resulted in an average of 12.1 mm day<sup>-1</sup>. The rainfall data indicated a drier than average year for 2002 and Kalgoorlie fell within the “below average – very much below average rainfall” category for the period 1 May 2001 – 30 April 2003 (BOM 2003). Rainfall averages were downloaded from the BOM website for the Kalgoorlie-Boulder airport, as historical data for Bulong were unavailable.

During March 2001 surface water was retained in the southern sections of Lake Yindarlgooda at control sites 1-3 and the northern impact sites 4 and 5, EP1 and EP2. The Swan Refuge contained a large volume of water. Control sites 6 and 7 in the northern section of Lake Yindarlgooda remained dry. Retention time for the water was from February 2001 to June 2001. All sites then remained dry for the duration of the sampling period up to September 2002. The exceptions were sites EP1 and EP2, which retained minimal surface water from the seepage of the LRSF.

Lake Yindarlgooda had an average water depth of 5 cm within the littoral zone (20 m from the shoreline). All sites recorded depths below 10 cm, sites 3 and 4 with the greatest depths of 7 cm. Within 2 m of the margins of Swan Refuge, a depth of 29 cm was recorded and accessibility away from the edges was restricted as the sediment was too soft to traverse.

### *3.3.1.2 Temperature*

Field data collected in March 2001 for Lake Yindarlgooda and Swan Refuge are shown in Table 3.2. The average water temperature in Lake Yindarlgooda for the March 2001 sampling was 21.7 °C and reflected the ambient air temperature of 22.5 °C (Bulong weather station). Minimal variation in the water temperature was observed between sites, the highest at sites EP1 and EP2 with a 2.8 °C difference.



**Figure 3.1:** Rainfall from Bulong Operation weather station (2001–2002). Readings were not available for June, August and September 2002 due to mechanical error. Average annual rainfall obtained from the Kalgoorlie–Boulder airport data (BOM 2003).

### 3.3.1.3 Wind

The average prevailing winds in the Eastern Goldfields are from the east and south east. Summer winds are predominantly west, northwest, though winter ones are from the east, southeast (BOM 2007).

## 3.3.2 Chemical limnology

### 3.3.2.1 pH, salinity, electrical conductivity and ionic composition

The physicochemical parameters for March 2001 for Lake Yindarlgooda, Swan Refuge and Lake Penny are shown in Tables 3.2 to 3.5. Variation in the pH values between control and impact sites in Lake Yindarlgooda was observed, as with the wetland sites.

#### *Lake Yindarlgooda*

The pH recorded at the control sites 1-3 was slightly alkaline with pH values of 8.01 at Site 1 and 3 and 7.85 at Sites 2. The impact site 4, EP1 and EP2 were all slightly acidic ranging from 5.72 to 6.0, while Site 5 was alkaline (Table 3.2). Data collected



in the same month from the boreholes around the LRSF by Bulong Operations showed pH of 5.0 to 5.7, similar to the surface water values. The pH of the aquifer water was consistent with values recorded in 2000 (Table 3.5).

The surface water at all sites in Lake Yindarlgooda was considered hypersaline in March 2001 with total dissolved solids (TDS) exceeding  $50 \text{ g L}^{-1}$  (Table 3.3). These values reflected the salinity measurements taken *in situ* with the lowest salinities at the control sites 1-3 (Table 3.2; Table 3.3). The impacted sites had much higher salinities with TDS readings of 130 and  $140 \text{ g L}^{-1}$  at sites 4 and 5, respectively (Table 3.3). Site EP2, which had received decant discharge water prior to the March 2001 field trip, recorded the highest TDS value of  $180 \text{ g L}^{-1}$ . Water samples collected from three sites around Lake Yindarlgooda in 2000 are shown in Table 3.5.

The electrical conductivity (EC) of the water reflected the salinity ranges at the site, the control sites again displaying lower values than the impact sites (Table 3.2, Table 3.3). The surface water at all sites was sodium and chloride dominated, though the ionic sequence differed between control and impact sites. The sequence for the control sites 1-3 followed a cation and anion pattern of  $\text{Na} > \text{Ca} > \text{Mg} > \text{K} : \text{Cl} > \text{SO}_4 > \text{HCO}_3 > \text{CO}_3$ , while the sequence for the impact sites was  $\text{Na} > \text{Mg} > \text{Ca} > \text{K} : \text{Cl} > \text{SO}_4 > \text{HCO}_3 > \text{CO}_3$ . Surface water data collected from near the control Site 1 in previous years by Bulong Operations followed the same sequence as the impact sites (Table 3.5). Differences in the pattern of the cations appear related to changes in the salinity.

#### *Wetlands: Swan Refuge and Lake Penny*

The pH of the adjacent wetlands was alkaline with a pH of 9.15 in Swan Refuge, measured *in situ*, while Lake Penny the pH was 7.6, measured in the laboratory.

The salinity levels in Swan Refuge were lower than that of Lake Yindarlgooda at  $14.7 \text{ g L}^{-1}$  (measured *in situ*) and a TDS of  $14 \text{ g L}^{-1}$ , considered hyposaline. The TDS measured in Lake Penny was similar to sites 1-3 in Lake Yindarlgooda at  $84 \text{ g L}^{-1}$ , indicating at collection this was a hypersaline lake. Previous TDS values measured from Lake Penny in 2000 recorded was less at  $9.2 \text{ g L}^{-1}$ . The EC measured in Swan Refuge was lower than those of Lake Yindarlgooda at  $21.8 \text{ mS cm}^{-1}$ . The ionic sequence for both the wetlands was as follows:  $\text{Na} > \text{Mg} > \text{Ca} > \text{K} : \text{Cl} > \text{SO}_4 > \text{HCO}_3 > \text{CO}_3$ .

### 3.3.2.2 Nutrients and chlorophyll

#### *Lake Yindarlgooda*

Nutrient levels in the control sites were generally low for Lake Yindarlgooda (Table 3.4). Nitrite-nitrate levels recorded from the control sites were consistent within the southern sites, 1–3, with values below  $0.0005 \text{ mg L}^{-1}$  recorded. The nitrogen levels, as total Kjeldahl nitrogen (TKN), ranged from  $0.81$  to  $1.2 \text{ mg L}^{-1}$  at these sites. The concentrations of TKN at the impact sites were higher, ranging from  $360 \text{ mg L}^{-1}$ , at Site 5, to  $3\,800 \text{ mg L}^{-1}$  at EP2 for the March 2001 samples.

The orthophosphate levels in the lake were low at the control sites and the impact sites 4 and 5. The levels at EP1 and EP2 were at least three times that of the others sites in Lake Yindarlgooda. In contrast, total phosphorous levels were the highest at the control sites 2 and 3.

In terms of productivity, the chlorophyll *a* (Chl *a*) and *c* levels were generally low at all sites (Table 3.4). The highest readings of chlorophyll *a* and *c* were recorded at site EP1, while EP2 had the lowest levels.

#### *Wetlands: Lake Penny and Swan Refuge*

The TKN concentrations in Swan Refuge were similar to those of the control sites at  $0.73 \text{ mg L}^{-1}$ , while Lake Penny had slightly higher levels though well below those of the impact sites (Table 3.4). Swan Refuge and Lake Penny had low total phosphorus concentrations, similar to the Lake Yindarlgooda control sites. The orthophosphate levels in Lake Penny,  $0.022 \text{ mg L}^{-1}$ , were slightly higher than Swan Refuge and similar to that of the impact sites EP1 and EP2. Both Swan Refuge and Lake Penny had low levels of chlorophyll *a* and *c*.

**Table 3.2:** Physicochemical parameters taken *in situ* during March 2001 from the Lake Yindarlgooda sampling sites. DOW = Depth of Surface Water. EC = electrical conductivity ( $\text{mS cm}^{-1}$ ) Salinity in  $\text{g L}^{-1}$ .

Sites	Time	pH	EC	Salinity	Temperature ( $^{\circ}\text{C}$ )	DOW (cm)
Site 1	8.30	8.01	73.9	54.7	17.8	4
Site 2	10.30	7.85	96.3	73.6	21.2	2
Site 3	11.50	8.01	89.1	67.4	26	7
Site 4	9.00	5.72	159.4	134.4	19.3	7
Site 5	10.25	8.23	150	125.7	26	5
Site EP1	17.00	6.19	149.5	125.3	22.2	4
Site EP2	17.30	6.01	163.9	140	19.4	NA
Swan Refuge	13.30	9.15	21.8	14.7	23.6	29

**Table 3.3:** Laboratory physicochemical measurements for March 2001. Lake Penny samples were taken two weeks later. TDS = total dissolved solids. EC = electrical conductivity ( $\text{mS cm}^{-1}$ ). Units in  $\text{mg L}^{-1}$ .

Sites	pH	EC	TDS	Na	Mg	Ca	K	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	CO <sub>3</sub>
Site 1	6.9	95	57 000	19 000	1 300	1 800	88	29 000	5 300	70	<1
Site 2	7.3	130	78 000	26 000	2 200	2 200	96	45 000	6 800	120	<1
Site 3	7.3	120	72 000	26 000	1 600	2 100	96	39 000	6 300	80	<1
Site 4	5.4	210	130 000	56 000	5 900	870	200	89 000	20 000	5	<1
Site 5	5.4	230	140 000	52 000	6 600	1 200	230	85 000	17 000	5	<1
Site EP1	4.6	222	130 000	50 000	6 100	980	180	76 000	16 000	<5	<1
Site EP2	5.7	300	180 000	57 000	14 000	430	210	91 000	54 000	45	<1
Swan Refuge	8.9	22	14 000	4 400	500	220	13	7 100	830	70	26
Lake Penny	7.6	138	84 000	26 000	2 600	2 100	120	44 000	7 700	150	<1

**Table 3.4:** Nutrients recorded from water samples taken in March 2001. Lake Penny sampled two weeks later. NA = measurements were not recorded. Units in mg L<sup>-1</sup>.

Sites	NH <sub>3</sub> -N	NO <sub>2</sub> -N	NO <sub>3</sub> -N	NO <sub>3</sub>	TKN	PO <sub>4</sub> <sup>-3</sup>	TP	TC	TOC	SiO <sub>2</sub>	Chl <i>a</i>	Chl <i>c</i>
Site 1	0.013	<0.005	<0.005	<0.2	0.81	0.009	0.03	19	8.2	3	0.0015	0.0009
Site 2	<0.005	<0.005	<0.005	<0.2	1.2	0.007	0.09	26	7.9	2.6	0.0019	<0.0010
Site3	0.005	<0.005	<0.005	<0.2	0.84	0.006	0.06	17	5.1	2.2	<0.0010	<0.0010
Site 4	NA	0.1	0.02	0.5	650	<0.003	0.01	12	11	8	0.0043	<0.0005
Site 5	NA	1.4	0.04	5.9	360	0.005	<0.01	11	11	8.3	0.019	0.0081
Site EP1	NA	4.1	0.17	18	520	0.027	<0.05	14	13	11	0.021	0.013
Site EP2	NA	1.3	0.06	6.4	3800	0.029	<0.05	20	19	54	<0.0005	<0.0005
Swan Refuge	0.019	<0.005	<0.005	<0.2	0.73	0.01	0.04	27	8.5	2	0.0007	<0.0005
Lake Penny	NA	0.009	NA	<0.2	2.3	0.022	0.09	44	22	1.4	0.0097	0.0011

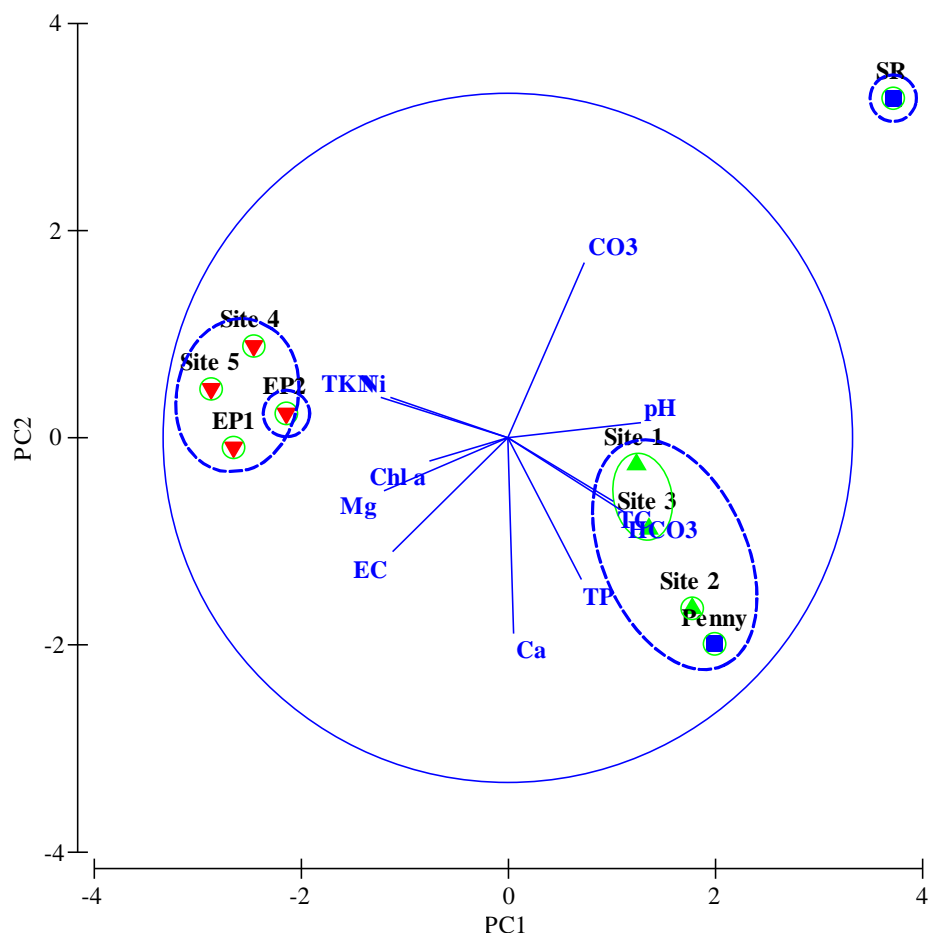
**Table 3.5:** Surface water (SW) for Lake Yindarlgooda and Lake Penny, and borehole (BH) data for Lake Yindarlgooda. Rocky Dam located in the northern section of the lake, Grunts Dam and Goddards Dam in the southern section. Goddards Dam is approximately at site1. BH1 and BH2 located at the LRSF on Lake Yindarlgooda. Samples collected on the 23/6/2000. Lake Penny surface water samples collected on the 28/4/2000. Data collected by Bulong Nickel. EC measured in mS cm<sup>-1</sup>, pH in pH units, all other parameters in mg L<sup>-1</sup>.

Parameter	Lake Yindarlgooda (SW)			Lake Penny (SW)	Lake Yindarlgooda (BH)	
	Rocky Dam	Grunts Dam	Goddards Dam		BH1	BH2
pH	7.9	7.9	7.9	9	5.6	5.8
EC	420	370	270	17	550	460
TDS	240 000	200 000	140 000	9 200	340 000	270 000
Salinity	220 000	190 000	140 000	8 000	290 000	240 000
Na	69 000	61 000	45 000	2 200	95 000	75 000
K	170	250	210	12	310	270
Ca	1 300	1 500	2 200	350	430	490
Mg	7 800	5 500	3 400	220	12 000	12 000
Cl	140 000	120 000	78 000	4 200	180 000	140 000
OH	< 10	< 10	< 10	< 10	< 10	< 10
CO <sub>3</sub>	< 10	< 10	< 10	10	< 10	< 10
HCO <sub>3</sub>	160	110	150	30	< 10	< 10
SO <sub>4</sub>	7 900	6 500	3 600	970	19 000	30 000
NO <sub>3</sub>	0.17	0.04	0.02	< 0.01	0.03	0.03
NH <sub>3</sub> -N	1.7	4.3	0.3	< 0.2	200	230

### 3.3.2.3 Comparison of sites

The relationships between the sites and environmental parameters were explored using the PCA ordination (Figure 3.2). 79.1% of the total variation between the sites in terms of the water chemistry was explained on the first two principal component axes, PC1 with 57.1% and PC2 with 22.0%. The impacts sites were grouped based on nitrogen (TKN) and Ni concentrations, EP2 being the most influenced by these factors. The control sites were grouped away from the impact sites based on total carbon (TC), total phosphorous (TP) and pH. Generally, the impacts sites showed a stronger association, or correlation, with salinity in the form of conductivity (EC) and TDS. Because of collinearity between these two parameters TDS was removed from the ordination plot.

Lake Penny had a salinity level similar to Site 2, the two grouped close together on the ordination plot. In contrast, Swan Refuge showed a strong inverse relationship with salinity, and was affected primarily by  $\text{CO}_3$ . The change in the cationic sequence in the control site with the Ca concentrations greater than Mg at the three control sites was apparent in the ordination. Many of the anions and cations were collinear with salinity and Mg, while the nitrates, reactive silica, and chlorophyll *c* were all collinear with TKN and Chlorophyll *a* and were not shown on the plot. The ordination displays a separation between the impact and control sites.



**Figure 3.2:** 2-dimensional correlation-based PCA ordination of physicochemical parameters, data  $\log(x + 1)$  transformed, and sample sites, March 2001. Collinear variables were removed from the graph. PC1 (x-axis) and PC2 (y-axis) together account for 79.1% of the total variability. Group-average clustering from Euclidean distances superimposed on the PCA ordination. SR = Swan Refuge; Penny = Lake Penny. TP = total phosphorus, EC = electrical conductivity, TC = total carbon, TKN = total Kjeldahl nitrogen. ■ = Wetland sites, ▲ = Control sites, ▼ = Impact sites.

### 3.3.3 Sediment composition

#### 3.3.3.1 Salinity (total soluble salts)

##### *Lake Yindarlgooda*

Variation of the total soluble salts (TSS) from September 2001 to September 2002 between the control sites 3, 6 and 7, was minimal, Site 1 displaying an increase in 2002 and Site 2 a decrease (Figure 3.3). The lowest salinity levels were recorded at sites 6 and 7 for both September 2001 and 2002 and showed little variation between the sampling periods. Salinity levels at impact sites 4 and EP2 increased from

September 2001 to September 2002. Site EP1 and site 5 recorded a decrease in sediment salinity in May 2002. Site 5 in September 2002, returned to salinity levels similar to those of 2001. Site EP1, however, doubled in September 2002 compared to September 2001. Comparison of the sites showed that generally the control sites had lower sediment salinity than the impact sites, in particular sites 6 and 7. Site 4 was adjacent to EP2 and variation during all sampling periods was minimal.

*Wetlands: Lake Penny and Swan Refuge*

Swan Refuge and Lake Penny both showed an increase in salinity during the sampling periods. Lake Penny had higher levels than the impact sites for both sampling periods, as did Swan Refuge for September 2002.

*3.3.3.2 Total organic carbon*

*Lake Yindarlgooda*

The control sites 1, 2, and 3 all displayed an increase in total organic carbon (TOC) in the sediment from March to September 2001 (Figure 3.4). Sites 6 and 7 were sampled for the first time in September 2001 and recorded levels similar to the southern control sites. In September 2002, the TOC levels at sites 2, 6 and 7 were lower than the previous sampling, while Site 3 had doubled. With the exception of Site 5 and EP2, the TOC levels were similar between sites, the majority below 0.2%w/w of total organic carbon. No trends at the sites from one sampling period to the next were observed.

*Wetlands: Lake Penny and Swan Refuge*

The pattern in the adjacent wetlands was similar to that observed in Lake Yindarlgooda. TOC levels had dropped in September 2001 but then increased in September 2002. Lake Penny was a particularly productive site with TOC readings nearly five times that of the control sites at Lake Yindarlgooda. The TOC levels at Swan Refuge were similar to those of the impact sites and much lower than Lake Penny.

*3.3.3.3 Heavy metals: Nickel and arsenic*

*Lake Yindarlgooda*

The levels of nickel (Ni) in the surface sediment at the control sites, 1-3 and 6-7, were low, all below 200 mg kg<sup>-1</sup>, with minimal variation (Figure 3.5; Table 3.6). The impact sites had higher Ni readings than the control sites, in particular site EP2

in March 2001. Site 4 remained consistent with minimal fluctuation between sampling periods compared to the other sites. The Ni levels at EP2 stabilised after March 2001, while sites EP1 and 5 showed similar fluctuations between sampling periods. Analyses of the surface sediment from Lake Yindarlgooda in 2000 showed the Ni levels in the sediment to be higher in the southern sites than that recorded in this study (Table 3.7).

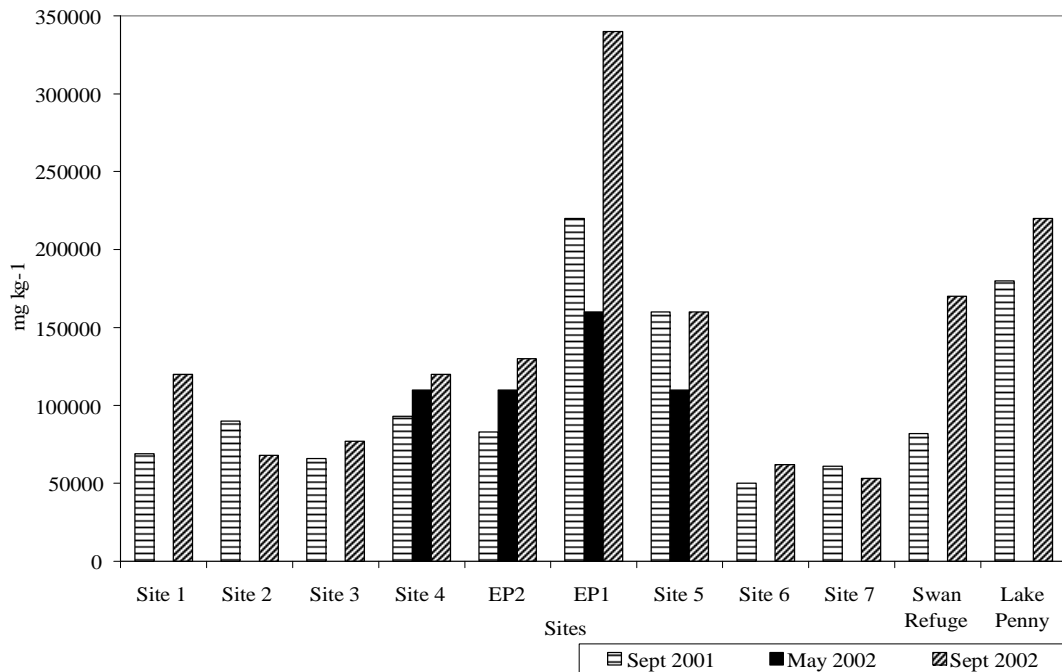
The arsenic (As) levels in the sediment varied between sites and the sampling periods, though no recognisable pattern was identified (Figure 3.6; Table 3.6). The highest levels of As in March 2001 was recorded at site EP1, followed by Site 4 and then Site 1. The As levels at Site 1 exceeded those of sites EP2 and 5. The control sites 1-3 showed increased levels of As in September 2002. The As levels in the sediment were higher in the northern control sites, 6 and 7, than any of the impact sites. Fluctuations of sediment As levels at the impact sites displayed no specific pattern (Figure 3.6). Of the impact sites, EP1 recorded the highest As levels, indicating the influence of the LRSF. Historical sampling showed that background levels of As in the sediment were naturally high in Lake Yindarlgooda (Table 3.7).

Two groundwater samples taken by Bulong Nickel in March 2001 showed that Ni levels were at 23 and 62 mg L<sup>-1</sup>, while As was below detection. These Ni levels were slightly higher than those recorded in the surface water at the sites 4, 5 and EP1, though below those of EP2 (Table 3.6).

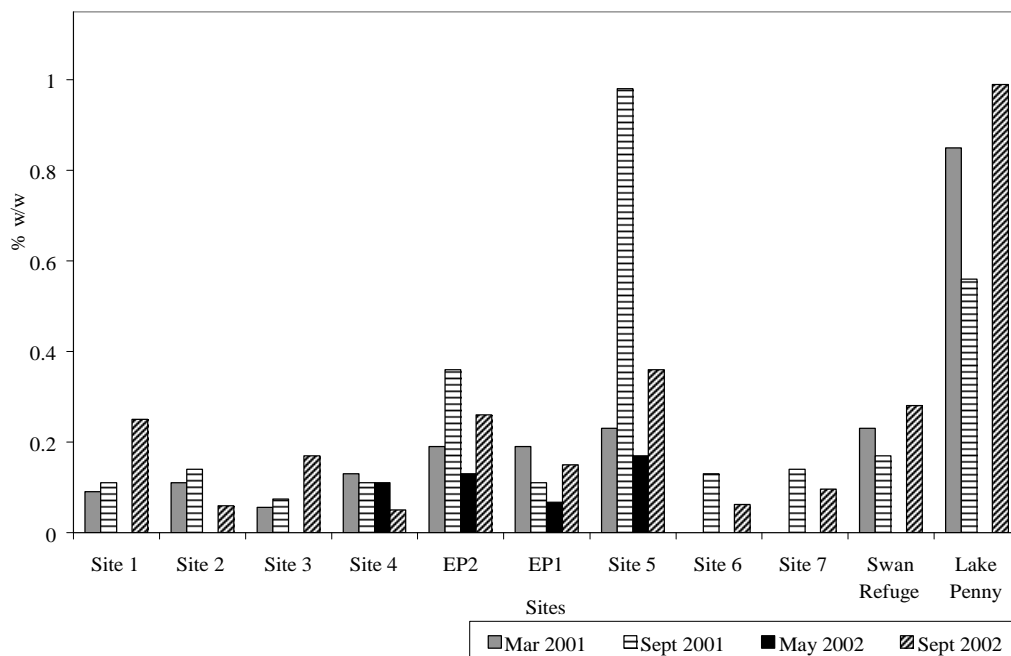
*Wetlands: Lake Penny and Swan Refuge*

The nickel levels in the wetlands were low and similar to those of the control sites 1-3. The arsenic levels in the sediment were higher than the impact sites and similar to the northern control sites 6 and 7.

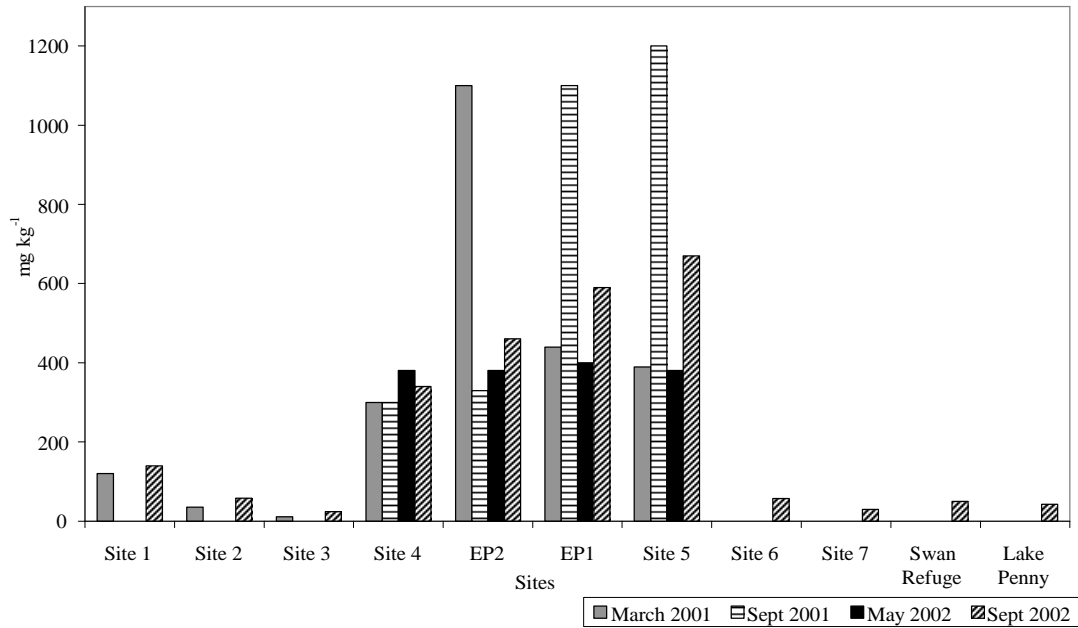




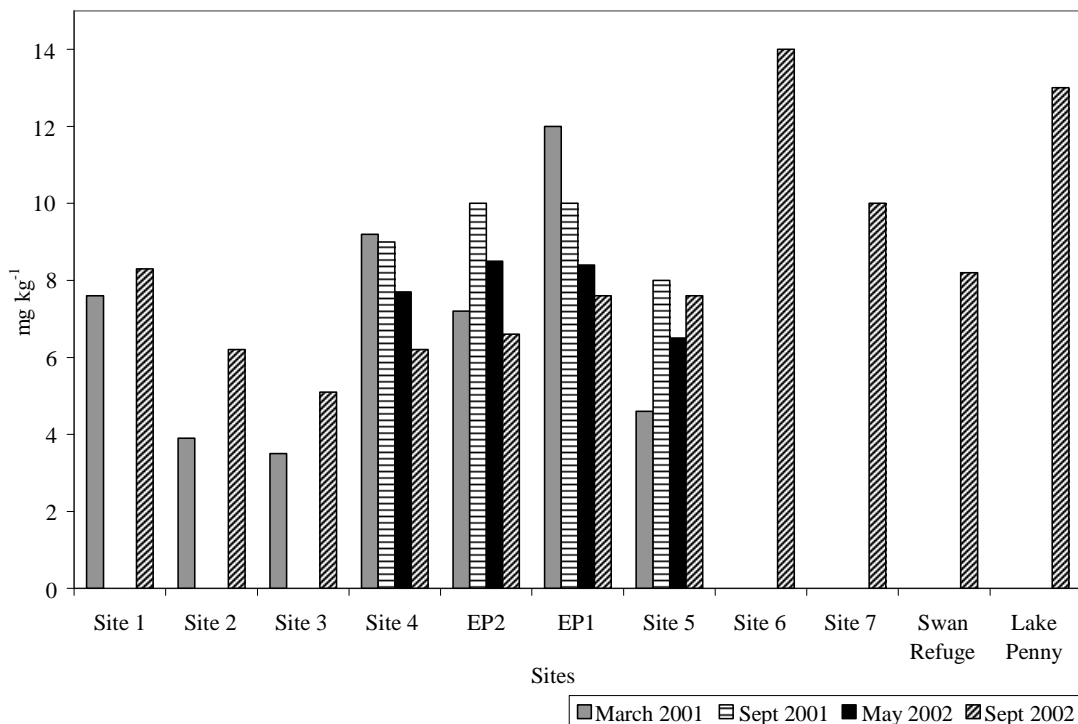
**Figure 3.3:** Total soluble salts in the surface sediments at all sites (Sept 2001 - Sept 2002). Only the impact sites 4, 5, EP1 and EP2 were sampled in May 2002. Sites EP2 and EP1 are placed in between sites 4 and 5 according to location in Lake Yindarlgooda. Sites 6 and 7 are located in the far northeastern arm of the lake.



**Figure 3.4:** Total organic carbon (TOC) in the surface sediment at all sites for the four sampling surveys (2001 -2002). Only the impact sites 4, 5, EP1 and EP2, were sampled in May 2002. Sites 6 and 7 were not sampled in March 2001. Sites EP1 and EP2 are positioned on the x-axis according to their location in Lake Yindarlgooda.



**Figure 3.5:** Nickel (Ni) levels recorded from sediment samples 2001 - 2002. (Only impact sites were sampled during all field trips). Sites 6 - 7, Swan Refuge and Lake Penny were not tested for Ni in March 2001.



**Figure 3.6:** Arsenic (As) levels recorded from sediment samples 2001 - 2002. (Only impact sites were sampled during all four field trips). Sites 6 - 7, Swan Refuge and Lake Penny were not tested for As in March 2001.

**Table 3.6:** Comparison of arsenic (As), and nickel (Ni) levels in the surface water and sediment from Lake Yindarlgooda, Swan Refuge and Lake Penny, March 2001.

Sites	Surface water (mg L <sup>-1</sup> )		Sediment (mg kg <sup>-1</sup> )	
	As	Ni	As	Ni
Site 1	<0.005	<0.5	7.6	120
Site 2	<0.005	<0.5	3.9	36
Site 3	<0.005	<0.5	3.5	11
Site 4	<0.005	26	9.2	300
Site 5	<0.005	18	4.6	390
EP1	<0.005	10	12	440
EP2	<0.005	210	7.2	1100
Swan Refuge	<0.005	<0.05	NA	NA
Lake Penny	NA	NA	NA	NA

**Table 3.7:** Sediment pH, TDS, TSS, and metals recorded from Lake Yindarlgooda southern sites (Grunts and Goddards Dam) and northern sites. Samples collected in 23/6/2000 by Bulong Nickel. All parameters in mg kg<sup>-1</sup>, pH in pH units.

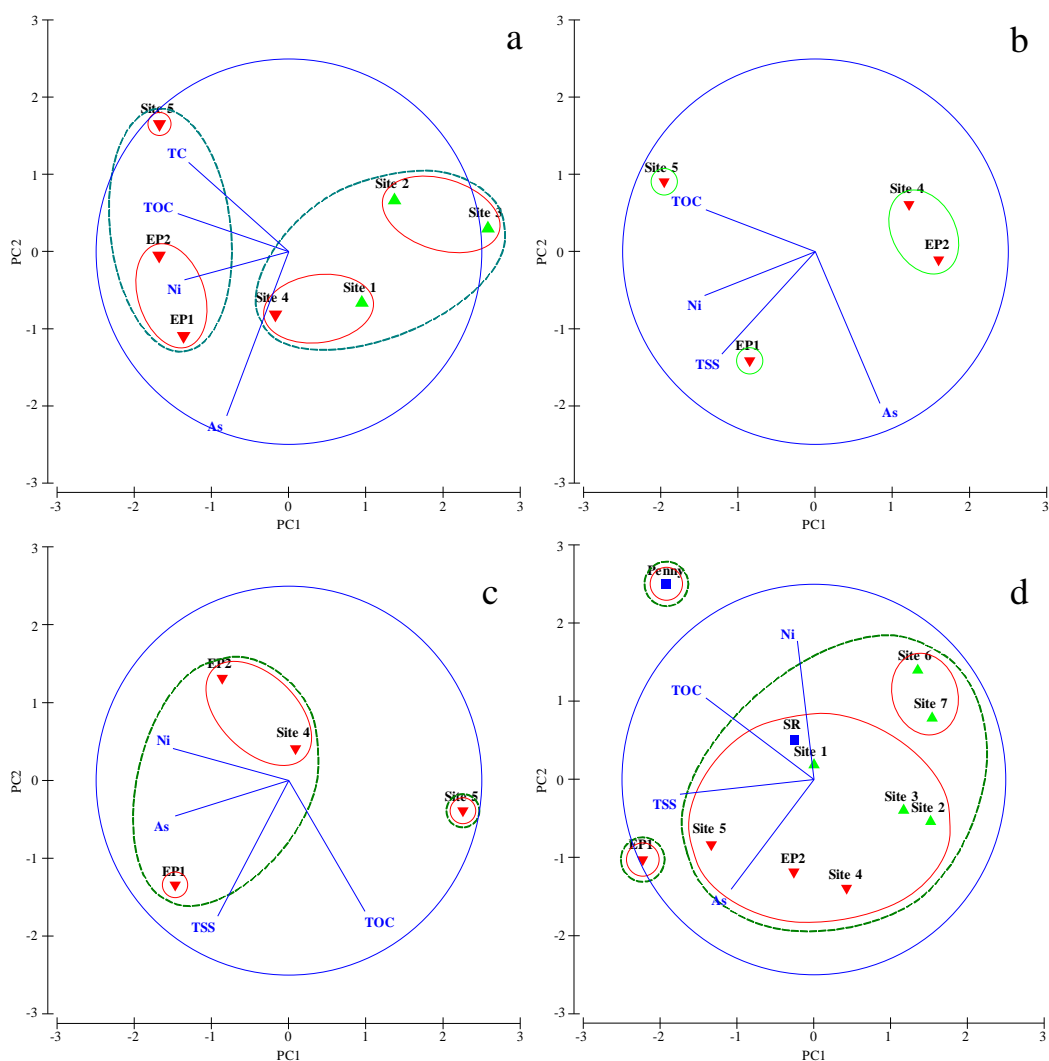
Parameter	Lake Yindarlgooda		
	Rocky Dam	Grunts Dam	Goddards Dam
pH	8.1	8.2	8
TDS	53 000	38 000	21 000
TSS	110 000	66 000	24 000
As	17	16	17
Cd	0.2	< 0.1	< 0.1
Cr	110	580	1500
Cu	30	24	20
Pb	3	2	9
Ni	88	890	220
Zn	96	48	32
Hg	< 0.02	< 0.02	< 0.02
Se	< 2	< 2	< 2

#### 3.3.3.4 Comparison of sites

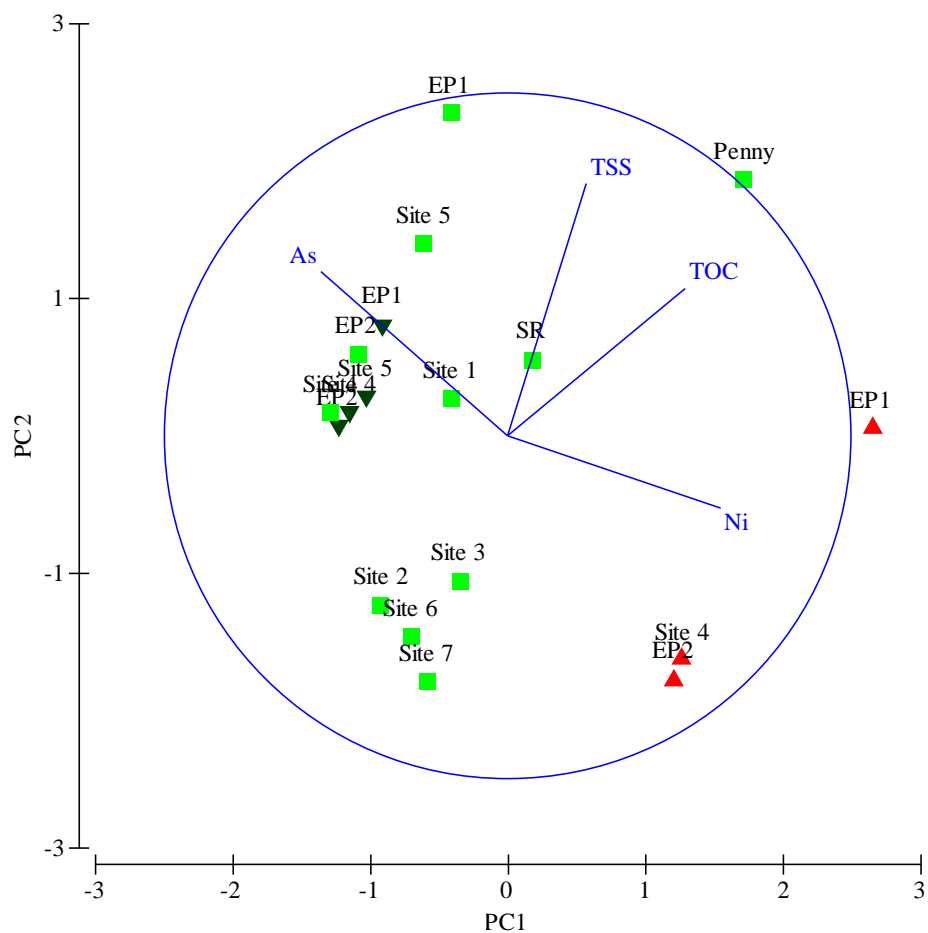
A strong association between the impact sites, and Ni and TOC, was observed in the March 2001 sediment samples with 93.6% of the variation explained on the first two axes (PC1 = 70.5%, PC2 = 23.1%), (Figure 3.7a). The impact sites showed stronger

associations with Ni, in particular sites EP2 and EP1. In the September 2001 samples, a strong association between EP1 and sediment salinity (TSS) was observed. Site 5 was strongly influenced by TOC (Figure 3.7b). Sites 4 and EP2 did not appear to be as greatly influenced by the sediment TSS and Ni as EP1. 98.1% of the variation was explained on the first two axes (PC1 = 71.4%, PC2 = 26.7%), indicating a strong association of the sites with the parameters. The impact sites, EP2 and EP1, were strongly influenced by Ni, As and TSS in May (Figure 3.7c), indicating the continued influence from the LRSF.

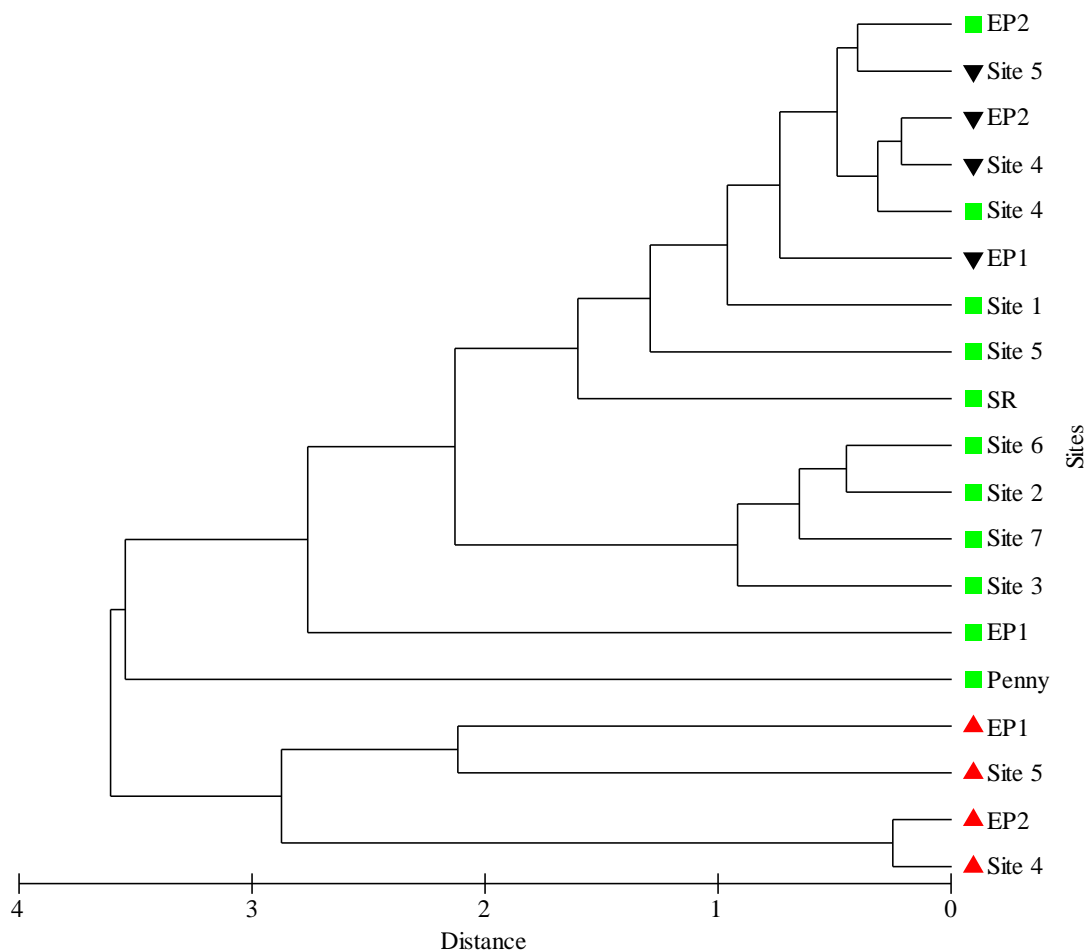
A distinction between sites was observed in September 2002 sediment according to the salinity levels (Figure 3.7d). The differences between sampling periods May 2002 and September 2002 was not observed on the ordination, though there was a separation between September 2001 and the 2002 samples (Figure 3.8). 85.2% of the variation was explain by the first two axes with PC1 accounting for 48.1%. A group-average clustering of the PCA confirmed the September 2001 were more closely related than the 2002 samples. The impact sites in May 2002 showed similarities to impact sites 4 and EP2 in September 2002 as a result of the As levels, while the salinity placed EP1 (September 2002) with the control sites (Figure 3.9).



**Figure 3.7:** 2-dimensional correlation-based PCA ordination of sediment parameters and sample sites for Lake Yindarlgooda and the wetlands, Swan Refuge and Lake Penny (2001-2002). Data was square root transformed, prior to normalisation. Group-average clustering from Euclidean distances superimposed on the PCA ordination. **(a)** March 2001 sediment, all sites sampled. **(b)** September 2001, only impact sites analysed for the four parameters. **(c)** May 2002, only impact sites sampled. **(d)** September 2002, all sites sampled. TC = total carbon, TOC = total organic carbon, TSS = total soluble salts, Ni = nickel, As = arsenic. ■ = Wetland sites, ▲ = Control sites, ▼ = Impact sites. SR= Swan Refuge, Penny = Lake Penny.



**Figure 3.8:** 2-dimensional correlation-based PCA ordination of sediment parameters and sample sites for Lake Yindarlgooda and the wetlands, Swan Refuge and Lake Penny for the three sampling periods September 2001, May 2002 and September 2002. Data coded according to sampling period. Data was  $\log(x+1)$  transformed. 87.2% of the variation shown on the first two axes (PC1 = 50.5%, PC2 = 36.7%).  $\blacktriangle$  = September 2001,  $\blacktriangledown$  = May 2002,  $\blacksquare$  = September 2002. SR = Swan Refuge, Penny = Lake Penny.



**Figure 3.9:** Group-averaged clustering from Euclidean distances for sediment parameters and sampling sites for September 2001, May 2002 and September 2002, as shown in PCA ordination. Data was  $\log(x+1)$  transformed.  $\blacktriangle$  = September 2001,  $\blacktriangledown$  = May 2002,  $\blacksquare$  = September 2002.

### 3.4 Discussion

The physicochemical limnology of Lake Yindarlgooda is typical of many of the large Western Australian inland salt lakes. It is a large, temporary playa with an average background salinity, for March 2001, of  $82 \text{ g L}^{-1}$ , classifying it as hypersaline (*sensu* Hammer 1986). Information from mining company reports suggest that during the normal wet cycle during the winter months, surface water on Lake Yindarlgooda is extensive and persists through to August (Turner 1999). Depths of up to 30 cm and an average surface salinity of  $38 \text{ g L}^{-1}$  have been recorded (Kinhill 1996). In March 2001, the lake only partially filled to no greater than 10 cm. During this time, Western Australian experienced a less than average rainfall (BOM 2003) and

subsequently only one wet sample set could be collected and the true limnological features may not have been observed.

Playas such as Lake Yindarlgooda have developed in regional groundwater discharge zones. They typically have waters that are saline to hypersaline (Arakel *et al.* 1990; Salama *et al.* 1999), influenced by the groundwater and the catchment flow, as well as climatic conditions (Hingston and Gailitis 1976; Bowler 1981). During March 2001, Lake Yindarlgooda displayed a NaCl dominance characteristic of inland salt lakes in Western Australia (Geddes *et al.* 1981; Handley 2003; Boggs *et al.* 2007). The normal ionic sequence for Lake Yindarlgooda, according to historical data, is similar to other inland waters with Mg>Ca for the cations. A deviation from this was observed in the surface water from the control sites with a cationic sequence of Na>Ca>Mg>K. While changes in the ionic pattern have been recorded from numerous inland waters (Williams and Buckney 1976) this sequence has mostly been observed in freshwater dams (Hart and McKelvie 1986) or in hyposaline Tasmanian salt lakes (De Deckker and Williams 1982). A similar pattern was recorded in samples from Lake Miranda in the Northern Goldfields at salinities of 25 g L<sup>-1</sup> (Finucane 2001; John 2003). Water samples were collected two weeks after heavy rains had ceased. The “first flush” may result in the release of Ca from the surrounding gypsum (CaSO<sub>4</sub>) dunes altering the ionic composition in the water (Smith 2003). Geochemical influence has been attributed to a similar deviation in many lakes (Hart and McKelvie 1986) with Lake Buchanan an example where Ca ≈ Mg (Chivas *et al.* 1986). Both the surrounding wetlands, Lake Penny and Swan Refuge, displayed similar ionic patterns to that of the impacts site in Lake Yindarlgooda, even at lower salinities.

The control and impact sites in Lake Yindarlgooda were differentiated by their salinity levels, as EC, TDS in the water and TSS in the sediment, the amount of nickel in the sediment, and the levels of total nitrogen in the surface water. The TDS and pH levels recorded at the impact sites reflected those of the groundwater and therefore the decant discharge water stored in the LRSF. This confirmed that the LRSF was directly influencing the physicochemical properties of the water and sediment in the vicinity of the facility. Of the factors impacting the lake, salinity was considered to be the greatest overall as seen in the PCA of the data. This was also clearly visible during subsequent field trips with the presence of a thick surficial salt



crust at the sites directly in front of the LRSF. The sites away from the LRSF all had light halite crusts and considered to be the natural condition for Lake Yindarlgooda. This thick crust that formed was typical of that found in tailing dams in Western Australia and shown to reduce the evaporation rate of the hypersaline water (Newson and Fahey 2003). This explains the layer of water at the impact sites EP1 and EP2 throughout the study.

The areas on which these salt lakes occur, the Archean greenstone belt, is generally nitrogen limited (Kinhill 1996; Smith *et al.* 2004). The transport of allochthonous material to salt lakes is low (Reuter *et al.* 1993) resulting in a deficiency in nutrients such as nitrogen, as was observed at the control sites in Lake Yindarlgooda. Globally, saline lakes have low nitrogen concentrations, the exceptions due to high productivity such as a large phytoplankton population (Hammer 1986; Oren 2002) or as a result of increased loading from anthropogenic sources (Reuter *et al.* 1993). The nitrogen (TKN) levels around the LRSF were several thousand times that of the control sites and indicated that this was not a result of allochthonous input after heavy rains. Groundwater data collected in 2000 from Lake Yindarlgooda confirmed that the high nitrogen was from the LRSF.

Terrestrial carbon inputs to aquatic systems in the arid zones are lower than in more temperate areas (Davis *et al.* 1993; Bunn *et al.* 2003), and nutrient deficiency typical (Stafford Smith and Morton 1990). The low organic carbon levels in Lake Yindarlgooda compared to those of Swan Refuge and Lake Penny were considered a reflection of both habitat type and the source of carbon. Dense macrophyte meadows were not observed in Lake Yindarlgooda compared to the two wetlands (Chapter 2.0) which was reflected in the organic carbon levels measured. Another inland salt lake, Lake Miranda, also had large numbers of *Lamprothamnium* (Charophyte) with corresponding high organic carbon levels (John 2003). All three were smaller than Lake Yindarlgooda. Smaller salt lakes accumulate higher allochthonous organic material than larger playas (Hammer 1986).

The Salinaland of Western Australia is also an area rich in mineral deposits. The salt lakes in this area act as a sink to the mineral deposits that occur naturally in this setting (Lyons *et al.* 1990) and the groundwater in the palaeochannels receiving a chemical imprint from the geology they flow through (Mann 1982; Morgan 1993). Background metal concentrations in remote areas have been found to vary, in both

the soil and groundwater, according to their underlying geology (ICME 1996). Because of their geological setting, the background levels adopted as reference sites often exceed the Australian and New Zealand Environment and Conservation Council (ANZECC) guidelines for marine water and sediment quality (Finucane 2001) posing a problem for regulating impacts (Batley *et al.* 2003). These guidelines are used for monitoring the quality of water and sediment for the protection of aquatic ecosystems. While they are a useful reference point, these guidelines are based on marine and freshwater systems; they are often not indicative of the processes in inland salt lakes and the use of site-specific studies is recommended (Batley *et al.* 2003; Smith *et al.* 2004). The Ni levels in the sediment at the control sites of Lake Yindarlgooda exceeded the ANZECC guidelines (ANZECC 2000) as did the levels in the wetland sites. Lake Yindarlgooda has rich deposits of Ni and the higher background readings are not surprising. However, the Ni levels in the sediment from the impact sites might not be a reflection of the geology. Instead, they may have originated from the discharge water from the LRSF with levels in excess of  $1000 \text{ mg kg}^{-1}$ , ten times that of the control sites. Inland salt lakes are closed systems with internal drainage. Unlike exorheic systems such as rivers that drain to the ocean, the increase in salt load accompanied by the associated heavy metals is retained in lakes, such as Yindarlgooda, and the effects on the biota are yet to be fully understood.

### **Conclusions**

Opportunistic, or “one-off” sampling is never ideal, particularly for aquatic systems (Timms 1998). Because of climatic conditions, rainfall for the Goldfields region was below average and wet samples could only be collected once for this study, limiting the range of limnological conditions.

From this study an understanding of the physicochemical limnological characteristics of the lake was still possible and differences between control and impact sites were easily distinguished. The main factors that separated control from the impact sites in the lake were salinity, nickel and nitrogen. Lake Yindarlgooda was found to be naturally a hypersaline lake, though when precipitation is higher the lake may be mesosaline, hypersalinity occurring mostly during drawdown. The lake is limited in organic nutrients such as carbon and nitrogen. The background levels of nickel were high, though the amounts detected in the sediment around the LRSF were clearly

anthropogenically derived. Of the two wetlands, Swan Refuge was found to be hyposaline and Lake Penny, hypersaline.

The impact sites could be easily distinguished from the control site according to their elevated salinity in water and sediment, as well as high nitrogen levels and excessive nickel concentrations. With this information the effects of salinity, being the major factor, on the dominant biota can be investigated further. Previous to this study, limnological information on Lake Yindarlgooda was unavailable.

## **Chapter 4.0. Baseline study of Lake Yindarlgooda, Swan Refuge and Lake Penny: the aquatic biota**

### **Abstract**

Different biotic communities with low taxonomic diversity were recorded in Lake Yindarlgooda and Swan Refuge, characteristic of temporary inland waters. Hatching and germination trials on sediment from Lake Penny yielded only large numbers of *Lamprothamnium* sp. (Charophyceae). Extensive benthic microbial mats, characteristic of some hypersaline salt lakes, were not observed in Lake Yindarlgooda or the wetlands. Instead, the microbial communities consisted of a thin film of halotolerant diatoms on the surface sediment, or as epiphytes in Swan Refuge. The presence of a well established “seed” bank in both Lake Yindarlgooda and Lake Penny was evident with high numbers of *Lamprothamnium* oospores and the seeds of *Ruppia* (Potamogetonaceae) in the sediment.

Crustaceans were the dominant invertebrate fauna in Lake Yindarlgooda and Swan Refuge. Differences in the invertebrate assemblages were identified between control and impact sites in Lake Yindarlgooda and Swan Refuge. Swan Refuge recorded a higher proportion of hyposaline species, while in Lake Yindarlgooda, the Ostracoda dominated the southern control sites, while *Parartemia* dominated the impact sites.

Large numbers of waterbirds were recorded in Swan Refuge and the floodplains of Lake Yindarlgooda in March 2001. The different habitats provided by Lake Yindarlgooda and Swan Refuge resulted in the presence of a variety of waterbird functional groups.

### **4.1 Introduction**

No published information on the biotic communities of Lake Yindarlgooda or any of the surrounding wetlands was available with the exception of a few vegetation surveys of the Bulong Nickel Laterite Project as part of their compliance conditions. With the onset of a hydroperiod in February 2001, a baseline survey was conducted to investigate the limnological characteristics of the lake. An ecosystem is made up of abiotic and biotic components. In order to assess any impacts to that system, both components and how they interact must be understood. This chapter is the second of

the baseline studies on Lake Yindarlgooda and the two wetlands and identifies the biotic components, for the first time.

The importance of the benthic microbial communities (BMCs) in salt lakes was emphasised by Bauld (1981; 1986) as true phytoplankton are often absent. The microbial communities may be dominated by filamentous cyanobacteria (John 1999; Burke and Knott 1989), or by eukaryotic algae, such as diatoms (Bauld 1981). Much of the productivity in the salt lakes is restricted to these mats which may be considered as sinks with relatively high nutrient concentrations in comparison to the overlying water (Bauld 1986).

The diversity of submerged macrophytes, or halophytes, are limited in salt lakes, their restriction regulated more by the fluctuations in environmental parameters associated with a transient water regime than by salinity (Brock 1986; Boulton and Brock 1999). Generally only one or two species of halophytes are found in saline waters such as *Ruppia*, a seagrass, and the stonewort, *Lamprothamnium* (Porter 2007). Their ability to withstand periods of desiccation and fluctuating water levels is essential to their survival. They regenerate from propagules contained within the sediment referred to as “seed banks”. For these wetlands, the presence and viability of these seed banks is vital for their resilience (Brock 1998; Brock *et al.* 2003; Capon and Brock 2006).

Aquatic invertebrates can survive the drying phase of a wetland by dispersing as adults or by producing desiccation resistant stages that enable them to maintain long-term dormancy (Caceres 1997). Much of the biota in temporary systems remains buried in the sediment and the various groups often having different environmental requirements for emergence. It is only after exceptional rainfall events when the lake is full that the entire biota is revealed with many of the hyposaline species appearing in the early filling stages of the lake (Timms 2005).

In Australia, endemic waterbirds are known to frequent the arid zone (Roshier *et al.* 2001) with up to 8 million estimated to have utilised these wetlands in 1995 (Kingsford 1995; Kingsford and Halse 1998). With the decline of coastal wetlands in Western Australia, the importance of inland salt lakes and their surrounding floodplains has increased. Waterbird is a collective name commonly used for non-

passerines and include the ducks, geese, swans, herons, terns, shorebirds and cormorants. They are a highly mobile fauna and at times require different wetland types for breeding and feeding (Kingsford 1998). Waterbirds are used as indicators of ecological status and for their intrinsic conservation interest in many parts of the world (Owino *et al.* 2001). Their anatomical adaptations, such as bill and leg shape, ensure access to a wide variety of food (Perrins 1990).

The wetlands in Australia's arid zone include fresh to saline lakes, floodplains, pans, lagoons, billabongs and man-made dams. While many birds may be seen foraging in salt lakes, adjacent fresh water bodies are necessary for the provision of drinking water with waterfowl breeding in hypersaline wetlands reportedly preferring the fresher portions of the wetland (Adamus and Brandt 1990). The breeding of waterbirds usually occurs when the food supply is high (Kingsford 1989).

### **Objectives**

The objectives of this chapter are:

- To investigate the biological communities of Lake Yindarlgooda and two adjacent wetlands, Lake Penny and Swan Refuge,
- Identify the dominant biotic groups in Lake Yindarlgooda and investigate any impacts from mining activities on biodiversity.

## **4.2 Methods**

### **4.2.1 Surface sediment collection for dormant egg/seed bank identification**

Surface sediment samples were collected from all study sites during the 2001 - 2002 sampling period. A 50 x 50 cm surface scraping of the first centimetre of the sediment was collected from three random sites within each site (Figure 4.1). The surface sediment layer is considered to be the "active dormant egg bank" in nature (Caceres and Hairston 1998). Each sample was placed in a calico bag, which were then oven dried at 30 °C, weighed and stored for the various analyses.

A 500 g sub-sample of each of the collected sediment was sieved through stacked 500 µm and 180 µm Endecott® brass sieves. The material retained in the 180 µm sieve was then washed through a plastic 125 µm sieve and then immediately oven dried. 180 µm was considered to be the size of the majority of the invertebrate resting stages as observed in preliminary investigations of the sediment. This

sediment was examined manually with the aid of a Leica MZ6 stereomicroscope for the presence of algal, plant and invertebrate resting stages.

#### **4.2.2 Macrophytes and algae**

The presence of macrophyte communities was recorded at each of the sites. In the absence of live samples, resting stages in the sieved samples were used to record their presence. Charophyte resting stages (oospores and gyrogonites) were identified using Garcia (2002).

Phytoplankton samples were collected by submersing a 1 L plastic bottle just below the surface of the water. Samples were preserved with Lugol's Iodine for microscopic examination.

Benthic microbial communities (BMCs) were collected from the surface scrapings of sediment using an open plastic vial, approximately 8 cm in length. The samples were preserved in Transeau's algal preserve (6 water:3 ethylalcohol:1 formaldehyde) for microscopic examination. Core samples for the analysis of the diatom communities were collected by inverting an open specimen jar (5.5 cm length, diameter 4.5 cm with a 5 mm hole drilled in the base) and removing a core from the lake bed (up to 5.5 cm in depth). Cores were stored frozen for later digestion and enumeration.

##### *4.2.2.1 Examination of surface scrapings and phytoplankton*

Preserved surface scrapings were examined microscopically by making wet mounts. Small sections of the sediment were placed on a drop of water on a glass slide and the sediment gently macerated. Slides were examined under high power (400x) for the presence of any microalgae. Phytoplankton samples were examined under high power using a calibrated Lund cell.

Microalgae and macrophyte specimens were photographed using an Olympus CZH10 stereo microscope with an Olympus SC35 mounted camera. Cyanobacteria, algae and charophytes were identified using Bourrelly (1970), Desikachary (1972), Geitler (1985), Baker and Fabbro (1999), and Garcia (2002).

##### *4.2.2.2 Rewetted samples (germination of resting spores and seeds)*

Sub-samples of the sediment were rewetted to initiate the germination of any macrophyte or algal resting stages. A portion of the sediment from each site was

placed in 500 ml plastic containers and 400 ml of deionised water added to the sediment, allowed to settle and placed on a windowsill.

### **4.2.3 Aquatic invertebrates**

#### *4.2.3.1 Collection of zooplankton*

Zooplankton was collected by isolating a column of water using a plastic tube (110 cm circumference and 80 cm in height). The water column was cleared of all aquatic invertebrates using a 50 µm zooplankton net. The water was then gently agitated to dislodge and capture any benthic invertebrates. Three replicate samples were collected from each site. This method was adapted from Chaplin *et al.* (1999). Each sample was placed in a plastic vial, fixed with 4% formalin then transferred to 70% alcohol.

#### *4.2.3.2 Identification and enumeration*

Specimens were identified using Williams (1980), De Deckker (1981a; 1981b), Davis and Christidis (1999), Halse and McRae (2004), and Timms (2004a). It should be noted that detailed taxonomy of the different invertebrates collected was not a priority for this study; instead the focus was on identifying the dominant taxa that would be most at risk from the impacts from the LRSF. Voucher specimens were preserved in 70% alcohol, except for the *Parartemia* which were preserved in formalin, and deposited in the invertebrate collection of the Environmental Biology Dept, Curtin University of Technology. Specimens were photographed using an Olympus CZH10 stereo microscope with an Olympus SC35 mounted camera.

Abundance counts were performed with the aid of a Leica MZ6 Stereomicroscope. *Parartemia* were counted by placing the entire sample in a petri dish and recording all individuals present. Other invertebrates specimens < 3 mm were enumerated using a Sedgwick-Rafter Chamber (volume=1 mL), up to 10 chambers per sample, and all specimens counted. The number of individuals per litre of water was then calculated (Gannon 1971).

#### *4.2.3.3 Treatment of data*

Non-metric multidimensional scaling (MDS) was employed to determine differences between sites according to the dissimilarity of their invertebrate community structure. The data was first square root transformed and the Bray-Curtis similarity matrix calculated using PRIMER 6 (Clarke and Gorlet 2006). Site ordination was undertaken using MDS. To examine which sites in the ordination shared the greatest



similarity a group-average cluster analysis was performed on the MDS data and the hierarchical clustering displayed in a dendrogram.

#### 4.2.4 Waterbirds

Waterbird surveys were performed at all sites from 2001 to 2002 and included opportunistic surveys. Observations were made using a Kowa TSN-821 Spotting Scope with a TSN-820 20-60× eyepiece and binoculars. The absence of waterbirds was also noted, especially during repeat field trips. Observations of courtship behaviour, evidence of nesting and general habitat use were noted. The birds were identified using Slater *et al.* (2000), and photographs taken using a Canon EOS 500 with an 80-200 mm lens.



**Figure 4.1:** Collection of surface sediment for the examination of resting stages and for use in hatching trials. Sediment was collected using a plastic half pipe and placed in calico bags.

### 4.3 Results

#### 4.3.1 Macrophytes and algae

##### 4.3.1.1 Macrophytes

Macrophyte diversity in Lake Yindarlgooda was restricted to two known taxa, *Ruppia* sp. (Potamogetonaceae) and *Lamprothamnium* sp. (Charophyceae). While *Ruppia* meadows were observed in the field in March 2001 at the control sites 1 to 3, only the resting stages (oospores and gyrogonites) of *Lamprothamnium* sp. indicated

their presence in Lake Yindarlgooda. During subsequent surveys, dried *Ruppia* mats were recorded along the shorelines of Swan Refuge and Lake Penny, as well as spatially in the southern sites of Lake Yindarlgooda.

Examination of the sediment recorded gyrogonites and oospores of *Lamprothamnium* sp. from Lake Yindarlgooda, Swan Refuge, and Lake Penny (Table 4.1; Figure 4.2). Growth trials on rewetted sediment indicated a well established seed bank. A thick *Lamprothamnium* meadow grew within a week of the sediment from Lake Penny being rehydrated, confirming an abundant seed bank in this lake. An unknown bryophyte was also germinated from the rewetted sediment from Site 1 in Lake Yindarlgooda.

#### 4.3.1.2 Algae

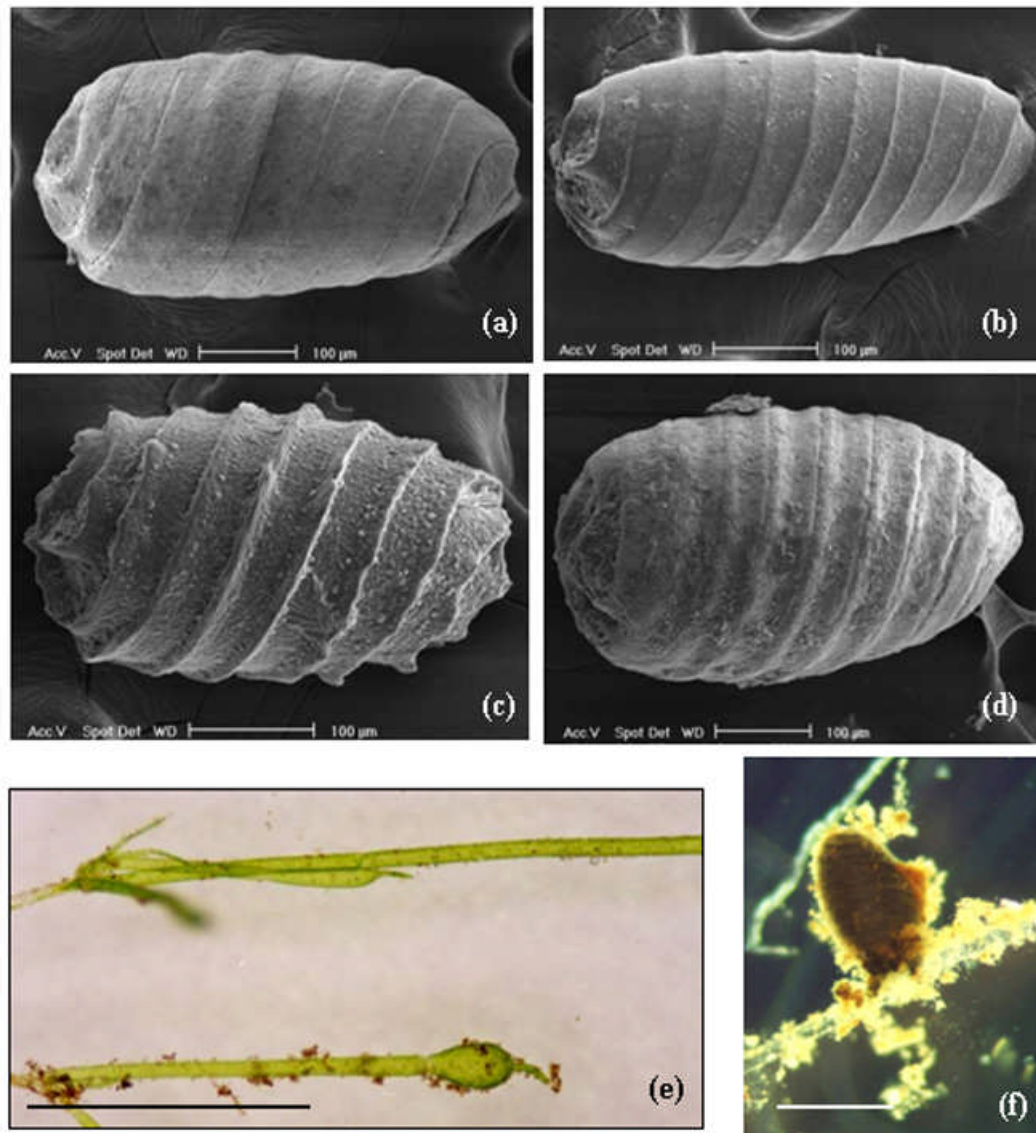
Representatives from the cyanobacteria and algae were sparse in the samples collected from the study sites. No cohesive microbial mats were observed from Lake Yindarlgooda or Swan Refuge. Examination of the sediment samples did not reveal a diverse algal community, the exception being the diatoms. A few taxa were cultured from the rewetted sediment and cyanobacterial and algal taxa were identified from both collected and rewetted samples (Table 4.1). No true phytoplankton (euplankton) was recorded in the water samples collected in March 2001. Rather, benthic diatoms that were dislodged from the surface sediment were present.

Cyanobacteria from the order Nostocales and the filamentous *Phormidium* sp. (Oscillatoriales) were recorded in the rewetted sediment (Figure 4.3a & b). The filamentous green alga, *Oedogonium* sp. (Figure 4.3c) and *Klebsorbidium* sp. (Figure 4.3d) were recorded from EP2 rewetted sediment. Salt crust samples from Lake Yindarlgooda, collected in March 2002 (C. Vivian, Bulong Nickel) contained palmelloid stages of *Dunaliella viridis*.

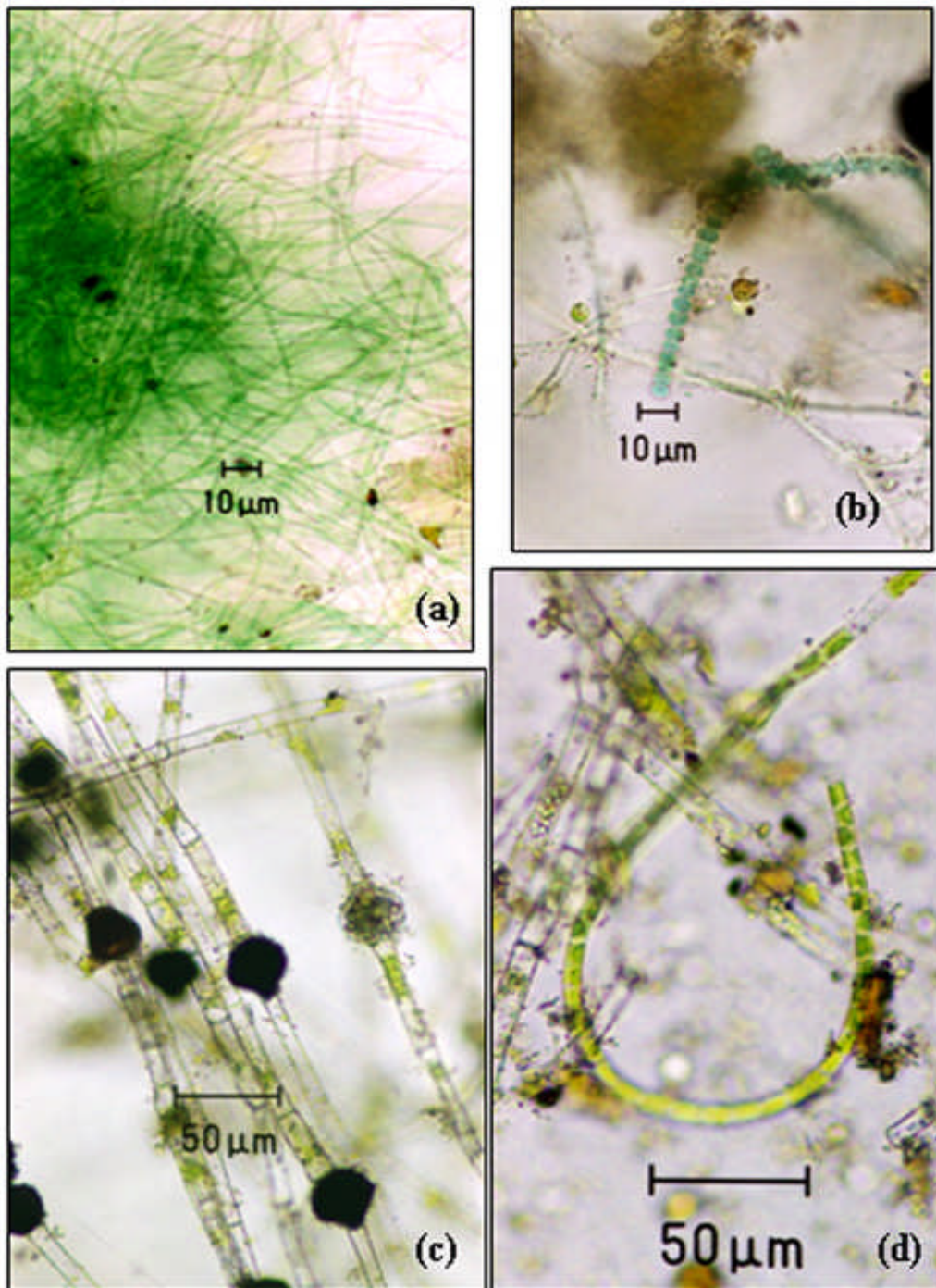
In total, 13 diatom taxa, typical of saline waters, were recorded from digested sediment samples from Lake Yindarlgooda and periphytic samples from Swan Refuge. Diatom diversity was slightly higher in Swan Refuge with 11 species. Nine were recorded from Lake Yindarlgooda. Differences in community composition were apparent. The diatoms are examined in detail in Chapter 6.0.

**Table 4.1:** Cyanobacteria and algal taxa identified from Lake Yindarlgooda, Swan Refuge and Lake Penny. Samples included periphytic, benthic and rewetted sediment. The Bacillariophyceae are treated separately in Chapter 6.0.

<b>Taxa</b>	<b>Lake Yindarlgooda</b>	<b>Swan Refuge</b>	<b>Lake Penny</b>
<b>Cyanobacteria</b>			
Nostocales	*		
<i>Phormidium</i> sp.	*		
<b>Chlorophyceae</b>			
<i>Oedogonium</i> sp.	*		
<i>Klebsorbidium</i> sp.	*		
<i>Dunaliella viridis</i>	*		
<b>Charophyceae</b>			
<i>Lamprothamnium</i> sp.	*	*	*
<b>Bacillariophyceae</b>	*	*	



**Figure 4.2:** *Lamprothamnium* sp. (Charophyceae) recorded from Lake Yindarlgooda and Lake Penny sediment. **(a)** SEM of gyrogonite (calcified oogonium) from Lake Penny. **(b)** SEM oospore from Lake Penny. **(c)** SEM oospore from Site 4, Lake Yindarlgooda. **(d)** SEM of gyrogonite from Site EP2, Lake Yindarlgooda. **(e)** Branchlet germinated from collected sediment (scale bar = 2 mm). Inflated branchlet segment shown in specimen at base of (e). **(f)** Oospore of *Lamprothamnium* sp., rhizomes seen at base of oospore (scale bar = 1 mm).



**Figure 4.3:** Cyanobacteria and algae from rewetted sediment, Lake Yindarlgooda. (a) Oscillatoriales (Cyanobacteria) mat cultured from Site 4 sediment. (b) Nostocales (Cyanobacteria) trichome amongst filaments of *Phormidium* sp., EP2 sediment. (c) *Oedogonium* sp. (Chlorophyceae) displaying oogonia, EP2 sediment. (d) *Klebsorbidium* sp. (Chlorophyceae) from EP2 sediment.

### 4.3.2 Aquatic invertebrates

During this study, 12 aquatic invertebrate taxa were collected in March 2001, 11 taxa belonging to the Crustacea and one to the Insecta (Table 4.2; Figure 4.4). The majority of those recorded were as juvenile or adult stages, with only hyposaline taxa identified as resting stages in Lake Yindarlgooda. The invertebrate communities of Lake Yindarlgooda were co-dominated by the ostracods and *Parartemia*, while Swan Refuge recorded similar percentages of cladocerans, ostracods and copepods (Figure 4.4).

#### 4.3.2.1 Lake Yindarlgooda

Eight Crustacean taxa were recorded from Lake Yindarlgooda. The greatest diversity was displayed by the ostracods, with four Cypridid genera recorded (Table 4.2). Other taxa included one species of cyclopoid copepod, the cladoceran *Daphniopsis* sp., and one species of *Parartemia*, identified as *Parartemia* n. sp. d. The ostracods were the dominant taxa at the control sites 1, 2 and 3, while *Parartemia* n. sp. d dominated the impact sites EP1 and 5 (Figure 4.4). Site 4 had equal percentages of both ostracods and *Parartemia*. No zooplankton was collected from Site EP2 due to insufficient water levels.

The resting eggs of ostracods (red and white eggs), *Parartemia* and *Branchinella* were observed in the zooplankton samples, possibly dislodged from the surface sediment (Figure 4.3a). While adult *Branchinella* were not collected in the zooplankton, their eggs were recorded in the surface sediment from a number of sites around Lake Yindarlgooda. *Parartemia* were not collected in the zooplankton samples from Site 2 but were present in sparse numbers in the water column and their eggs were recorded in the sediment. The *Parartemia* are discussed in detail in Chapters 7.0 - 9.0.

#### 4.3.2.2 Wetlands: Swan Refuge and Lake Penny

Six crustacean taxa and one taxon from the Insecta were recorded from Swan Refuge (Table 4.2). The percentage abundance of the cladoceran, *Daphniopsis* sp. (Figure 4.5) was higher in Swan Refuge, and a different assemblage of ostracod species were collected in March 2001. *Parartemia* were not recorded from Swan Refuge. Large numbers of *Triops* (Figure 4.4b) were observed in the floodplains in the northern sections of Lake Yindarlgooda together with conchostracans and tadpoles.

No fauna were identified from Lake Penny during this study. Samples could not be collected during the March 2001 sampling trip as the lake was inaccessible. During subsequent surveys Lake Penny was dry. Sediment rewetting was unsuccessful, the cultures quickly becoming anoxic. Examination of the sediment proved difficult and did not reveal any invertebrate resting stages.

#### 4.3.2.3 Comparison of sites

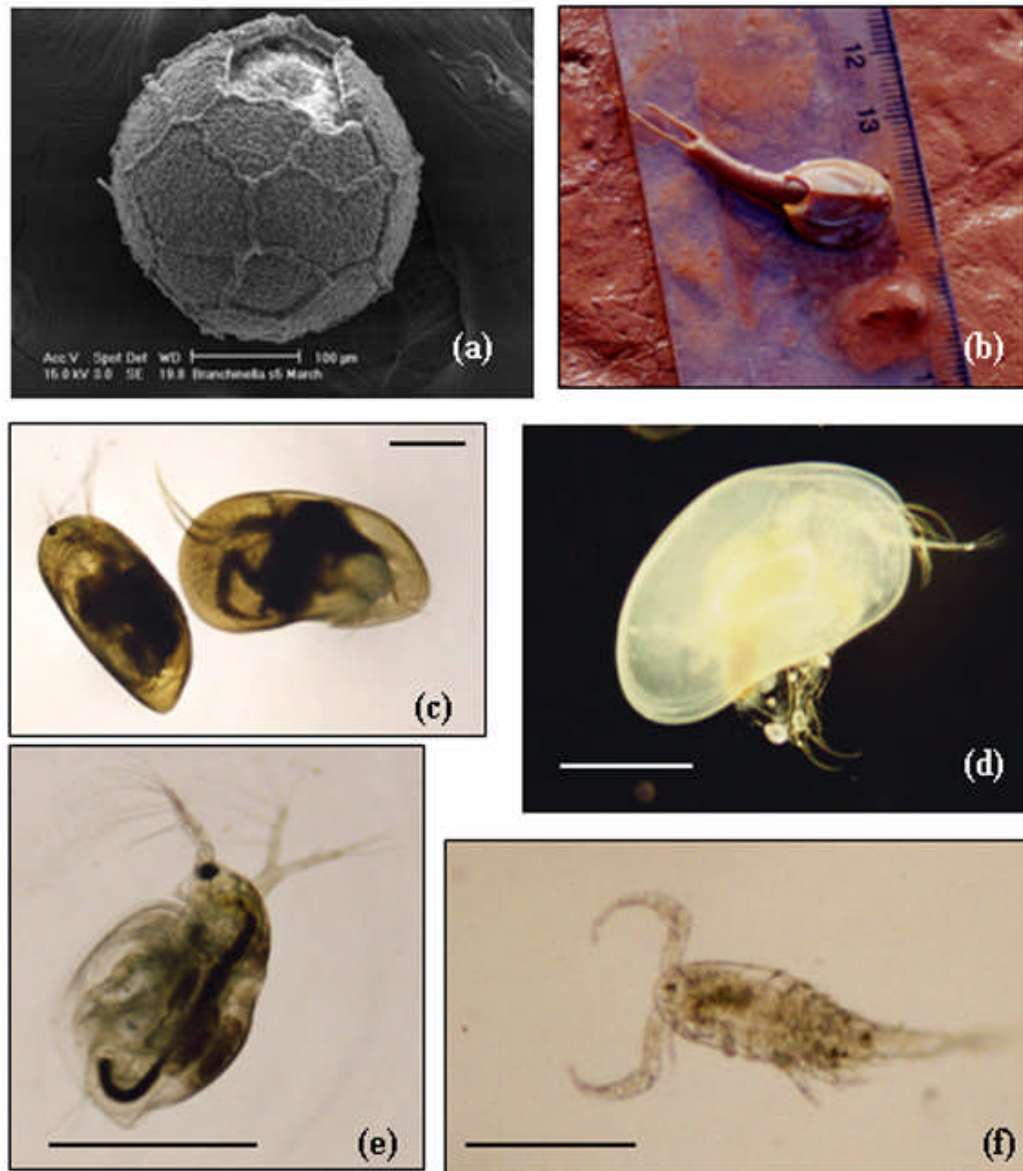
Differences in the invertebrate community structure between Swan Refuge and Lake Yindarlgooda are clear on the MDS ordination (Figure 4.6). The wetland Swan Refuge showed the greatest dissimilarity to all the Lake Yindarlgooda sites. This was due to the absence of *Parartemia*, the high number of *Daphniopsis* and the cyclopoida in Swan Refuge compared to the playa sites. Of the playa sites there were differences in the groupings, the most obvious was Site 2 with the greatest distance on the ordination to the other playa sites. This may be explained by the absence of *Parartemia* in the zooplankton counts.

The group-average clustering of the data showed that the impact sites 5 and EP1 had similar invertebrate assemblages (85% similarity) and also shared 60% similarity with Site 4 (Figure 4.7). The control sites 1 and 3 were 90% similar in their invertebrate assemblages. These groupings have occurred because of the dominant taxa with the invertebrate assemblages at the impact sites dominated by *Parartemia* while the control sites had a higher proportion of ostracods.

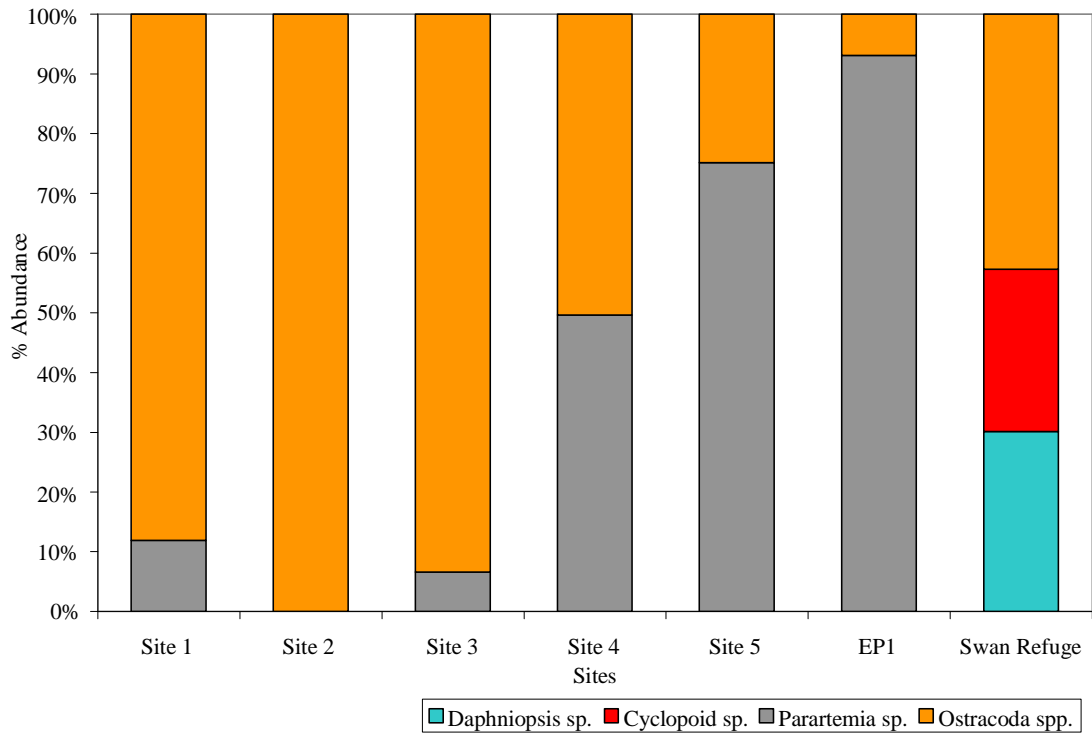
**Table 4.2:** Aquatic invertebrate taxa recorded from Lake Yindarlgooda, Swan Refuge and the peripheral floodplains in March 2001. *Branchinella* sp. was recorded in the samples only as a resting egg. The taxa list was collated from zooplankton samples, sediment samples (as resting stages or grown in culture from rewetted sediment), and field observations.

<b>Taxa</b>	<b>Location</b>
<b><u>Crustaceae</u></b>	
<b>Anostraca</b>	
<i>Parartemia</i> n. sp.d	Lake Yindarlgooda (all sites)
<i>Branchinella</i> sp. (egg)	Swan Refuge, Lake Yindarlgooda (Site 5, Site 4, EP1)
<b>Notostraca</b>	
<i>Triops</i> sp. 1	Swan Refuge, peripheral floodplains
<b>Ostracoda</b>	
<b>Cyprididae</b>	
<i>Australocypris</i> sp.	Lake Yindarlgooda (all sites)
<i>Mytilocypris</i> sp.	Swan Refuge
<i>Heterocypris</i> sp.	Swan Refuge, Lake Yindarlgooda (all sites)
<i>Diacypris</i> sp.	Lake Yindarlgooda (all sites)
<i>Reticypris</i> sp.	Lake Yindarlgooda (all sites)
<b>Diplostraca</b>	
Conchostraca	Peripheral floodplains
<b>Cladocera</b>	
<i>Daphniopsis</i> sp.	Swan Refuge, Site 4
<b>Copepoda</b>	
Cyclopoida	Swan Refuge, EP1
<b><u>Insecta</u></b>	
<i>Berosus</i> larvae	Swan Refuge

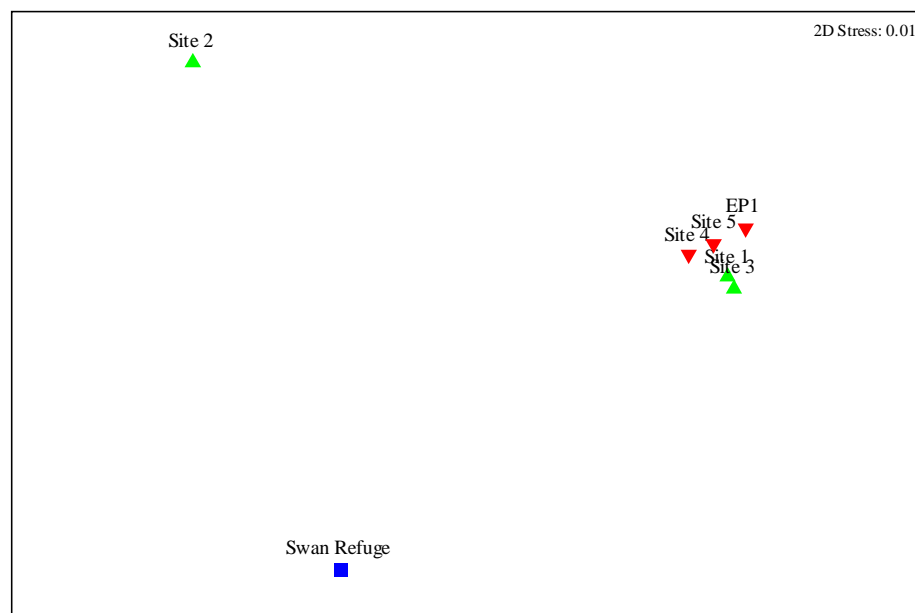




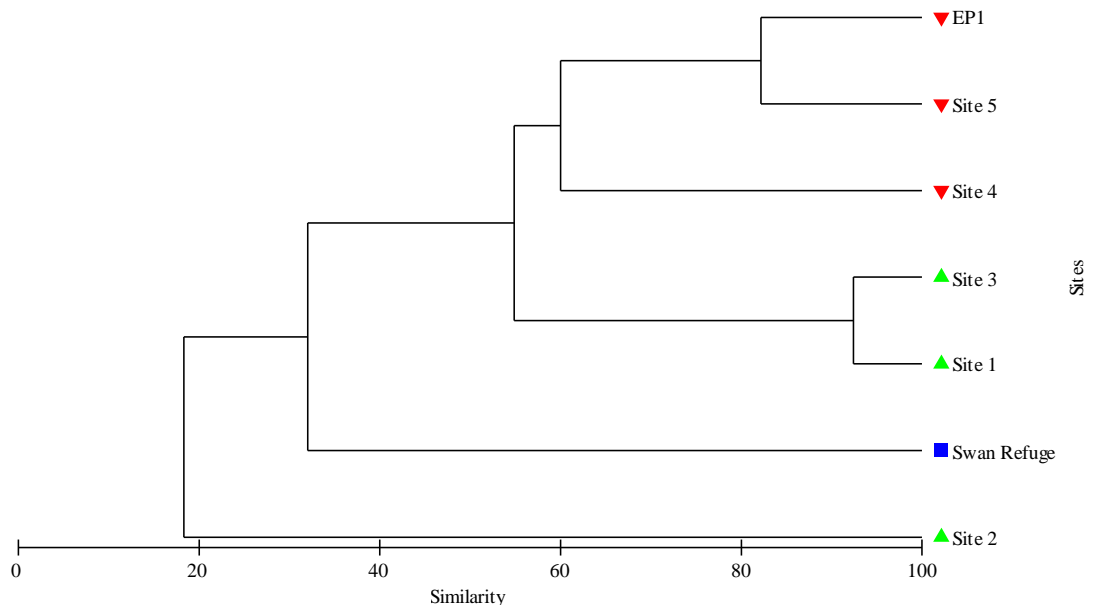
**Figure 4.4:** Aquatic invertebrates from Lake Yindarlgooda, Swan Refuge and the floodplains. **(a)** SEM of *Branchinella* sp. resting egg (cyst) collected from Site 5, Lake Yindarlgooda (scale bar = 100  $\mu$ m). **(b)** *Triops* sp. recorded from the northern floodplains of Lake Yindarlgooda. **(c)** *Australocypris* sp. (Cyprididae) collected from Lake Yindarlgooda (scale bar = 1 mm). **(d)** Cyprididae from Swan Refuge (scale bar = 0.5 mm). **(e)** *Daphniopsis* sp. (Cladocera), Swan Refuge (scale bar = 1 mm). **(f)** Male cyclopoid copepod, Swan Refuge (scale bar = 0.5 mm).



**Figure 4.5:** Percentage abundance of aquatic invertebrate taxa recorded from zooplankton samples, Lake Yindarlgooda and Swan Refuge (March 2001). The different ostracods were graphed together as Ostracoda. No samples were collected from Site EP2 and Lake Penny in March 2001.



**Figure 4.6:** Non-metric multidimensional scaling (MDS) ordination of the sample sites and invertebrate abundances for March 2001. Stress = 0.01. MDS obtained from Bray-Curtis similarity after square root transformation. ■ = Wetland site, ▲ = Control sites, ▼ = Impact sites.



**Figure 4.7:** Group-average clustering from Bray-Curtis similarities for invertebrate abundances at the sampling sites as shown on MDS ordination. ■ = Wetland site, ▲ = Control sites, ▼ = Impact sites.

### 4.3.3 Waterbirds

Waterbirds were recorded in Lake Yindarlgooda and Swan Refuge in March 2001. The subsequent three surveys did not record any waterbirds due to the absence of water. Observations made by Bulong Nickel personnel are included as opportunistic surveys. In total, eight species of waterbirds, mostly waterfowl, were recorded from Lake Yindarlgooda, Swan Refuge and the surrounding floodplains (Table 4.3). The functional groups and the preferred diets of the waterbirds recorded in this study are given in Table 4.4.

#### 4.3.3.1 Lake Yindarlgooda

Many of the dabblers recorded in Lake Yindarlgooda, such as the Australian Shelduck (*Tadorna tadornoides*) and Grey Teal (*Anas gracilus*), were located along the shorelines, while the waders were recorded in the shallow water near the LRSF. The Red-capped Plover (*Charadrius cucullatus*) and a breeding pair of Hooded Plovers (*Thinornis rubricollis*) were recorded from the impact sites 4, EP1 and EP2. No birds were observed at Site 5. Signs of breeding by Red-capped Plovers were noted near the LRSF in the form of a nest with an egg found in the wall of the newly constructed LRSF (C. Vivian pers comm., 2001). Sightings of large numbers of

Banded Stilts on Lake Yindarlgooda at the LSRF were made in early 2002. The birds appeared to have rested over night, departing the following day (L. Cahill *pers comm.*, 2002).

#### 4.3.3.2 Wetlands: Swan Refuge and Lake Penny

The highest diversity of waterbirds was recorded at Swan Refuge in March 2001. Counts of up to 400 Australian Shelducks, 248 Grey Teal and 108 Black Swans (*Cygnus atratus*) were recorded (Table 4.3). The White-fronted Heron (*Ardea novaehollandiae*) and Pacific Black Duck (*Anas superciliosa*) were also present. Swans were counted whilst in the water, the rest of the waterbirds were roosting on a sandbank along the margin of the clay pan. The site was named Swan Refuge for this study because of the loud “hooting” created by the large numbers of Black Swans, which could be heard before reaching the site.

Waterbird counts from Lake Penny could not be performed during March 2001. Observations by Birchell Jones, the lease holder of Hampton Hill Station, noted large numbers of Banded Stilts in April 2001 at Lake Penny (C. Vivian, *pers comm.* 2001). Numerous Black Swan nests, containing shell fragments, were found on raised, vegetated sandbanks during visits in September 2001 to Lake Penny.

#### 4.3.3.3 Floodplain

Observations made whilst travelling to each of the sites in Lake Yindarlgooda in March 2001 indicated a highly fertile floodplain, interspersed with numerous small wetlands. Small pools of water were teeming with *Triops*, conchostraca and tadpoles. Throughout the floodplain herons and predatory birds were also observed.

**Table 4.3:** Waterbird count from Lake Yindarlgooda and surrounds, March 2001. No birds were recorded from any of the sites during the May 2001, September 2001 and September 2002 field trips due to the absence of water. Obs = observation made, but not by author.

Site	Common Name	Scientific Name	Count
Site 1	Australian Shelduck	<i>Tadorna tadornoides</i>	44
	Grey Teal	<i>Anas gracilus</i>	600
Site 2	Black Swan	<i>Cygnus atratus</i>	20
Site 3	Australian Shelduck	<i>Tadorna tadornoides</i>	21
	Grey Teal	<i>Anas gracilus</i>	300
Site 4/EP2	Hooded Plover	<i>Thinornis rubricollis</i>	2
	Australian Shelduck	<i>Tadorna tadornoides</i>	2
	Red-capped Plover	<i>Charadrius ruficapillus</i>	30
EP1	Red-capped Plover	<i>Charadrius ruficapillus</i>	4
Swan Refuge	Grey Teal	<i>Anas gracilus</i>	248
	Australian Shelduck	<i>Tadorna tadornoides</i>	490
	White-fronted Heron	<i>Ardea novaehollandiae</i>	15
	Pacific Black Duck	<i>Anas superciliosa</i>	2
	Black Swan	<i>Cygnus atratus</i>	108
Lake Penny	Banded Stilt	<i>Cladoryhynchus leucocephalus</i>	Obs.

**Table 4.4:** Known diets of waterbirds recorded at Lake Yindarlgooda and surrounds. (Sourced from Blakers *et al.* 1984; Kingsford 1998).

Common Name	Scientific Name	Diet	Functional Group
Australian Shelduck	<i>Tadorna tadornoides</i>	Algae, invertebrates, plants, seeds. (Omnivore)	Grazing waterfowl
Black Swan	<i>Cygnus atratus</i>	Submerged vegetation, algae. (Herbivore)	Deep-water foragers
Pacific Black Duck	<i>Anas superciliosa</i>	Aquatic vegetation, invertebrates. (Omnivore)	Dabbling ducks
Grey Teal	<i>Anas gracilus</i>	Seeds, bulbs, vegetation, insects. (Omnivore)	Dabbling ducks
White-fronted Heron	<i>Ardea novaehollandiae</i>	Small fish, tadpoles, lizards, aquatic invertebrates, large crustaceans.	Piscivore
Hooded Plover	<i>Thinornis rubricollis</i>	Insects, crustaceans, zooplankton.	Small waders
Red-capped Plover	<i>Charadrius ruficapillus</i>	Beetles, insect larvae, crustaceans, zooplankton, plant matter.	Small waders

## 4.4 Discussion

The biodiversity in Lake Yindarlgooda and the two wetlands was low compared to that of other inland salt lakes, particularly for invertebrate species. In Lake Wyara, eastern Australia, 34 invertebrate species were recorded (Timms 2001) while 107 were found in Lake Carey, a large playa in the Goldfields region of Western Australia, and its surrounding wetlands (Timms *et al.* 2006). The taxa recorded in this study were typical of large saline playas and the low diversity attributable to the episodic nature of the lake (De Deckker 1983; Timms *et al.* 2006; Timms 2007). While species composition in Lake Yindarlgooda and Swan Refuge differed slightly, the overall diversity was similar.

Lake Yindarlgooda and Swan Refuge did not contain extensive, cohesive benthic microbial communities (BMCs) described as typical of salt lakes (Bauld 1981) and lacked a true phytoplankton community. Instead, the BMCs were dominated by diatoms, sparsely distributed in the surface sediment. Similar findings were recorded by Boggs *et al.* (2007) on studies of salt lakes in the northern agricultural region of Western Australia. The BMCs in those lakes consisted of cohesive to loosely mucilaginous mats of two species of filamentous algae, confined to the smaller pans, or as thin films of diatoms in the larger playas. The diatom communities in Lake Yindarlgooda and Swan Refuge consisted of saline taxa with cosmopolitan distribution (Blinn 1993; Gell and Gasse 1994; Ehrlich 1995), though diversity was not as high as in other Western Australia salt lakes (John *et al.* 2000; Handley 2003; Taukulis and John 2006). The technique of rewetting sediment proved useful in this study and has been adopted in other research (Timms 1998; John 1999; Sim *et al.* 2006). It allowed for the presence of the macrophytes to be identified as an important component of the system.

Few macrophytes are able to survive the high, fluctuating salinities and unpredictable water regimes experienced in these systems and in Australia they are restricted to a few taxa (Brock 1981; Brock and Shiel 1983; Brock 1997). The macrophytes recorded from Lake Yindarlgooda and the surrounding wetlands during this study were limited to two taxa, *Ruppia*, and *Lamprothamnium*, these two genera known to coexist in saline wetlands in the Australian arid zone (Brock 1986). In these systems it is often not salinity but water regime that is the driving factor (Boulton and Brock

1999) with the timing, frequency, duration and depth of inundation all influencing the plant species and its establishment (Brock 1998).

Studies by Porter (2007) found that the coexisting *Lamprothamnium macropogon* and *Ruppia tuberosa* had different germination response to flooding. While *R. tuberosa* responded immediately, *L. macropogon* employed a late germination strategy. In Lake Yindarlgooda *Lamprothamnium* sp. was not observed in the field, though numerous oospores were recorded in the sediment. In contrast, *Ruppia* was seen scattered throughout the playa. Plant communities are an important structural and functional component of these shallow systems, however episodic, providing a resource for many life forms (Brock *et al.* 2003; Capon and Brock 2006) either directly in the case of the herbivorous birds or eventually as decomposed forms for the detritivores and decomposers. Their ability to withstand long periods of desiccation by producing resistant propagules ensures that these arid wetlands maintain a seed bank, that when inundated, will provide sufficient resources in an otherwise limited environment (Brock *et al.* 2003).

Lake Yindarlgooda and Swan Refuge had an aquatic invertebrate population dominated by the crustaceans, typical of many Australia inland salt lakes (Brendonck and Williams 2000). Diversity was lower compared to other inland saline lakes in Western Australia such as Lake Carey (Timms *et al.* 2006) and Lake Miranda (John *et al.* 2000). Generally in episodically filled saline lakes the diversity is lower (De Deckker 1983). The species richness of a wetland can be correlated with its size and the extent of the hydroperiod, and often there are differences in the species assemblages between proximate wetlands at a given time (Brendonck and Williams 2000) often due to the heterogeneity of habitat (Timms 1997). While Lake Yindarlgooda and Swan Refuge did not recorded differences in species diversity, the community composition varied with more hyposaline taxa dominating Swan Refuge, and may have been a reflection not only of the differences in salinity but also in habitat.

Differences in the invertebrate community structure in Lake Yindarlgooda between the control and impact sites may be due to abiotic factors other than salinity. The salinity tolerance of invertebrate species is known to be influenced by ionic composition (Halse *et al.* 1998). The dominance of the ostracods in the southern sites of Lake Yindarlgooda may have been a reflection of the differences in ionic

composition in March 2001, rather than salinity. The ostracods identified in this study were all known halobiont taxa (Halse 2002; Pinder *et al.* 2005). The presence of halophilous ostracods in some systems have been reported as due to changes in the ionic structure of the lake water (Radke *et al.* 2003). In March 2001, the ionic sequence of the southern control sites differed from that of the impact sites with higher calcium ratios (Chapter 3.0). Many of the halophilous and halobiont ostracods studied by Radke *et al.* (2003) were found to prefer NaCl dominated waters with higher Ca ( $\text{Ca}^{2+} > \text{Alk.}$ ) ratios.

The resident biotic community of temporary systems often remains buried in the sediment as resting stages (Brendonck and Williams 2000; Brock *et al.* 2003) and may not emerge until conditions are suitable. These egg banks ensure the survival of the species in an unpredictable environment and the biota of temporary waters must have adaptations to cope with their fluctuating environment, either by dispersal as adult stages, or by the development of dormancy mechanisms (Williams 1985). The Ostracoda, Anostraca, and Copepoda have lifecycles involving diapause and/or dormancy stage (De Deckker and Geddes 1980; Dussart and Defaye 1995; Sergeev and Williams 1983; Williams and Geddes 1991). Examination of the sediment from Lake Yindarlgooda revealed that a number of other groups also formed part of the biota, notably *Branchinella*, which were not collected as adult stages in the zooplankton. Timms (2002; 2005) states that the presence of a hyposaline community may only be found after major filling events, when the lake is “fresher” than usual, and they are often overlooked. The invertebrate community in Lake Yindarlgooda and Swan Refuge, though depauperate compared to other lakes, was numerically sufficient to provide a source of food for the different waterbirds recorded.

The Australian arid zone wetlands have been known to support an impressive number of waterbirds, often in numbers not found in other wetlands (Kingsford and Halse 1998; Kingsford *et al.* 1999). Not only are these sites important in the migratory pattern of many trans-equatorial species, they have also proven to be the breeding grounds for a number of waterbirds, the best known being the Banded Stilt (Burbridge and Fuller 1982; Bellchambers and Carpenter 1990). These wetlands span the full range of wetland ecosystems, ranging from fresh to saline lakes, clay pans, billabongs and floodplains (Kingsford 1998). Lake Yindarlgooda and its



surrounding floodplains displayed such a mosaic of different wetland types, the different habitats fulfilling the requirements of the many functional groups recorded at the time of sampling.

The foraging behaviour of waterbirds differs from species to species (Laubhan and Gammonley 2000) and their anatomical adaptations ensure that a variety of different foods are available within a wetland (Perrins 1990). The distribution of the food usually determines the waterbird community (Kingsford 1998), as is evident in this study. Swan Refuge displayed a predominantly waterfowl community while the absence of the waders was noted. The waterbird diversity was higher at Swan Refuge and dominated by the Black Swans (*Cygnus atratus*) and the Australian Shelduck (*Tadorna tadornoides*), predominantly herbivores that would profit from the presence of extensive *Ruppia* meadows. High numbers of *Daphniopsis* in the water and the samphire marshes fringing the wetland provided a valuable food source in the form of insects and seeds (Datson 2002) for the omnivorous birds.

Banded Stilts and Red-capped plovers have been described as two of the three Australian bird species that prey on salt lake invertebrates (Bayly 1993) and both were seen foraging in the northern impact sites around the LRSF which recorded high numbers of *Parartemia*. Lane (1987) also recorded the Red-capped plover as feeding on anostracans. Shorebirds (waders) prefer the shallow flooded areas that produce abundant invertebrates (Laubhan and Gammonley 2000). Large numbers of Grey Teal (*Anas gracilus*) were recorded at sites 1 and 3 on Lake Yindarlgooda. These nomadic waterbirds prefer the shallow waters salt lakes provide (Blakers *et al.* 1984).

Birds have a high nutritional demand when breeding (Kingsford 1989). Both the courtship behaviour noted in the Hooded Plover and a Red-capped Plover nest located at the LRSF site, support the notion that there was an adequate food supply in Lake Yindarlgooda, at least to initiate breeding in the waders. No bird nests were recorded from Swan Refuge and those of the Black Swan were found on islands at Lake Penny. Whether or not they were from the 2001 hydrocycle is difficult to tell but they are evidence that the area can support breeding birds.

The absence of the waterbirds when Lake Yindarlgooda and surrounds were dry was significant. Climatic variation experienced in inland waters results in nomadism in the waterbirds (Johnstone *et al.* 2000) and “boom” and “bust” periods are

characteristic (Roshier *et al.* 2002). Records from inland wetlands following a rain event have shown that bird species move inland from the coast. Newbey (1996) reported an exodus of waterbirds from the West Australian coast to inland lakes 48 hours after a cyclone. The habitat and foraging behaviour of the Hooded Plover after cyclone Bobby in 1995 was heavily influenced by rainfall, the birds moving inland soon after the event (Weston and Elgar 2000). The fluctuation of waterbird numbers at Lake Gregory was described by Halse (1990) and showed when there was very low water levels the bird numbers was minimal compared to the thousands recorded during high water levels. As is evident in Lake Yindarlgooda when there was no water there were no waterbirds, a common observation (Kingsford *et al.* 1999; Roshier *et al.* 2002).

The water level in wetlands not only initiates breeding, it can also terminate it. Waterbirds have been known to abandon their nests when water levels drop (Kingsford and Porter 1994), the changing levels presumably a measure of food availability for colonially breeding birds (Kingsford 1998). The initiation of the hydrocycle in February 2001 may have been premature for many of the waterbirds, as the drought had dried the wetlands by June that year. Any breeding may also have been unsuccessful.

Of significance was the presence of the endangered Hooded Plover, listed as Priority 4 by CALM and classed as Rare under IUCN definition (Garnett 1992). The characteristic courtship behaviour of the Hooded Plover and the nests of the Red-capped Plover indicate that Lake Yindarlgooda provides an important habitat for these species. With the decline of coastal tidal flats many plovers are looking further inland for nesting sites. Disturbance by humans has led to their decline and isolated places such as salt lakes are becoming increasingly important refugia these birds. The sighting of the breeding pair in March 2001 was the northeastern most sighting of this species recorded (RAOU 2001).

It should be noted that birds are highly mobile fauna and their numbers are variable because of this. They are good ecological indicators and as has been shown in other studies (Owino *et al.* 2000). Used in conjunction with complementary information such as water quality parameters, invertebrate counts and so on, an accurate indication of the conditions determining their absence or presence can be obtained. In Lake Yindarlgooda, the defining impact on the waterbirds was water regime. This

determined the availability of food and therefore the presence of the waterbirds. The quality of the water also determines the presence of the food and there were sections of Lake Yindarlgooda that were constantly inundated yet no biota were recorded.

### **Conclusions**

The dominant biotic communities of Lake Yindarlgooda, Swan Refuge and Lake Penny were identified from this baseline study. The diversity was taxonomically low, typical of large inland salt lakes which display habitat homogeneity and are episodic in nature. The surrounding floodplains proved to be important sites for many nomadic and migratory birds forming a mosaic of wetlands supporting a diversity of functional groups.

Diatoms and *Parartemia* were identified as the dominant aquatic communities and therefore the most suitable taxa to study the effects of the LRSF on the biota. While numerically the dominant crustacean was the ostracods, *Parartemia* were recorded at all sites and, importantly, in high numbers around the LSRF, and a variety of salinities. The ease of identifying the well established egg bank of the *Parartemia* made them preferable for use in hatching trails compared to the ostracods. Only one species of *Parartemia* was recorded in Lake Yindarlgooda, compared to several ostracods, which again made them preferential for use as a monitoring tool in assessing the impacts of the LRSF.

## **Chapter 5.0. Riparian zone of Lake Yindarlgooda: vegetation and biological soil crusts**

### **Abstract**

Studies on the riparian zones of inland salt lakes in Western Australia are few and investigations on linkages between the lake and these regions even rarer. The riparian zone of Lake Yindarlgooda, though sparse, supported a diverse plant community, dominated by the Chenopodiaceae. The vegetation communities most proximal to the lake were found to be similar, indicating habitat homogeneity. Variation was observed away from the margins and a reflection of changes in the topography, particularly gradient and soil type.

This study investigates the biological soil crusts associated with the riparian zone of a Western Australian salt lake the first time. All southern sites in Lake Yindarlgooda had crusts covering the area between vascular plants. Only one of these was found to be biological. It was dominated by the filamentous cyanobacteria, *Microcoleus* sp. and associated with a moss, both common components of biological soil crusts. Evidence of livestock trampling was observed in the northern sites and biological crusts were not observed. Whether biological or physical, both types play an important role in soil stabilisation of the riparian zone of Lake Yindarlgooda, ultimately protecting the aquatic environment.

### **5.1 Introduction**

Riparian zones are the interfaces between terrestrial and aquatic systems. Though not easily delineated, they usually extend from the limits of flooding and upward into the canopy (Gregory *et al.* 1991). They are important in maintaining the stability of stream banks, preventing erosion, and contribute organic material to the aquatic systems (Schindler and Scheuerell 2002). The riparian zones of the inland salt lakes are as important functionally as they are for streams, though the literature is limited. Limnological studies seldom assume an integrated approach, omitting the role of the fringing vegetation and concentrating on the pelagic zone. This chapter examines the riparian zones of Lake Yindarlgooda, which were confined to the control sites, as part of an integrated limnological study.

The shorelines of salt lakes support a diverse halotolerant angiosperm community with most species belonging to the Chenopodiaceae (Williams 1998a; Jacobs 1999). These communities are limited in their extent, often to within 2-3 m from the shoreline (Hacker 1987). Vegetation groups usually occur in zones and is a common observation in Western Australian wetlands such as those in the Eastern Goldfields (Barrett 2006) and the seasonal wetlands of the Carnarvon Basin (Gibson *et al.* 2000).

Zonation of the fringing plant communities of inland salt lakes is a result of edaphic conditions, primarily soil salinity (Ungar 1974; Barrett 2006; van Etten and Vellekoop 2006), followed by other factors such as soil waterlogging and topography. Within the salt tolerant taxa such as *Halosarcia*, distinct species zonation is displayed (Datson 2002; van Etten and Vellekoop 2006). The combined effects of salinity and water-logging dictate the growth of *Halosarcia* (English 2001; 2004) and the extent of their zones (van Etten and Vellekoop 2006).

Greater species diversity is found in the dune vegetation communities of the salt lakes, the increase of the gradient away from the margins of the lake resulting in a decrease in salinity. In Western Australia, the *Halosarcia* dominated floodplains give way to low shrublands such as *Atriplex* and *Maireana* species on the better drained soils as recorded at Lake Raeside (Keighery *et al.* 1994) and Lake Lefroy (Barrett 2006). Further up the gradient where the soils are no longer strongly saline, the communities of tall shrubs and trees of *Acacia* or *Eucalyptus* species dominate (Keighery *et al.* 1994). Although the vegetation of large salt lakes is limited and the distribution often sparse, these areas provide protection from aeolian and sheet erosion, both factors that continue to shape these regions. Their functional role as shelter for many breeding waterbirds and a source of food as the habitat for numerous terrestrial invertebrates (Datson 2002) should not be underestimated in this environment.

While the distribution of vascular plants in the arid zone may be sparse, the large areas between the plants may be occupied by biological soil crusts. Globally, soil crusts are a prominent feature of the arid and semiarid regions. They can be either biological or physical (abiotic), the two can also be closely associated (Eldridge *et al.* 2000). Biological soil crusts are an intimate association between soil particles, edaphic cyanobacteria, eukaryotic algae, such as diatoms (Hawkes and Flechtner

2002), microfungi, lichens and bryophytes. They are often referred to as microbiotic, cryptobiotic or cryptogamic crusts. By definition they do not include communities that do not form an aggregation as a result of the associations, such as littoral algal mats or moss and lichens mats growing on the surface of decaying material, though the boundaries can be fluid (Belnap *et al.* 2003a).

Both biological and physical soil crusts are important for the stability of the surface soil, their binding properties preventing erosion. Much of the internal structure of crusts in desert regions is formed by large filamentous cyanobacteria, which aggregate soil particles and provide great tensile strength. The anchoring structures of mosses and lichens also contribute to the strength of the crust (Belnap 2003b). The dominant cyanobacterium in most desert soils is *Microcoleus* species (Karnieli *et al.* 1999; Johansen *et al.* 2001; Redfield *et al.* 2002) although investigations have found that in hot desert regions *Schizothrix* dominate (Johansen 1993; Issa *et al.* 1999)

Wind erosion is prevalent in arid regions where there is little protection from vegetation and consequently minimal litter production, resulting in high aeolian deposition. In the absence of vascular plant cover, soil crusts provide the structural stability. The binding properties of cyanobacteria are documented in studies on benthic microbial communities associated with stromatolites (Walter 1976). The secretions of large amounts of polysaccharide material and the binding of sediments by their gliding motions result in the laying down of laminations. Similarly, edaphic filamentous cyanobacteria aggregate soil particles. The role of cyanobacteria on structural stability documented by Issa *et al.* (2001a) revealed an intricate network of filamentous cyanobacteria and extracellular polymer secretions, which bind and entrap mineral particles on the soil surface and below the superficial crusts. Biological soil crusts are important contributors of nutrients such as nitrogen (Issa *et al.* 2001b; Aranibar *et al.* 2003) and carbon, increasing the soil polysaccharides and total carbon levels nearly three fold (Rogers and Burns 1994). Uptake of minerals by vascular plants, particularly short-lived herbs, is also increased in the presence of biological soil crusts (Harper and Belnap 2001).

Biological soil crusts are a common component of the Australian arid and semi-arid landscape with the greatest diversity restricted to the rangelands (Rogers 1982; Eldridge 2003). Research tends to differentiate between lichen dominated crusts and

those dominated by cyanobacteria and bryophytes (Eldridge 2003). The squamulose and crustose lichen crusts appear to be restricted to the arid regions of Australia and more strongly developed on calcareous soils (Eldridge 1996). They prefer more stable soils as they are slower growing than bryophyte and cyanobacteria dominated crusts. Both bryophytes and lichen crusts prefer fine-textured soils, but are not found on sands, with the lichens restricted to loamy soils and the bryophytes appearing on mounds associated with perennial shrubs on swelling clays (Eldridge and Tozer 1996). The cyanobacteria are active on all soil types. In Australia, the extent and diversity of crusts increase southwards as the winter dominated rainfalls increase. Many of the crusts in the Australian subtropical regions are dominated by bryophytes with their diversity increasing with rainfall, though in many of these areas they are seen as soil mats rather than true biological soil crusts (Eldridge 2003).

While the floristics of the lichens and the bryophytes associated with biological soil crusts in Australia have been well studied, there is little information on the cyanobacteria components in comparison to other regions of the world (for an extensive review see Belnap and Lange 2003). In a very early study Rogers *et al.* (1966) found that cyanobacteria and lichens in crusts covered 30% of the arid zone of Australia.

The importance of the riparian zone to the ecology of lentic systems is well known yet limnological studies of inland waters is dominated by research on pelagic zones with studies on the riparian habitats of lakes nearly absent (Schindler and Scheuerell 2002). In Australia research on the vegetation of inland waters is focussed primarily on submerged halophytes (Brock 1981, 1997, 1998) or on arid zone streams (Bunn *et al.* 2003). A State of the Environment Report on Inland Waters discussed primarily rivers and wetlands with very little mention of larger salt lakes (Ball *et al.* 2001).

Among the published information on arid zone lakes, Timms (2001b) described the fringing vegetation of freshwater lakes. Cale *et al.* (2004) included the vegetation types of saline lakes in the Western Australian Wheatbelt, though they were not integrated in their eventual findings. Published work on the vegetation communities within the Salinaland can be found in biological surveys performed by the Western Australian Museum (Keighery *et al.* 1994). Other studies include Barrett (2006) on the vegetation communities of Lake Lefroy and their relationship to soil conditions

and groundwater depth, while Hacker (1987) looked into the response of halophytic communities to grazing in a small section of Lake Raeside.

Research on biological soil crusts in Australia has been limited to the arid woodlands of eastern, south and central Australia (Eldridge 1998; Eldridge and Myers 2001; Eldridge 2003), while in Western Australia it has been limited to lichen and moss floristics on the Nullarbor Plain (Johnson and Baird 1970). Studies on biological salt crusts on the margins of playas are rare and confined to their presence being noted (Hacker 1987; Barrett 2006). The only detailed publication on the margins of salt lakes is for Lake Gilles, South Australia by Ullman and Budel (2003).

## **Objectives**

This chapter investigates the riparian vegetation and soil crusts as part of an integrated approach in studying the limnology of Lake Yindarlgooda. The objectives of this chapter are:

- To identify the vegetation communities of the riparian zone of Lake Yindarlgooda and the two wetlands, Lake Penny and Swan Refuge,
- To identify and analyse the biological soil crust present at these sites,
- To discuss the possible role of the riparian zone, including the biological soil crusts, in the limnology of Lake Yindarlgooda.

## **5.2 Methods**

### **5.2.1 Vegetation**

A one-day field survey of seven study sites was conducted around the perimeter of Lake Yindarlgooda on 27 November 2001. Prior to the field survey, use was made of aerial photography at a scale of 1:25 000 in selecting areas for traverses, and giving preliminary vegetation classification.

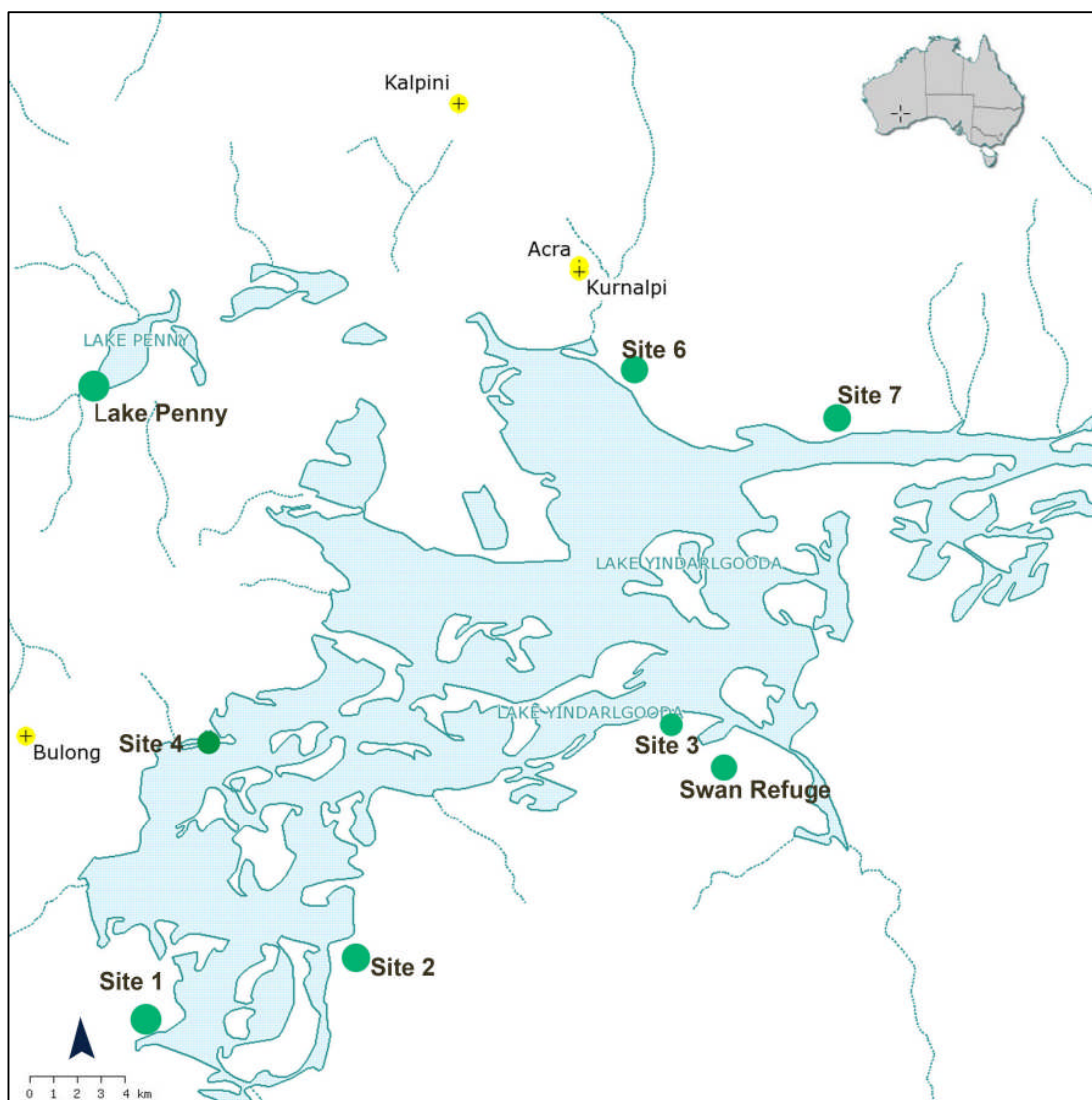
Vegetation types for the project area were described and mapped as 'map-units' rather than as communities or associations, which have specific ecological connotations (Table 5.1; Figure 5.1). The vegetation map-units provide realistic information about the environment. Description of vegetation structure follows the height, life form and density classes of Muir (1977). This is largely a structural classification suitable for broader scale mapping, but considering all ecologically significant strata.



Voucher specimens were collected and identification verified later for those species that could not be identified in the field. Nomenclature follows that of Green (1985; 1987) and the Western Australian Herbarium.

**Table 5.1:** Location of seven sites at Lake Yindarlgooda assessed for flora and vegetation on 27 November 2001, with all vegetation map-units identified at each site listed. With the exception of Site 4, all impact sites did not have riparian vegetation zones.

<b>Site</b>	<b>Map-units Identified</b>	<b>Location</b>
Site 1	1A, 1C, 2C, 3A	30°46.972'S 121°52.116'E
Site 2	1A, 1B, 2B	30°46.972'S 121°56.810'E
Site 3	1A, 1B, 2B	30°42.341'S 122°06.801'E
Site 4	1A, 2A	30°42.131'S 121°53.618'E
Site 6	1A, 1B	30°34.482'S 122°05.659'E
Site 7	1A, 1B	30°36.289'S 122°11.976'E
Swan Refuge	1A, 2A	30°43.271'S 122°07.776'E
Lake Penny	1A	30°32.010'S 121°53.181'E



**Figure 5.1:** Site locations for the vegetation surveys and collections of biological soil crusts from Lake Yindarlgooda, Swan Refuge and Lake Penny. Sample sites shown as green dots. Site 4 was the only impact site with vegetation. Base map from [www.australianmines.gov.au](http://www.australianmines.gov.au).

## 5.2.2 Biological soil crusts

### 5.2.2.1 Collection of soil crusts

Surface crusts were collected from sites around Lake Yindarlgooda with riparian zones (Figure 5.1). Control sites 1, 2, 3 and 6 were the only sites with obvious crusts. Four samples from each site were collected close to the margins of the lake, within 20 m of the riparian zone. The surface crust, including some subsurface soil, were collected using a small hand trowel, placed in lock seal plastic bags and laid flat

in a secure container for transportation to the research laboratory, Department of Environmental Biology, Curtin University of Technology. Field observations on the soil type and characteristics of the crusts (texture, colour, cohesiveness) were recorded as well as any obvious disturbance to the area.

#### 5.2.2.2 Laboratory techniques: Moistened soil method (MSM)

Dried soil crust samples were examined for cohesiveness and those of similar size were selected for rewetting. The biological components were studied by following the MSM (moistened soil method) technique adapted from Johansen *et al.* (2001). Three to five grams of crust from each of the sites were placed in petri dishes, moistened with 10 ml of deionised water. The petri dishes were placed under 12:12 h neon illumination for a period of 28 days, rewetting when needed.

Observations of the crusts were made daily to record changes in appearance. Each crust was also examined microscopically using a Leica MZ6 stereo microscope. Wet mounts were made of any obvious algal component and examined under high magnification. Sub-samples from all the crusts were examined under high power at the termination of the trials. Crusts were photographed using an Olympus CZH10 stereomicroscope with an Olympus SC35 mounted camera. The biological components of the crusts were recorded qualitatively and taxa identified to their lowest possible category with available literature. Classification of the cyanobacteria was made according to Bourrelly (1970) and Geitler (1985). The bryophytes were identified using Meagher and Fuhrer (2003).

## 5.3 Results

### 5.3.1 Flora and vegetation

In total, 84 plant species were recorded from the study sites in Lake Yindarlgooda, representing 52 genera and 26 families. The Chenopodiaceae (29), Poaceae (8), Asteraceae (6), Myoporaceae (5) and Mimosaceae (3) displayed the greatest species diversity of the families recorded. These five families accounted for 51 of the total 84 species recorded (Appendix 5.1). Of the species identified from the seven study sites, none were assigned to special conservation status under the Wildlife Conservation (Rare Flora) Notice (1994) and Declared Rare and Priority Flora List for Western Australia (Atkins 1996).

Seven vegetation map-units, categorised into three broad vegetation groups, were described from the study sites at Lake Yindarlgooda (Table 5.2; Figure 5.2). The vegetation composition and structure is similar for all seven sites assessed along the immediate margins of Lake Yindarlgooda, but changed abruptly with increasing distance from the lake edge. The commencement of the incline marked the transitional zone between the non-vegetated sediment of the lake bed and the first vegetation complex. The surrounding relief and the potential for periodic inundation, following significant rainfall, dictated the distance of the transitional zone.

**Table 5.2:** Description of the map-units identified at lake Yindarlgooda, Lake Penny and Swan Refuge (November 2001).

Map-unit	Description
<b>1</b>	<b>HALOPHYTIC SHRUBLANDS</b>
1A	<i>Halosarcia</i> Dwarf Scrub D
1B	<i>Atriplex</i> / <i>Frankenia</i> / <i>Hemichroa</i> Dwarf Scub C
1C	<i>Cratystylis subspinescens</i> Open Low Scrub B above <i>Gunniopsis quadrifida</i> Open Dwarf Scrub D
<b>2</b>	<b>LOW WOODLANDS</b>
2A	<i>Acacia ramulosa</i> / <i>Eremophila miniata</i> Low Woodland B
2B	<i>Callitris</i> Open Low Woodland B over <i>Lawrencia helmsii</i> Open Dwarf Scrub C on Low Kopi Dunes
2C	Mulga / <i>Callitris</i> Open Low Woodland A over <i>Gunniopsis quadrifida</i> Dwarf Scrub D
<b>3</b>	<b>HUMMOCK GRASSLANDS</b>
3A	<i>Eucalyptus griffithsii</i> Open Tree Mallee over Mid-Dense <i>Triodia basedowii</i> Hummock Grassland

### 5.3.1.2 Description of map-units

#### *Map-unit 1A: Halosarcia Dwarf Scrub D*

For all seven sites surveyed, the broad structural classification of the first halophytic community encountered along the beach area was *Halosarcia* Dwarf Scrub D, with the low shrub cover generally less than 0.5 m in height. The soil was a heavy clay medium with evidence of salt crusting.

The Chenopodiaceae, including *Halosarcia*, *Atriplex* and *Maireana*, dominated the low shrubland cover with other taxa including *Frankenia*, *Cratystylis* and *Gunniopsis* also present (Table 5.3). The change in species composition with distance from the lake edge was attributed to increasing relief, change in soil type, and susceptibility to episodic inundation.

*Halosarcia halocnemoides* dominated within the lowest points closest to the lake proper. *H. pergranulata*, *H. undulata* and *Frankenia setosa* were other dominants

situated on slightly higher ground, occurring with *Maireana amoena*, *M. appressa*, *Frankenia pauciflora*, *Gunniopsis quadrifida*, *Atriplex nana*, *Dysphyma crassifolium* ssp. *clavellatum*, *Scaevola collaris* and *Zygophyllum* spp. The grass *Eragrostis dielsii* and the daisies *Kippistia suaedifolia* and *Senecio lautus* best represented the ephemerals in the ground cover.

**Table 5.3:** Species common to *Halosarcia* Dwarf Scrub D. Map-unit 1A.

Low Shrubs	Ground Cover
<i>Halosarcia halocnemoides</i>	<i>Eragrostis dielsii</i>
<i>Halosarcia pergranulata</i>	<i>Austrostipa elegantissima</i>
<i>Halosarcia undulata</i>	<i>Enneapogon caerulescens</i>
<i>Frankenia setosa</i>	<i>Kippistia suaedifolia</i>
<i>Frankenia pauciflora</i>	<i>Senecio lautus</i>
<i>Atriplex nana</i>	<i>Podolepis capillaris</i>
<i>Maireana amoena</i>	<i>Dysphania kalpari</i>
<i>Maireana appressa</i>	
<i>Gunniopsis quadrifida</i>	
<i>Disphyma crassifolium</i>	
<i>Scaevola collaris</i>	
<i>Zygophyllum</i> spp.	
<i>Atriplex codonocarpa</i>	
<i>Sclerolaena eriacantha</i>	

*Map-unit 1B: Atriplex/Frankenia/Hemichroa Dwarf Scrub C*

Shallow aeolian quartz sand interspersed with shallow pockets of gypsum extend up to 100 m from the samphire flats of the lake margin. Low shrubs less than 1m tall provided up to 30% ground coverage and were the prominent life form within Map-unit 1B (Table 5.4; Figure 5.2).

The dominant plant taxa were *Atriplex vesicaria*, *Frankenia setosa* and *Hemichroa diandra*, growing to a height of 0.7 m and forming Dwarf Scrub C. Plants grew on raised pockets of coarse sand and a general increase in species richness was recorded within this zone in comparison to Map-unit 1A.

A variety of low shrubs in association with the dominants included *Gunniopsis quadrifida*, *Darwinia diosmoides* (Site 2), *Maireana glomerifolia*, *M. pentatropis*, *Ptilotus obovatus* and *Solanum orbiculatum*. The ground cover comprised of shrubs and grasses including *Disphyma crassifolium* ssp., *Swainsona affinis*, *Sclerolaena* spp., *Eragrostis dielsii* and *Austrostipa* spp.

**Table 5.4:** Species common to *Atriplex/Frankenia/Hemichroa* Dwarf Scrub C. Map-unit 1B.

Low Shrubs	Ground Cover
<i>Atriplex vesicaria</i>	<i>Swainsona affinis</i>
<i>Frankenia setosa</i>	<i>Sclerolaena eriacantha</i>
<i>Frankenia pauciflora</i>	<i>Sclerolaena diacantha</i>
<i>Halosarcia</i> spp.	<i>Disphyma crassifolium</i>
<i>Gunniopsis quadrifida</i>	<i>Eragrostis dielsii</i>
<i>Maireana glomerifolia</i>	<i>Podolepis capillaris</i>
<i>Darwinia diosmoides</i>	<i>Austrostipa elegantissima</i>
<i>Maireana amoena</i>	<i>Austrostipa scabra</i>
<i>Maireana petatropis</i>	
<i>Maireana tomentosa</i>	
<i>Maireana pyramidata</i>	
<i>Lycium australe</i>	
<i>Ptilotus obovatus</i>	
<i>Solanum lasiophyllum</i>	
<i>Solanum orbiculatum</i>	

Map-unit 1C: *Cratystylis subspinescens* Open Low Scrub B above *Gunniopsis quadrifida* Open Dwarf Scrub D

Inland from the lake margins at Site 1 the soils were of heavy clay and the plants were categorised as Map-unit 1C. *Cratystylis subspinescens* was a dominant mid shrub to 1.2 m in height, cohabiting with *Eremophila miniata*, *E. scoparia* and *Senna filifolia* to form Open Low Scrub. *Gunniopsis quadrifida* was dominant in an otherwise open ground cover comprising a variety of low shrubs typically found along the shore, including *Atriplex vesicaria*, *Frankenia pauciflora* and *Maireana tomentosa* (Table 5.5; Figure 5.2). The prostrate grass *Eragrostis dielsii* had a patchy distribution between the taller shrubs.

**Table 5.5:** Species common to *Cratystylis subspinescens* Open Low Scrub B above *Gunniopsis quadrifida* Open Dwarf Scrub D. Map-unit 1C.

Mid Shrubs	Low Shrubs	Ground Cover
<i>Cratystylis subspinescens</i>	<i>Gunniopsis quadrifida</i>	<i>Eragrostis dielsii</i>
<i>Eremophila miniata</i>	<i>Atriplex vesicaria</i>	<i>Sclerolaena eriacantha</i>
<i>Eremophila scoparia</i>	<i>Frankenia pauciflora</i>	<i>Sclerolaena diacantha</i>
<i>Senna filifolia</i>	<i>Solanum lasiophyllum</i>	
<i>Maireana pyramidata</i>	<i>Ptilotus obovatus</i>	
	<i>Maireana tomentosa</i>	

*Map-unit 2A: Acacia ramulosa/Eremophila miniata* Low Woodland B

Map-unit 2A occurred on red sandy soils immediately inland of *Halosarcia* Dwarf Scrub D at Swan Refuge and Site 4. The most prominent stratum of this unit were *Acacia ramulosa* and *Eremophila miniata* which formed the dominant components of the upperstorey vegetation cover, as trees and shrubs. Less conspicuous contributors to the canopy included *Acacia aneura*, *A. tetragonophylla*, *Casuarina obesa*, *Melaleuca lateriflora* and *Callitris glaucophylla*.

Salt tolerant mid and low shrub species, including chenopods and eremophilas, were recorded in the understorey of Map-unit 2A (Table 5.6, Figure 5.2). Species dominance was evenly spread between the above taxa. The grasses *Monochather paradoxus* and *Eragrostis eriopoda*, were common at ground level.

**Table 5.6:** Species common to *Acacia ramulosa/Eremophila miniata* Low Woodland B. Map-unit 2A.

Trees / Tall Shrubs	Mid Shrubs	Low Shrubs	Ground Cover
<i>Acacia ramulosa</i>	<i>Eremophila scoparia</i>	<i>Atriplex vesicaria</i>	<i>Monochather paradoxus</i>
<i>Eremophila miniata</i>	<i>Pimelea microcephala</i>	<i>Atriplex codonocarpa</i>	<i>Eragrostis eriopoda</i>
<i>Acacia aneura</i>	<i>Dodonaea viscosa</i>	<i>Dissocarpos paradoxus</i>	<i>Austrostipa elegantissima</i>
<i>Casuarina obesa</i>	<i>Senna filifolia</i>	<i>Maireana georgei</i>	<i>Austrostipa scabra</i>
<i>Melaleuca lateriflora</i>	<i>Eremophila glabra</i>	<i>Maireana triptera</i>	<i>Aristida contorta</i>
<i>Acacia tetragonophylla</i>	<i>Cratystylis subspinescens</i>	<i>Enchylaena tomentosa</i>	<i>Eragrostis dielsii</i>
<i>Callitris glaucophylla</i>	<i>Scaevola spinescens</i>	<i>Solanum orbiculatum</i>	
	<i>Rhagodia drummondii</i>	<i>Ptilotus obovatus</i>	
	<i>Eremophila serrulata</i>	<i>Sclerolaena diacantha</i>	
		<i>Solanum lasiophyllum</i>	

*Map-unit 2B: Callitris Open Low Woodland B over Lawrencia helmsii Open Dwarf Scrub C on Low Kopi Dunes*

Map-unit 2B was restricted to narrow kopi (calcium sulphate) dunes of aeolian deposition. Surface kopi layers were covered by a hardened crust, below which materials are friable. *Callitris glaucophylla* was restricted to the gypsum medium occurring as a scattered low tree (less than 5 m in height) above the distinctive low shrub *Lawrencia helmsii*, which forms Open Dwarf Scrub C. Other characteristic species at ground level included *Sclerolaena fimbriolata* (low shrub), the grasses *Austrostipa elegantissima*, *A. scabra*, *Aristida contorta*, *Enneapogon caerulescens* and *Eragrostis dielsii*, and the daisy *Kippistia suaedifolia* (Table 5.7, Figure 5.2).

Although not prominent components of Map-unit 2B, a number of mid-level shrubs were recorded including the succulents *Lycium australe* and *Maireana amoena*, *Senna filifolia*, *Eremophila miniata*, *E. scoparia* and *Rhagodia drummondii*.

The more common low shrubs included *Frankenia setosa*, *F. pauciflora*, *Atriplex vesicaria*, *A. nana*, *Maireana glomerifolia*, *M. pentatropis*, *M. amoena*, *Swainsona affinis* and *Sclerolaena diacantha*.

*Map-unit 2C: Mulga/Callitris Open Low Woodland A over Gunniopsis quadrifida Dwarf Scrub D*

This map-unit occurred on the banks of deep red/orange quartz sand bordering Lake Yindarlgooda at Site 1. *Acacia aneura*, *Callitris glaucophylla* and *Eremophila miniata* were the characteristic upperstorey species up to 6 m tall and forming Open Low Woodland A. Other scattered tall shrubs included *Pittosporum phylliraeoides* and *Eremophila scoparia*, above *Exocarpos aphyllus*, *Dodonaea viscosa*, *Maireana sedifolia* and *Cratystylis subspinescens* (Table 5.8, Figure 5.2).

Mid shrubs were scattered but include *Eremophila scoparia*, *Scaevola spinescens*, *Dodonaea lobulata*, *Sida calyxhymenia*, *Rhagodia drummondii* and *Enchylaena tomentosa*. The two latter species were common around the base of mulga trees (*A. aneura*). The dominant low shrub (less than 0.5 m tall) in the Dwarf Scrub D cover was *Gunniopsis quadrifida*, cohabiting with *Ptilotus obovatus*, *Atriplex vesicaria*, *Hemichroa diandra*, *Solanum lasiophyllum*, *S. orbiculatum* and *Zygophyllum aurantiacum*. A suite of grasses and daisies completed the ground layer. *Aristida contorta* and *Eragrostis eriopoda* were the dominant grasses, with *Enneapogon*



*caerulescens* prominent in basins of lower lying ground. *Austrostipa* species occurred in more open areas with *Eragrostis dielsii* and *Calandrinia polyandra*. Isolated patches of *Triodia basedowii* were observed forming characteristic rings.

**Table 5.7:** Species common to *Callitris* Open Low Woodland B over *Lawrencia helmsii* Open Dwarf Scrub C on Low Kopi Dunes. Map-unit 2B.

Trees	Mid Shrubs	Low Shrubs	Ground Cover
<i>Callitris glaucophylla</i>	<i>Lycium australe</i>	<i>Lawrencia helmsii</i>	<i>Austrostipa elegantissima</i>
	<i>Maireana amoena</i>	<i>Frankenia setosa</i>	<i>Austrostipa scabra</i>
	<i>Senna filifolia</i>	<i>Frankenia pauciflora</i>	<i>Aristida contorta</i>
	<i>Eremophila miniata</i>	<i>Atriplex vesicaria</i>	<i>Enneapogon caerulescens</i>
	<i>Eremophila scoparia</i>	<i>Atriplex nana</i>	<i>Eragrostis dielsii</i>
	<i>Rhagodia drummondii</i>	<i>Maireana glomerifolia</i>	<i>Kippistia suaedifolia</i>
		<i>Maireana pentatropis</i>	<i>Asteridea chaetopoda</i>
		<i>Maireana amoena</i>	
		<i>Swainsona affinis</i>	
		<i>Sclerolaena fimbriolata</i>	
		<i>Sclerolaena diacantha</i>	
		<i>Solanum lasiophyllum</i>	

**Table 5.8:** Species common to Mulga/*Callitris* Open Low Woodland A over *Gunniopsis quadrifida* Dwarf Scrub D. Map-unit 2C.

Trees / Tall Shrubs	Mid Shrubs	Low Shrubs	Ground Cover
<i>Acacia aneura</i>	<i>Scaevola spinescens</i>	<i>Gunniopsis quadrifida</i>	<i>Aristida contorta</i>
<i>Callitris glaucophylla</i>	<i>Lycium australe</i>	<i>Atriplex vesicaria</i>	<i>Enneapogon caerulescens</i>
<i>Eremophila miniata</i>	<i>Rhagodia drummondii</i>	<i>Ptilotus obovatus</i>	<i>Austrostipa scabra</i>
<i>P. phylliraeoides</i>	<i>Sida calyxhymenia</i>	<i>Enchylaena tomentosa</i>	<i>Eragrostis dielsii</i>
<i>Eremophila scoparia</i>	<i>C. subspinescens</i>	<i>Hemichroa diandra</i>	<i>Monochather paradoxa</i>
	<i>Exocarpos aphyllus</i>	<i>Solanum orbiculatum</i>	
	<i>Dodonaea viscosa</i>	<i>Solanum lasiophyllum</i>	
	<i>Maireana sedifolia</i>	<i>Zygophyllum aurantiacum</i>	

*Map-unit 3A: Eucalyptus griffithsii* Open Tree Mallee over Mid-Dense *Triodia basedowii* Hummock Grassland

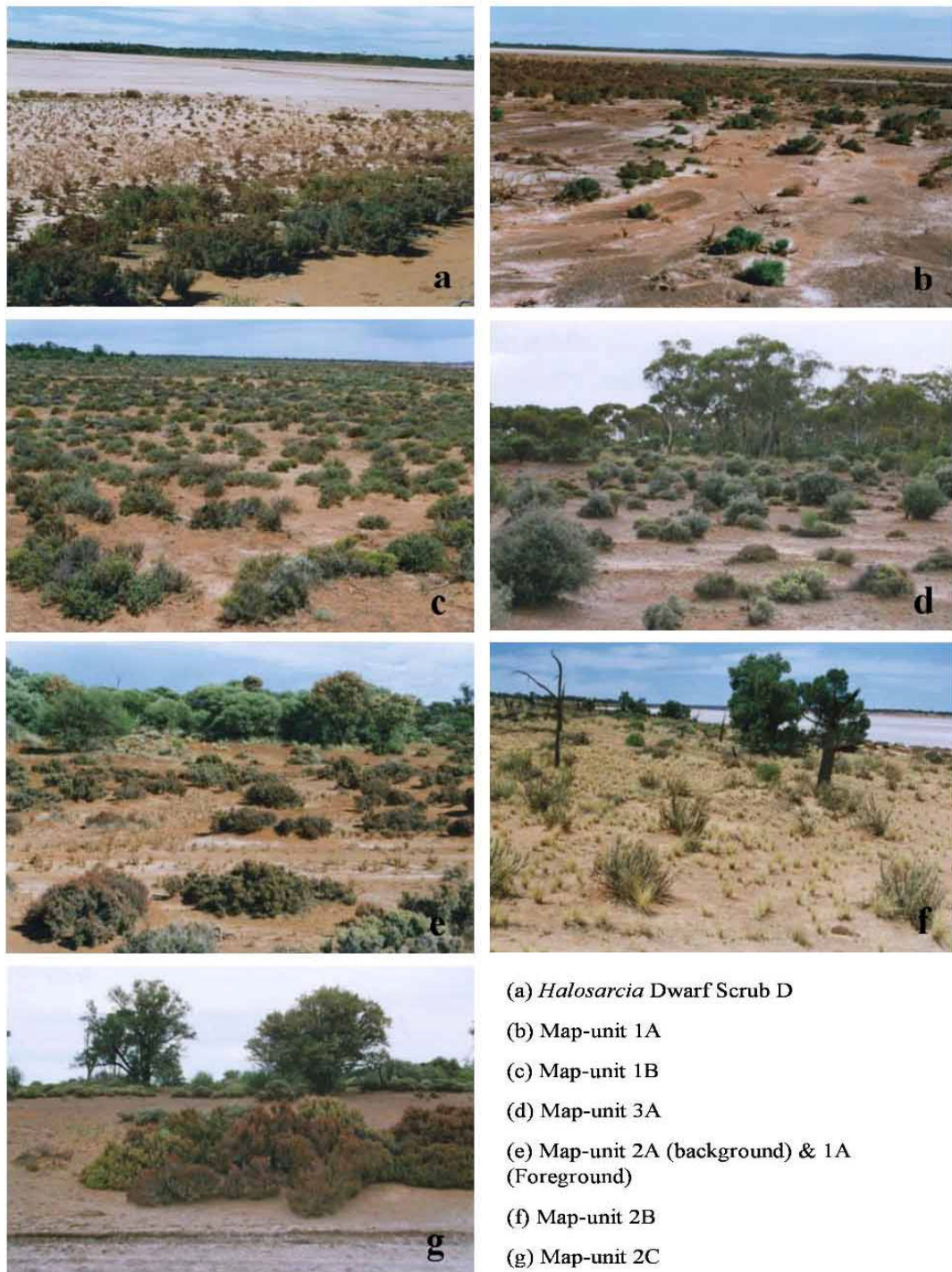
Map-unit 3A was characterised by the spinifex hummock grassland supported by deep earthy red sands. The sandplain complex occurred around the base of a banded ironstone ridge extending east and inland of Map-unit 2C.

*Eucalyptus griffithsii* was the dominant upperstorey species as open tree mallee to a height approximating 8 m. Occasional trees of *Acacia aneura* were present. A

mixture of scattered mid and low shrubs to 1.5 m in height included *Dodonaea lobulata*, *Eremophila scoparia*, *Scaevola spinescens* and *Solanum lasiophyllum* (Table 5.9, Figure 5.2). *Triodia basedowii* provided up to 70 % ground cover, forming mid-dense hummock grassland. *Eragrostis eriopoda* occurred in localised patches amongst the spinifex.

**Table 5.9:** Species common to *Eucalyptus griffithsii* Open Tree Mallee over Mid-Dense *Triodia basedowii* Hummock Grassland. Map-unit 3A.

<b>Mallee / Tall Shrubs</b>	<b>Mid / Low Shrubs</b>	<b>Ground Cover</b>
<i>Eucalyptus griffithsii</i>	<i>Dodonaea lobulata</i>	<i>Triodia basedowii</i>
<i>Acacia aneura</i>	<i>Eremophila scoparia</i>	<i>Eragrostis eriopoda</i>
	<i>Scaevola spinescens</i>	
	<i>Exocarpos aphyllus</i>	
	<i>Senna filifolia</i>	
	<i>Solanum lasiophyllum</i>	
	<i>Rhagodia drummondii</i>	
	<i>Enchylaena tomentosa</i>	
	<i>Solanum lasiophyllum</i>	



**Figure 5.2:** Vegetation map units for Lake Yindarlgooda, Swan Refuge and Lake Penny, *Halosarcia* Dwarf Scrub D through to Map-unit 3A. Vegetation units classified according to (Muir 1977).

### 5.3.2 Soil crusts

#### 5.3.2.1 Field observations and description of soil crust

Soil crusts were recorded from sites 1, 2, 3 and 6, both as physical or biological crusts (Table 5.10). Large areas of the riparian zones in the southern sites 1, 2 and 3 were covered by intact crusts. These extended from just above the non-vegetated lake bed and into the riparian zone. The dark crust covering large parts of Site 1 was uniform and classified as smooth. While remaining intact on collection, it readily crumbled with the application of slight force (Figure 5.3a). The vegetation at this site was sparse. There were minimal signs of any water retention along the rise, the soil comprised of heavy clays at the lake margins while the banks were deep red/orange quartz sand.

A light brown, uniform crust covered the riparian zone of Site 2 extending from the base of the slope and into the scrubland (Figure 5.3b). The uniformity of the structure and colour of the crusts classified it as smooth. The vegetation at Site 2 was typically sparse. The soil was heavy clay at the lake margins with the riparian zone on low kopi (calcium sulphate) dunes. The soil beneath the crust was slightly damp and when collected, the crust remained intact though crumbled readily with the application of slight force. There were no signs of any disturbance at this site by livestock, though there marsupial scats were observed.

The greatest morphological and colour variation was observed in the crusts from Site 3. This site had an undisturbed (Figure 5.3c), cohesive rugose (pustular) crust that was pinkish in colour, intermingled with black and white segments (Figure 5.3d). Distribution of the crust was patchy amongst the vegetation, with thicker clumps of crust occurring next to low shrubs of *Lawrenzia helmsii* (Figure 5.3e). The vegetation at this site was a halophytic shrubland complex closer to the lake margins with *Callitris* open woodland over *Lawrenzia helmsii* open dwarf scrub restricted to narrow, low-rise kopi dunes. The crust was cohesive, remaining intact on collection and broke in large pieces rather than crumbling. The water retention appeared higher with the soil below the crust moist.

Site 6 in the northern section of the lake contained scatterings of soil crusts with a homogenous distribution. The crust appeared as a fine black surface covering with patches of slightly thicker crust in areas protected by vegetation. Much of this

showed signs of disturbance, trampled by livestock as evidenced by droppings and hoof prints. The soil was composed of fine red, sandy clay and was very dry. The vegetation was predominantly halophytic shrublands. Closer examination indicated this was a physical or chemical crust rather than a biological crust.

### 5.3.2.2 Microscopic investigations

Regeneration of biota was evident only in the crust sample from Site 3. The crust consisted of a thin layer approximately 1 mm in thickness with small black balls on the surface layer. Below this, the subsurface layer was dark brown and contained fibrous material, presumably rhizoids and possibly dried sheaths of filamentous cyanobacteria (Figure 5.4a). This crust when moistened had fine green filaments entwined over the coarse soil particles (Figure 5.4b & c) and growing over a large quartz pebble (Figure 5.4d). Within a week of hydration, a moss, *Bryum* sp. (Bryophyta: Musci: Bryaceae) had germinated (Figure 5.4b).

Microscopic examination revealed the thick, cohesive filaments of *Microcoleus* sp. Desmazières ex Gomont and smaller trichomes of *Phormidium* sp. Kützing ex Gomont. The thick polysaccharide sheaths of *Microcoleus* sp. were entwined amongst the branched rhizoids and formed a cohesive mass (Figure 5.4e & f). A coccoid chlorophyte and a moss protonema were also observed from the medium.

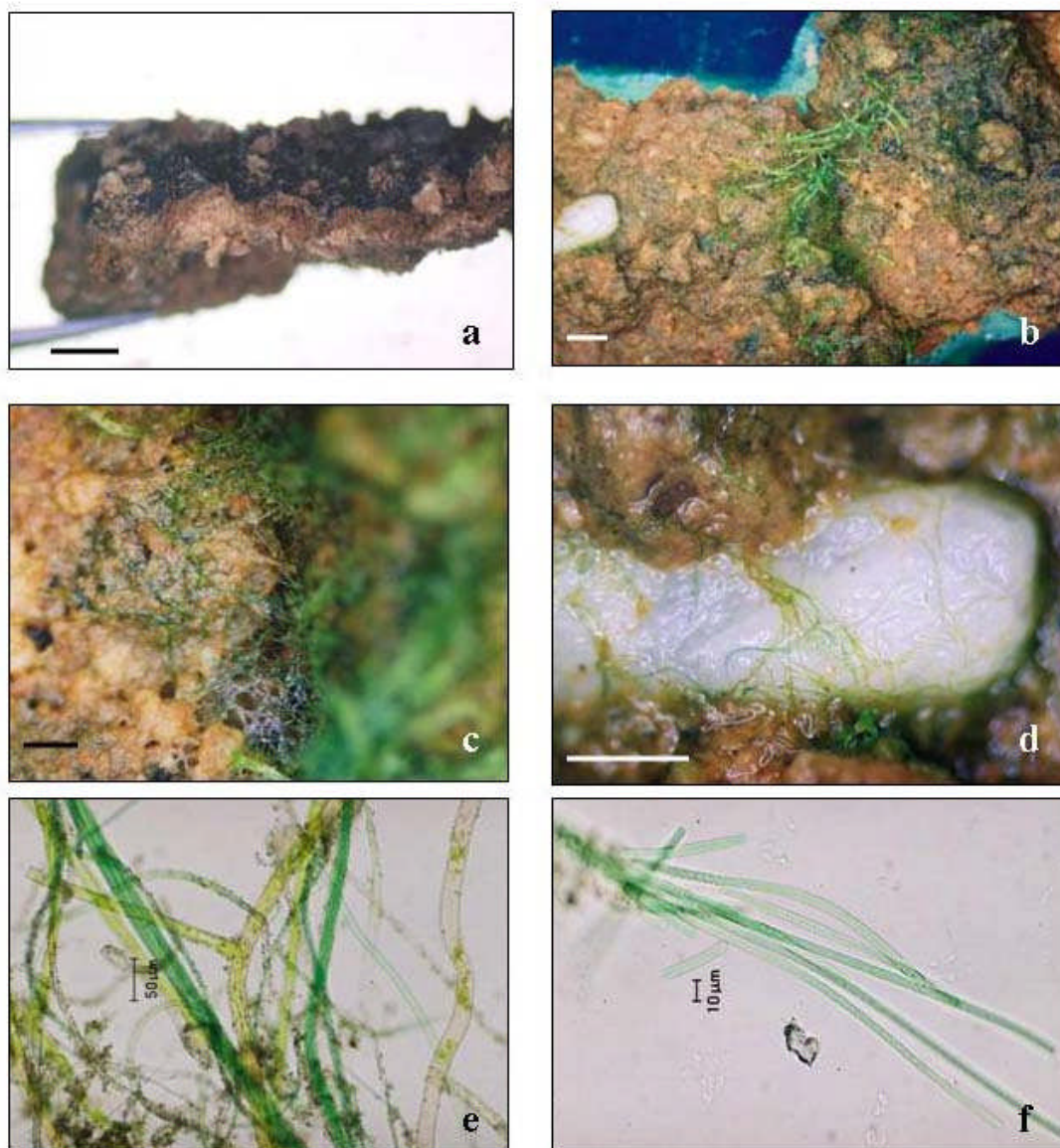
The crust from Site 3, a control site, was the only crust to remain intact when rewetted and retained sufficient moisture, only requiring rewetting every four to five days during the trial. By the end of the 28 days trial the crust was covered in a thick mat dominated by the moss. The crusts from Site 6 (northern control site, but disturbed by livestock) and Site 1 (control, no livestock disturbance) disintegrated upon rewetting. The crust from Site 2, remained intact though showed no colour change. Microscopic investigation of the crusts from sites 1, 2 and 6 did not reveal any biological activity or resting stages.

**Table 5.10:** Topographic classification of soil crusts and field observations for Lake Yindarlgooda. Classifications from Belnap *et al* (2003a).

Sites	Classification	Crust Type	Soil Type	Field Observations	Taxa
Site 1	Smooth	Physical	Quartz sand/pebbles	Black crust extending from shoreline into the riparian zone. Crust cohesive, remaining intact when collected, readily crumbled. Undisturbed site.	None recorded
Site 2	Smooth	Physical	clay/kopi	Light coloured, hard crust extending throughout the riparian zone. No variation in texture or colour. Cohesive, remained hard, though brittle and easily crumbled with minimal force. Undisturbed site.	None recorded
Site 3	Rugose	Biological	clay/kopi	Cohesive mat. Variation in structure and colour; black clumps amongst smooth pink crust. Extended from shoreline throughout the riparian zone. Crust remained intact when collected and broke into cohesive pieces when force was applied. Undisturbed site.	<u>Cyanobacteria</u> <i>Microcoleus</i> sp. <i>Phormidium</i> sp. <u>Algae</u> <u>Chlorophyta</u> Chlorococcales <u>Moss (Musci)</u> <i>Bryum</i> sp.
Site 6	Smooth	Physical	sandy clay	Very fine speckled covering, black crust remaining in small sections. Livestock disturbance. Uncohesive	None recorded



**Figure 5.3:** Soil crusts from Lake Yindarlgooda. (a) Site 1. Uniform, smooth black crust (physical/abiotic). Insert indicates cohesiveness on collection (b) Site 2. Uniform, smooth light brown crust (abiotic). (c) Site 3. Biological soil crust (rugose) seen throughout the riparian zone. (d) Rugose crust, Site 3, with small black clumps forming a cohesive layer. (e) Rugose crust next to *Lawrencia helmsii*, Site 3.



**Figure 5.4:** Microscopic examination of biological soil crust from Site 3. **(a)** Transverse view of dried, rugose crust (~ 1 mm thickness). Rhizoids extended into the darker brown sections of the aggregated soil particles (endedaphic zone) (Scale bar = 10 mm). **(b)** Moistened crust after 14 days; young, leafy moss growing across crust. Patches of green consisting of *Microcoleus* sp. and *Phormidium* sp. (scale bar = 1 mm). **(c)** Branched rhizoids forming a net intertwined with cyanobacteria filaments over moistened crust. (Scale bar = 1 mm). **(d)** Close up of figure (b) with filaments growing over quartz pebble. Darker green filaments of *Microcoleus* sp. and olive coloured rhizoids. (Scale bar = 1 mm). **(e)** Filaments of *Microcoleus* sp.; trichomes (dark green) amongst rhizoids (olive coloured and branching). **(f)** *Microcoleus* trichomes teased out from their sheath.



## 5.4 Discussion

Riparian zones are considered the interface between the terrestrial and aquatic ecosystems, they are not easily delineated and comprise a mosaic of different landforms, communities and habitats. Their boundaries extend outward to the limits of flooding and upward into the canopy (Gregory *et al.* 1991). The riparian zone of Lake Yindarlgooda was identified as extending from the lake floor, continuing up the rise. Vegetation was typically sparse and zonation was evident from the vegetation communities identified and appeared affected by salinity and inundation with all sites recoding a *Halosarcia* community as the immediate fringing vegetation.

The vegetation communities fringing Lake Yindarlgooda and the wetlands were typical of that found in other salt lakes in the Eastern Goldfields dominated by the Chenopodiaceae (Hacker 1987; Finucane 2001; Barrett 2006). Zonation was apparent with *Halosarcia halocnemoides* the dominant at the lowest points on the lake edge at all sites. This species has been recorded as being able to tolerate high salinities of up to 90 mS cm<sup>-1</sup> (Barrett 2006) indicating these areas are the most saline of the riparian zone. This area also had the highest susceptibility to inundation, again characteristic of this species (Datson 2002). As the gradient increased at sites 1 to 3 the soil type and vegetation communities changed accordingly with a greater species richness and diversity away from the shoreline, again indicating a decrease in salinity. Studies by Ungar (1974) found that as salinity decreased along the riparian zone of salt marshes the species diversity and densities increased.

While riparian zones are regarded as areas of potentially high productivity (Gregory *et al.* 1991; Decamps and Tabacchi 1994; Schindler and Scheuerell 2002) this is not always reflected in arid zones (Bunn *et al.* 2003) where the vegetation is typically sparse (Davis *et al.* 1993; Finlay 2001). Riparian vegetation controls the quantity and type of terrestrially derived organic matter that enters the aquatic systems (Gregory *et al.* 1991). The arid zones are nutrient deficient due to their antiquity (Stafford Smith and Morton 1990) and many of the plants have adapted to these conditions, though the output of nitrogen and carbon are therefore less than in more temperate and tropical climates. The total organic carbon levels recorded from Lake Yindarlgooda and the wetlands indicate low inputs with little variation among the Lake Yindarlgooda control sites, while the wetlands recorded higher levels (Chapter

3.0). The source of the carbon levels are difficult to determine, though observation of the sites indicates a high contribution from within the clay pans rather than the riparian zone (Chapter 4.0). Studies by Bunn *et al.* (2003) found that carbon inputs in arid zone rivers were of primary origin such as benthic algae and submerged macrophytes, rather than from terrestrial sources.

The effects of shading from the riparian vegetation are not a factor in Lake Yindarlgooda or Lake Penny with the fringing vegetation seldom close to the waters edge. The trophic structure of the aquatic invertebrate community is influenced by the type of allochthonous and autochthonous inputs (Gregory *et al.* 1991). The aquatic invertebrate community identified in Lake Yindarlgooda were sediment feeders and no shredders were recorded (Chapter 4.0). The absence of a number of different functional groups in the George Gill River, a relict arid stream, reflected the lower riparian input (Davis *et al.* 1993). While salinity has a strong influence on species diversity, in saline systems habitat homogeneity can be a controlling factor (Timms 1997).

Biological soil crusts cover extensive sections of the arid and semi-arid regions of the world (Belnap and Lange 2003) and are a common component of these regions in Australia (Eldridge 2003). They have shown to be important, not only in the stabilisation of the desert soil, but also in the retention of water and contribution to soil fertility as a result of the interactions of their biotic components (Johansen *et al.* 2001). Salt lakes are characteristically flat depressions that are enclosed by gypsum dunes of low relief. Drainage is endohreic and the riparian vegetation sparse. Stabilisation of these sandy soils surrounding the salt lakes is important in minimising siltation.

Biological soil crusts can be found on all soil types but are limited on clay soils, preferring the sandier soils with sparse vegetation (Belnap *et al.* 2003a). The variation in the type of crust from Site 1 to Site 3 was impressive. The crusts at site 1 and 2 were classified as chemical rehydration did not reveal any biological activity. Australian microbiotic crusts usually occur in association with chemically crusted surfaces (Eldridge 2003), though this was not observed in this study.

The soil crust at Site 3 was shown to be biological with exceptional binding properties, both when collected dry and on rewetting. *Microcoleus* sp., was one of the dominant components and is the most common cyanobacterium in microbiotic

crusts (Johansen *et al.* 2001) and together with the rhizoids of the moss succeeded in bind the soil aggregates. While the cyanobacteria have shown to provide more protection than eukaryotic green algae, when the crust associations include lichens and mosses the binding properties are greater than those of cyanobacteria alone (Belnap 2003a).

Research in Australia has shown that the flow of water and the movement of sediments over the soil surface have been influenced by the presence of microbiotic crusts (Eldridge 2003). The area located between the growing moss traps and transfers water to sections lower in the soil profile (Rogers 1982), an adaptation beneficial in semi-arid environments. Crusts can reduce the infiltration of water into soil subsurface by creating a hydrophobic surface (Greene and Tongway 1989) or by the swelling of the mucilaginous cyanobacteria (Belnap *et al.* 2003b). This in turn increases the amount of runoff while limiting sediment loss.

The northern control sites 6 and 7 in Lake Yindarlgooda were exposed to livestock, mostly sheep. The areas were severely trampled and very little in the way of crusts were found. Trampling is considered the most common disturbance caused by grazing animals to biological soil crusts. Within Australian and North America there is a growing consensus that the presence of these microbiotic crusts in the arid and semi-arid regions are indicators of healthy and stable landscapes (Warren and Eldridge 2003).

Recovery time after wind disturbance is much faster in soil with inherent aggregated stability, such as clays and gypsum with coarse soils shown to limit crust recovery (Belnap 2003a). Because the biological component of crusts are only active when wet, recovery in the arid zones can be slow. Soil characteristics that reduce wind erosion include rock cover, high salt or calcium carbonate content, high clay/silt content, physical crusts and extensive biological soil crusts. The coarse texture soils are more erodible when disturbed as they lack the clay and salt that eventually form a physical crust to prevent erosion. When biological soil crust are disturbed large aggregates are left, bound by unbroken filaments (Belnap and Gillette 1997; 1998). The red soils of Australia's semi-arid are susceptible to sheet erosion, particularly when vegetation cover is reduced, as much of the area has low relief (Tongway and Smith 1989).

Compared to biological soil crust studied in other countries the species diversity recorded from Lake Yindarlgooda was low. Hawkes and Flechtner (2002) recorded 35 morphotypes of cyanobacteria and eukaryotic algae in crusts from Florida, USA, compared to three at Lake Yindarlgooda. A comparison of crusts on salt lake margins from Tunisia and South Australia by Ullman and Budel (2003) found the average number of species was two and dominated by *Microcoleus* sp., a similar finding to this study. While rangeland biological soil crusts may have a high diversity of components those associated with salt lake margins may be typically low.

Associations with vegetation complexes and biological soil crust have been described (see Belnap and Lange 2003 for an extensive review). While some studies have found a negative relationship between biological soil crusts and plant cover (Johansen 1993) they also have a positive influence on plant growth in the arid regions of Australia (Graetz and Tongway 1986) especially after seed establishment. Water and nutrients are generally limiting factors in arid environments (Tongway and Ludwig 1990) and the water retention capability and increase in mineral uptake by vascular plants in the presence of biological soil crusts are beneficial (Graetz and Tongway 1986; Harper and Belnap 2001). Along the playa margins of Lake Gilles, South Australia, 50% of the crusts sampled were associated with halophytic plant communities such as *Halosarcia* and *Frankenia* species (Ullman and Budel 2003). The crust recorded from Site 3 in Lake Yindarlgooda was found growing alongside *Lawrencia helmsii*, a holophytic plant found on kopi or gypsum-based dunes in the Goldfield region of Western Australia (Mitchell and Wilcox 1994). Similar observations were made at Lake Maitland in the Northern Goldfields, with communities of *L. helmsii* on calcrete dunes and the entire area in between each plant covered by a *Microcoleus* dominated crust (*pers. obs.*). Distinct spatial patterns of the biological crust as seen in Lake Gilles may be true of many playas in Australia, not excluding Lake Yindarlgooda.

## Conclusions

The riparian zone of Lake Yindarlgooda is characteristically sparse compared to those of more temperate environments, though with a total of 84 plant species recorded from 26 families, it was not poor. The area was dominated by the Chenopodiaceae, typical of inland Australia. The species diversity and richness was

dictated by salinity and the affects of water logging with diversity increasing along the gradient at the southern control sites 1 to 3. The input of terrestrial carbon from the riparian zone appears to be low due to the type of vegetation. Habitat heterogeneity was not observed in Lake Yindarlgooda.

Both physical and biological soil crusts were recorded intact from the southern control sites and covered extensive areas of the riparian zone, left bare by vascular plants. The biological soil crust in this study was found to be an association between filamentous cyanobacteria, *Microcoleus* sp. and *Phormidium* sp. and a moss, *Bryum* sp. The intertwining of the filaments and rhizoids of the components formed a strongly cohesive structure that readily rehydrated and became active immediately after rewetting.

While the presence of productive biological soil crusts appear limited to one site, in the context of this study, the extensive physical soil crusts play an important role in the stability of the riparian zones. The importance of these crusts in the riparian zone of inland playas warrants further research. The distribution of biological soil crusts is determined by factors such as soil texture, pH, and salinity and further studies may indicate their limiting factors in Western Australian salt lakes, and used for rehabilitation work in these regions. While this study was limited, the presence of biological soil crusts were identified in Lake Yindarlgooda and their components identified, for the first time.

### Appendix 5.1.

Flora collected from the seven Lake Yindarlgooda study sites. Botanical names after Green (1985, 1987), common names from a variety of sources.

<b>Botanical Name</b>		<b>Common Name</b>
<b>AIZOACEAE</b>		
<i>Disphyma crassifolium</i> ssp.	L. Bolus	pigface
<i>Gunnioopsis quadrifida</i>	(F. Muell.) Pax in Engl.	sweet samphire
<b>AMARANTHACEAE</b>		
<i>Hemichroa diandra</i>	R. Br.	
<i>Ptilotus exaltatus</i>	Nees in Lehm.	pink mulla mulla
<i>Ptilotus obovatus</i>	(Gaudich.) F. Muell.	cotton bush
<b>ASTERACEAE</b>		
<i>Asteridia chaetopoda</i>	(F. Muell.) G. Kroner	
<i>Brachycome ciliaris</i>	(Labill.) Less.	variable daisy
<i>Cratystylis subspinescens</i>	F. Muell. & Tate	sage
<i>Kippistia suaedifolia</i>	F. Muell.	yellow buttons
<i>Podolepis capillaris</i>	(Steetz) Diels in Diels	invisible grass
<i>Senecio lautus</i>	G. Forster ex Willd.	groundsel
<b>CAESALPINIACEAE</b>		
<i>Senna artemisioides</i> ssp. <i>filifolia</i>	Gaudich. in DC.	desert cassia
<b>CASUARINACEAE</b>		
<i>Casuarina obesa</i>	Miq. In Lehm.	swamp oak
<b>CHENOPODIACEAE</b>		
<i>Atriplex codonocarpa</i>	P. Wilson	flat-topped saltbush
<i>Atriplex nana</i>	Parr-Smith	salt lake saltbush
<i>Atriplex vesicaria</i>	Heward ex Benth.	bladder saltbush
<i>Chenopodium gaudichaudianum</i>	(Moq.) P. Wilson	scrambling saltbush
<i>Dissocarpus paradoxus</i>	R.Br. F. Muell. ex Ulbr.	cannon balls
<i>Dysphania kalpari</i>	P. Wilson	green crumbweed
<i>Enchylaena tomentosa</i>	R. Br.	ruby saltbush
<i>Halosarcia halocnemoides</i>	(Nees.) P. Wilson	red samphire
<i>Halosarcia pergranulata</i>	(J. Black) P. Wilson	samphire
<i>Halosarcia undulata</i>	P. Wilson	samphire
<i>Maireana amoena</i>	(Diels.) P. Wilson	brittle bluebush
<i>Maireana appressa</i>	(J. Black) P. Wilson	bluebush
<i>Maireana atkinsiana</i>	(W. Fitzg.) P. Wilson	five-pin bluebush
<i>Maireana georgei</i>	(Diels) P. Wilson	George's bluebush
<i>Maireana glomerifolia</i>	P. Wilson	ball-leaf bluebush
<i>Maireana pentatropis</i>	(Tate) P. Wilson	erect mallee bluebush
<i>Maireana pyramidata</i>	(Benth.) P. Wilson	sago bluebush
<i>Maireana sedifolia</i>	(F. Muell.) P. Wilson	pearl bluebush
<i>Maireana tomentosa</i>	Moq.	felty bluebush
<i>Maireana triptera</i>	(Benth.) P. Wilson	three-winged bluebush
<i>Rhagodia drummondii</i>	Moq. in DC	lake-fringe rhagodia
<i>Rhagodia eremaea</i>	P. Wilson	tall rhagodia
<i>Salsola kali</i>	L.	roly poly
<i>Sclerolaena cuneata</i>	P. Wilson	yellow bindii
<i>Sclerolaena densiflora</i>	(W. Fitzg.) A.J. Scott	hairy bindii
<i>Sclerolaena diacantha</i>	(Nees) Benth	grey bindii
<i>Sclerolaena eriacantha</i>	F. Muell.	silky bindii
<i>Sclerolaena eurotioides</i>	(F. Muell.) A. J. Scott	fluffy bindii
<i>Sclerolaena fimbriolata</i>	(F. Muell.) A. J. Scott	salt-lake bindii
<b>CHLOANTHACEAE</b>		
<i>Spartothamnella teucriflora</i>	(F. Muell.) Mold.	mulga broombush

<b>Botanical Name</b>		<b>Common Name</b>
<b>CUPRESSACEAE</b>		
<i>Callitris glaucophylla</i>	R. Br.	white cypress pine
<b>FRANKENIACEAE</b>		
<i>Frankenia pauciflora</i>	DC.	frankenian
<i>Frankenia setosa</i>	W. Fitzg.	frankenian
<b>GERANIACEAE</b>		
<i>Erodium crinitum</i>	Carolin	crowsfoot
<b>GOODENIACEAE</b>		
<i>Scaevola collaris</i>	F. Muell.	
<i>Scaevola spinescens</i>	R. Br.	currant bush
<b>LORANTHACEAE</b>		
<i>Amyema maidenii</i>	(Blakely) Barlow	mistletoe
<b>MALVACEAE</b>		
<i>Lawrenzia helmsii</i>	(F.Muell.&Tate)N.Lander	dunna dunna
<i>Sida calyxhymenia</i>	Gay ex DC.	tall sida
<b>MIMOSACEAE</b>		
<i>Acacia aneura</i> var. <i>aneura</i>	F. Muell. ex Benth.	mulga
<i>Acacia ramulosa</i>	W. Fitzg.	horse mulga
<i>Acacia tetragonophylla</i>	F. Muell.	curara (dead finish)
<b>MYOPORACEAE</b>		
<i>Eremophila glabra</i> ssp. <i>tomentosa</i>	(R. Br.) Ostenf.	tar bush
<i>Eremophila latrobei</i>	F. Muell.	warty-leaf eremophila
<i>Eremophila miniata</i>	C. Gardner	kopi poverty bush
<i>Eremophila scoparia</i>	(R. Br.) F. Muell.	broom bush
<i>Eremophila serrulata</i>	Druce	
<b>MYRTACEAE</b>		
<i>Darwinia diosmoides</i>	(DC.) Benth.	
<i>Eucalyptus griffithsii</i>	Maiden	Griffith's mallee
<i>Melaleuca lateriflora</i>	Benth.	
<b>PAPILIONACEAE</b>		
<i>Swainsona affinis</i>	-	
<b>PITTOSPORACEAE</b>		
<i>Pittosporum phylliraeoides</i>	DC.	weeping pittosporum
<b>POACEAE</b>		
<i>Aristida contorta</i>	F. Muell.	kerosine/wind grass
<i>Austrostipa elegantissima</i>	Labill.	silver speargrass
<i>Austrostipa scabra</i>	Lindley in Mitch.	speargrass
<i>Enneapogon caeruleus</i>	(Gaudich.) N. Burb.	limestone grass
<i>Eragrostis dielsii</i>	Pilger ex Diels & Pritzel	Murchison red grass
<i>Eragrostis eriopoda</i>	Benth.	woolly butt
<i>Monochather paradoxus</i>	Steudel	broad-leaved wanderrie
<i>Triodia basedowii</i>	N. Burb.	hard spinifex
<b>PORTULACACEAE</b>		
<i>Calandrinia polyandra</i>	Benth.	parakeelya
<b>PROTEACEAE</b>		
<i>Hakea preissii</i>	Meissner in Lehm.	needlebush



<b>Botanical Name</b>		<b>Common Name</b>
<b>SANTALACEAE</b>		
<i>Exocarpos aphyllus</i>	R. Br.	leafless ballart
<i>Santalum acuminatum</i>	(R. Br.) A. DC. in DC.	quandong
<b>SAPINDACEAE</b>		
<i>Dodonaea lobulata</i>	F. Muell.	wild hopbush
<i>Dodonaea viscosa</i>	Jacq.	sticky hopbush
<b>SOLANACEAE</b>		
<i>Lycium australe</i>	F. Muell.	water bush
<i>Solanum lasiophyllum</i>	Dunal ex Poiret in Lam.	flannel bush
<i>Solanum orbiculatum</i>	Dunal ex Poiret in Lam.	wild tomato
<b>THYMELAEACEAE</b>		
<i>Pimelea microcephala</i>	R. Br.	banjine
<b>ZYGOPHYLLACEAE</b>		
<i>Zygodphyllum aurantiacum</i>	(Lindley) F. Muell.	shrubby twinleaf

## Chapter 6.0. The diatom communities of Lake Yindarlgooda and Swan Refuge

### Abstract

During March 2001 and September 2002, 13 diatom taxa, all cosmopolitan species and typical of saline waters, were recorded from the Lake Yindarlgooda and Swan Refuge study sites. Seven taxa were recorded from the playa sites of Lake Yindarlgooda and 11 from Swan Refuge. All the sites were dominated by the diatoms *Navicula incertata*, *Amphora coffeaeformis*, *Nitzschia pusilla* and *Hantzschia baltica*.

Variation in community structure between the peripheral wetland site and the playa sites was observed. No significant differences were found between control and impact sites in Lake Yindarlgooda, with a weak correlation between the environmental variables and the diatom assemblages. The benthic microbial communities were dominated by diatoms and were found to be an important part of the aquatic ecology of Lake Yindarlgooda. Further increases in salinity could be detrimental to the diatom community as many species were recorded at the higher end of their salinity range.

### 6.1 Introduction

Lake Yindarlgooda did not have extensive benthic microbial mats composed of filamentous cyanobacteria or halotolerant filamentous green algae. Diatoms were the dominant component of the benthic microbial communities (BMCs). This chapter investigates the diatom communities within Lake Yindarlgooda and Swan Refuge and the factors that may affect their distribution and community structure.

Numerically, diatoms are the most abundant biota in inland waters of Australia (Smith *et al.* 2004) forming an integral part of the BMCs (Bauld 1986). Diatoms are unicellular, eukaryotic microorganisms that belong to the phylum Bacillariophyta. They are unique in that they have a siliceous cell wall that is highly differentiated. The wall is made of two parts called valves that are intricately sculptured. The valves are held together by girdle bands and together are called frustules. Reproduction is either vegetative or sexual resulting in the formation of auxospores. This mode of reproduction restores the original size to the population as repeated cell

divisions in asexual reproduction decreases the size of the daughter cells (Round *et al.* 1990; John 2007).

Diatoms are able to withstand long periods of desiccation in temporary environments by producing resting stages (Round *et al.* 1990). These are usually in the form of spores or modified vegetative cells known as resting cells (Davis 1972). The morphology and physiology of the resting cells are distinctive from the parent cell. Spores (hynospores) have a thicker frustule, often rounder in shape with less elaborate surficial patterns, while resting cells have undergone physiological and cytoplasmic changes, but their morphology is similar to the vegetative cell (Round *et al.* 1990; McQuoid and Hobson 1996).

Diatoms are ubiquitous, found in almost every aquatic habitat as well as in certain terrestrial biotopes. Their distribution is affected by abiotic parameters such as acidity, salinity, light, temperature and nutrients (Ehrlich 1995; John 2000) and the autecology of no other biotic group has been as extensively studied (Stoermer and Smol 1999).

In many large saline lakes, diatoms are a major component of the microbial community. The phytoplankton of the Salton Sea, an inland salt lake in southern California, is dominated by diatoms from spring through to summer when flagellates succeed (Lange and Tiffany 2002). The Great Salt Lake in Utah is a hypersaline inland salt lake that has experienced much variation in water levels and consequently salinity. Along with the well-known halobiont green alga, *Dunaliella*, a number of diatom taxa make up the microbiotic community of the Great Salt Lake. They belong to a limited group of algae and cyanobacteria that are able to exist in salinities greater than 100 g L<sup>-1</sup> (Oren 2002). Observations on Mono Lake, California, showed that the microbial community was dominated by numerous benthic and lithophytic *Nitzschia* species (Kociolek and Herbst 1992), again tolerating salinities in excess of 100 g L<sup>-1</sup>.

Much of the research in Australia has focussed on the use of diatoms in river assessments (John 2000; Blinn and Bailey 2001; Newall and Walsh 2005), or on secondary salinisation of the wetlands in the Wheatbelt region of Western Australia (Blinn *et al.* 2004; Taukulis and John 2006). Published work on naturally saline inland lakes are limited (Blinn 1991; Gell and Gasse 1994), particularly in Western Australia where the information is confined to reports for mining companies (John

1999; John *et al.* 2000; John *et al.* 2002) or unpublished dissertations (Handley 2003).

## **Objectives**

This chapter investigates the diatom community structure within Lake Yindarlgooda and Swan Refuge as the dominant primary producer of the benthic microbial communities. The objectives of this chapter are:

- To identify the diatom communities in Lake Yindarlgooda and Swan Refuge,
- To investigate the factors that may be influencing their community structure and distribution within the lakes,
- To identify any differences between control and impact sites in Lake Yindarlgooda.

## **6.2 Methods**

Whenever there was sufficient standing water in the lake, artificial substrates (JJ Periphytometer) were used for collecting samples. On most occasions natural benthic samples were collected as there was insufficient surface water for the placement of artificial substrates.

### **6.2.1 Collection of samples**

Samples for diatom analyses were collected during March 2001 and September 2002 from control sites 1-3 and 6 and impact sites 4, 5, EP1 and EP2 in Lake Yindarlgooda and from Swan Refuge. Benthic samples were collected by inverting an open vial (5.5 cm length, diameter 4.5 cm with a 5 mm hole drilled in the base) and removing a core from the lake bed (up to 5.5 cm in depth). Two core samples were collected from each site. Cores were stored frozen for later digestion and enumeration.

The idea of core sampling was to obtain intact samples of benthic diatoms. The surface sediment up to 5 mm is expected to contain the living diatoms or recently living diatoms. Trials examining the different sections of the core showed that below 5 mm diatom frustules were not present, the top containing the highest number of diatom valves.

Artificial substrate samplers, the JJ Periphytometers, were placed in Swan Refuge. This was the only site in the study that had sufficient surface water. The samplers

containing ten glass slides were collected after 14 days. The use of an artificial substrate can ensure that the diatom assemblages are collected when the water quality parameters were measured. The periphyton (the vast majority being diatoms) were analysed in the laboratory at Curtin University, where each side of the ten slides was scraped using a 4 cm single sided square razor blade. The periphyton was preserved in vials with Lugol's iodine.

### **6.2.2 Diatom preparation and enumeration**

Frozen core sediment samples were cut using a diamond saw. The top 5 mm subsections along the length of one-half of the core were digested in 70% nitric acid. The pellets were washed and permanent slides made according to John (1983). Counts of up to 500 diatom valves were recorded for each sample. When counting, at least three permanent slides were traversed to reach the required number of valves. Diatoms were identified using a range of taxonomic texts, the main being: Foged (1978) Archibald (1983), John (1983), Gasse (1986), Krammer and Lange-Bertalot (1986, 1988), Ehrlich (1995), and Witkowski *et al.* (2000).

Diatoms were prepared for SEM by washing the samples repeatedly in deionised water and air dried on round coverslips and mounted on stubbs using doubled sided carbon tape. The samples were gold coated and the valves examined with a Philips XL30 SEM.

Specimens were photographed under oil immersion using an Olympus VANOX Photomicroscope using Kodak Technical Pan black and white film. Permanent slides of the diatoms are deposited in the International Diatom Herbarium at the Department of Environmental Biology, Curtin University of Technology, Perth, Western Australia.

### **6.2.3 Treatment of Data**

Non-metric multidimensional scaling was employed to determine differences in sites according to the dissimilarity of their diatom assemblages. The data were first square root transformed and the Bray-Curtis similarity matrix calculated using PRIMER 6 (Clarke and Gorlet 2006). Site ordinations were undertaken using MDS. To determine which sites in the ordination shared the greatest similarity a group-average cluster analysis was performed and the hierarchical clustering displayed in a dendrogram.

The relationships between the diatom community composition of the sites and the environmental variables were examined using PRIMER's BIOENV procedure (Clarke and Ainsworth 1993). The environmental variables chosen were the dominant factors that were found to differentiate control from impacts sites in Chapter 3.0. Environmental similarity matrices were calculated using normalised Euclidean distance and correlations calculated using the Spearman rank correlation coefficient. The environmental variables were square root transformed and normalised accordingly (Clarke and Warwick 2001).

Differences between the control and impact sites (set as *a priori*) were tested using ANOSIM according to the factors which best described community structure at the sites according to BIOENV.

## 6.3 Results

### 6.3.1 General description of diatom community composition

A total of 13 diatom taxa were recorded from the sampling sites in March 2001 and September 2002 (Table 6.1). Lake Yindarlgooda recorded a maximum of seven taxa and Swan Refuge 11. Core samples analysed in March 2001 were collected during the wet phase of the hydrocycle, while those examined in September 2002 were after an extended dry phase. Valve numbers were minimal in the sediment samples from Swan Refuge in March 2001 compared to those of the periphyton.

Sites from both Lake Yindarlgooda and Swan Refuge had similar species, in particular *Amphora coffeaeformis* complex, *Navicula incertata* and *Hantzschia baltica*. Many of the diatoms in the September 2002 samples displayed signs of encystment, or desiccation, with many of the frustules having thickened walls. *Entomoneis paludosa* was absent from the Swan Refuge samples, while *Brachysira* sp., *Rhopaloida musculus* and *Luticola mutica* were not recorded in Lake Yindarlgooda.

### 6.3.2 Lake Yindarlgooda

#### 6.3.2.1 March 2001

Similar diatom percentage abundances were observed in the control sites 1, 2 and 3, and impact Site 4, all dominated by *Amphora coffeaeformis* complex. The percentage abundances of *Hantzschia baltica*, *Navicella pusilla*, and *Nitzschia*

*pusilla* were also similar (Figure 6.1). The diatom abundance in Site 1 was sparse compared to Site 3, which had a greater abundance of diatoms. None were detected from Site 6.

Of the impacted sites, Site 5 was dominated by *H. baltica* contributing to over 60% of the population with quite a high abundance. Many of these frustules had also started to encyst, displaying thickened cell walls. The community structure observed at sites EP1 and EP2 were similar, with *A. coffeaeformis*, *H. baltica*, and *Navicula incertata* all forming similar percentage compositions. The abundance at EP2 compared to the other sites in Lake Yindarlgooda was the highest.

Total species richness for March 2001 in Lake Yindarlgooda was seven taxa, sites 1, 2 and EP1 recorded the highest diversity. Sites 5 and EP2 recorded five taxa while Site 3 and 4 had six.

#### 6.3.2.2 September 2002

The diatom community in the September 2002 sediment was dominated by *N. incertata* in the majority of the sites with over 60% of population at sites 1, 2 and 3. This was followed by *A. coffeaeformis*, *H. baltica* and *Navicella pusilla* (Figure 6.1). This showed a shift from the March 2001 dominance of *A. coffeaeformis* at most sites.

The impact site EP2, located at the drainage channel, was dominated by *A. coffeaeformis* and *N. incertata*. Site 4, adjacent to EP2, was dominated by *A. coffeaeformis*, while EP1 showed little change from March 2001. A shift in dominance was observed at Site 5 from *H. baltica* in March to *N. incertata* in September. Again, many of these species had entered encysted stages.

Diversity was only slightly higher in the September samples with a total of eight taxa at Site 1. Site EP1 again recorded a relatively high diversity with seven taxa while sites 3 had the lowest diversity of four taxa.

### 6.3.3 Swan Refuge

#### 6.3.3.1 March 2001

The periphyton of Swan Refuge was co-dominated by *N. incertata* and *H. baltica*, each contributing to 30% of the population. Another 10% was by *Navicella pusilla* followed by *A. coffeaeformis* (Figure 6.1). Swan Refuge had a higher diversity than

Lake Yindarlgooda with nine taxa identified. The composition was more evenly distributed with no taxa making up more than 30% of the population.

### 6.3.3.2 September 2002

The number of diatom taxa recorded in the September 2002 core sample was slightly higher compared to the March 2001 sample, with a species richness of 11. The community was dominated by *Navicella pusilla* (35%) with an increase in the number of *Brachysira* sp., a species common in brackish waters (Figure 6.2). *Rhopaloida musculus* was recorded in higher numbers in the September core sample, the only species absent was *Luticola mutica*. Again the distribution of the different taxa in Swan Refuge was more consistent than in Lake Yindarlgooda.

**Table 6.1:** Diatom taxa identified from the Lake Yindarlgooda and Swan Refuge study sites, March 2001 and September 2002, in alphabetical order.

Taxa	Lake Yindarlgooda	Swan Refuge
<i>Amphora coffeaeformis</i> (Ag.) Kützing complex	*	*
<i>Amphora paraveneta</i> Lange-Bertalot	*	*
<i>Brachysira</i> sp. Kützing		*
<i>Cocconeis placentula</i> (Ehr) Hustedt	*	
<i>Entomoneis paludosa</i> (W. Sm.) Reimer	*	
<i>Hantzschia baltica</i> Simonsen	*	*
<i>Luticola mutica</i> (Kütz.) Mann	*	*
<i>Mastogloia braunii</i> Grunow	*	
<i>Navicella pusilla</i> (Grun. Ex. A Schmidt) Krammer	*	*
<i>Navicula incertata</i> Lange-Bertalot	*	*
<i>Nitzschia pusilla</i> Grunow	*	*
<i>Pinnularia lata</i> (Bréb.) W.Smith	*	*
<i>Rhopaloida musculus</i> (Kütz.) O.Muller		*



### 6.3.4 Analysis of the diatom assemblages

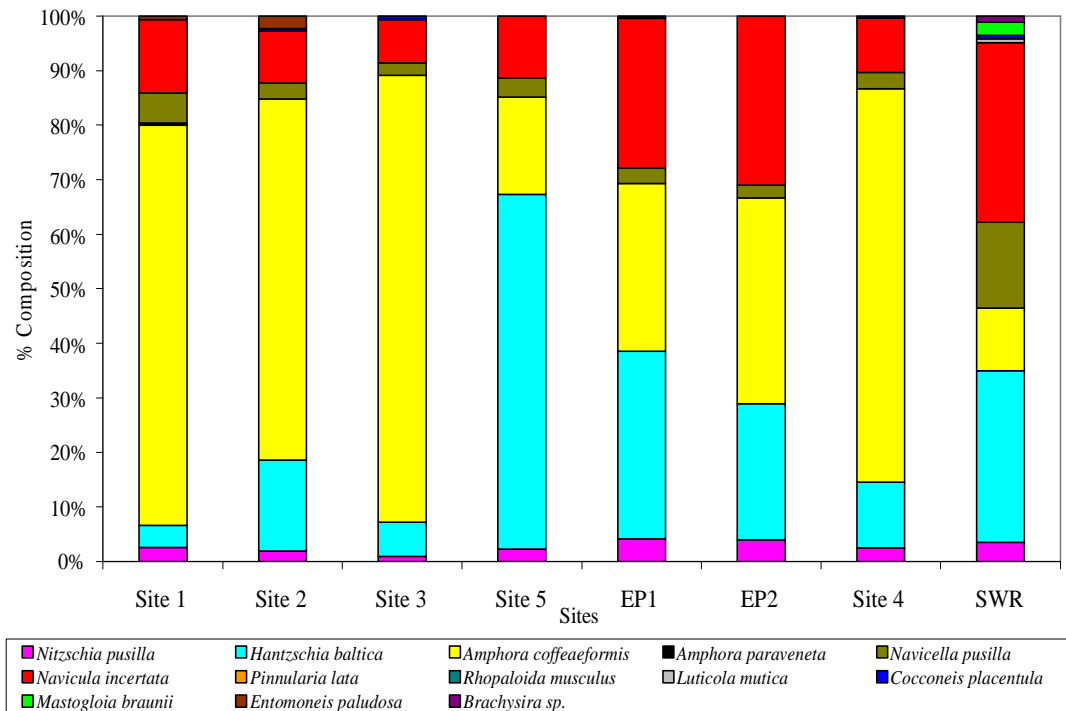
#### 6.3.4.1 March 2001

Ordination of the Bray-Curtis similarity matrix for the diatoms assemblages showed differences between the control, impact and wetland sites, plotting the sites according to their dissimilarities (Figure 6.3). Assemblages from sites 1-3 were grouped together with site 4, while the impact sites EP1 and EP2 displayed the highest dissimilarity to the control sites and Swan Refuge (wetland). Site 5 was distanced from all the other sites but was closer to the impact sites and the wetland site, Swan Refuge, had minimal similarity with any of the playa sites.

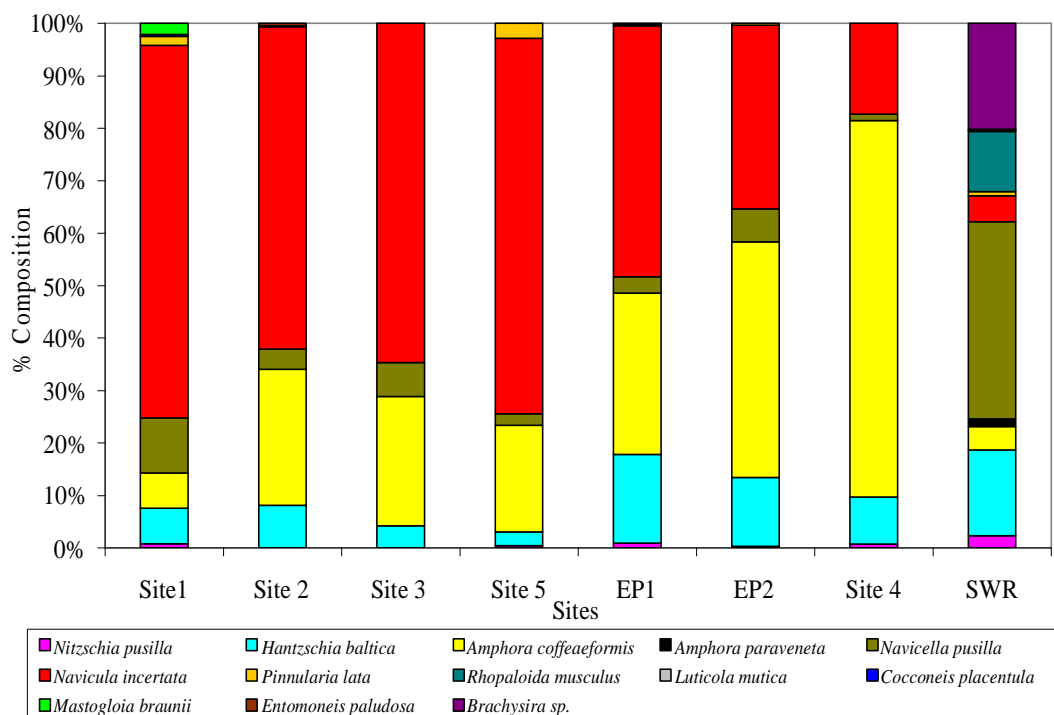
Closer groupings were shown with the cluster analysis of the MDS ordination as shown in the dendrogram (Figure 6.4). The control sites 1, 2 and 3 had approximately 86% similarity with each other and only 70% with the other impact sites. Swan Refuge displayed greater similarity with the impact sites 5, EP1 and EP2 (75%) than with the control sites. The impact sites EP1 and EP2 at 95% displayed the greatest similarity between sites. The sites 1-4 had similar percentage abundances of *A. coffeaeformis*, while sites 5, EP1 and EP2 had higher percentages of *Navicula incertata*, which was also shared by Swan Refuge (all above 30%).

#### 6.3.4.2 September 2002

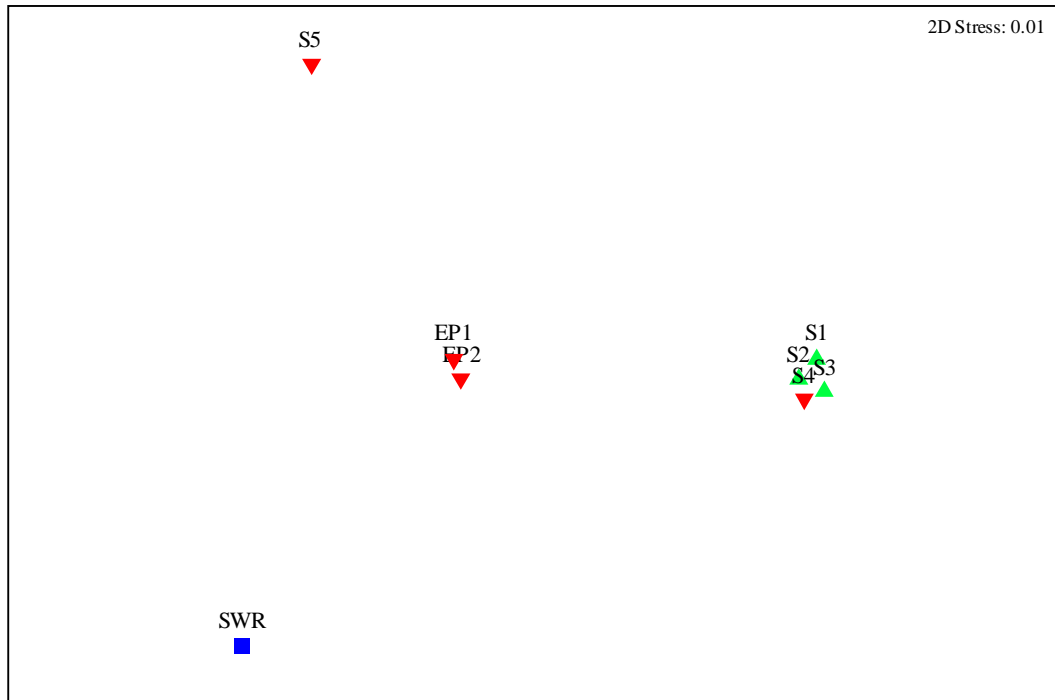
The diatom assemblages at Swan Refuge resulted in this site having the greatest dissimilarity to the playa sites. The impact sites, EP1 and EP2 were closer together and also to the control sites than Site 4. A group-average cluster analysis of the ordination gave a clearer indication of the similarities of each of the sites (Figure 6.6). The control sites 2 and 3 shared 90% similarity and 85% with Site 5. The impact sites 5 and EP1 and EP2 shared similar assemblages than with the control sites. The site with the least similarity was Swan Refuge, which only shared 45% similarity with the playa sites. The assemblages again appeared best explained by the percentage abundances of the dominant taxa, *A. coffeaeformis* and *N. incertata* in the impact sites.



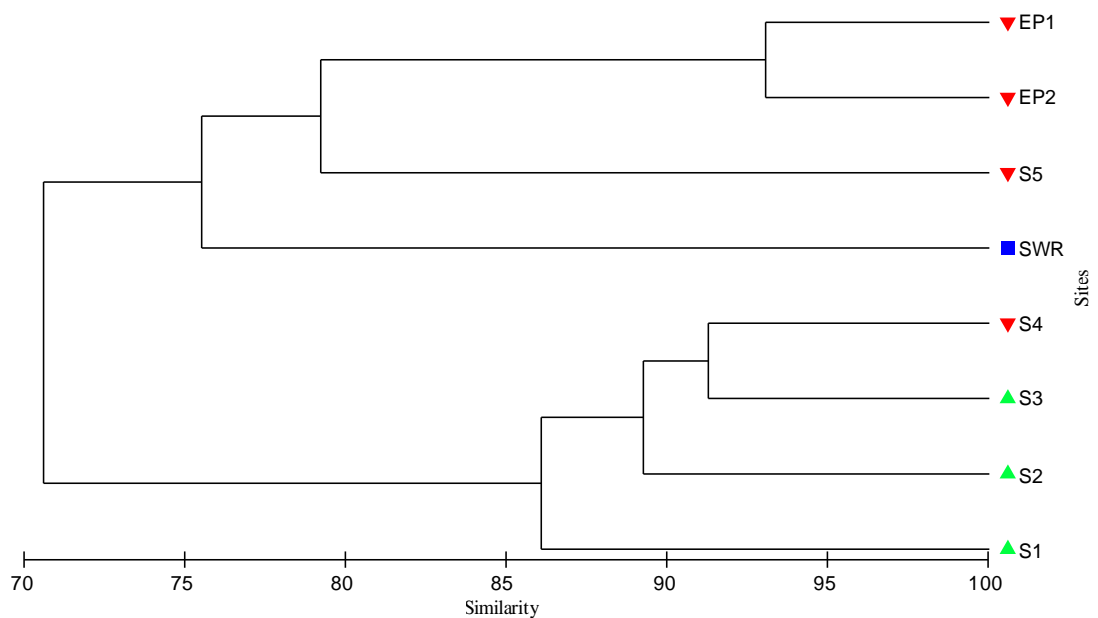
**Figure 6.1:** Diatom percentage abundance in surface core samples (< 5 mm) for sites in Lake Yindarlgooda and a periphyton sample for Swan Refuge (SWR) March 2001.



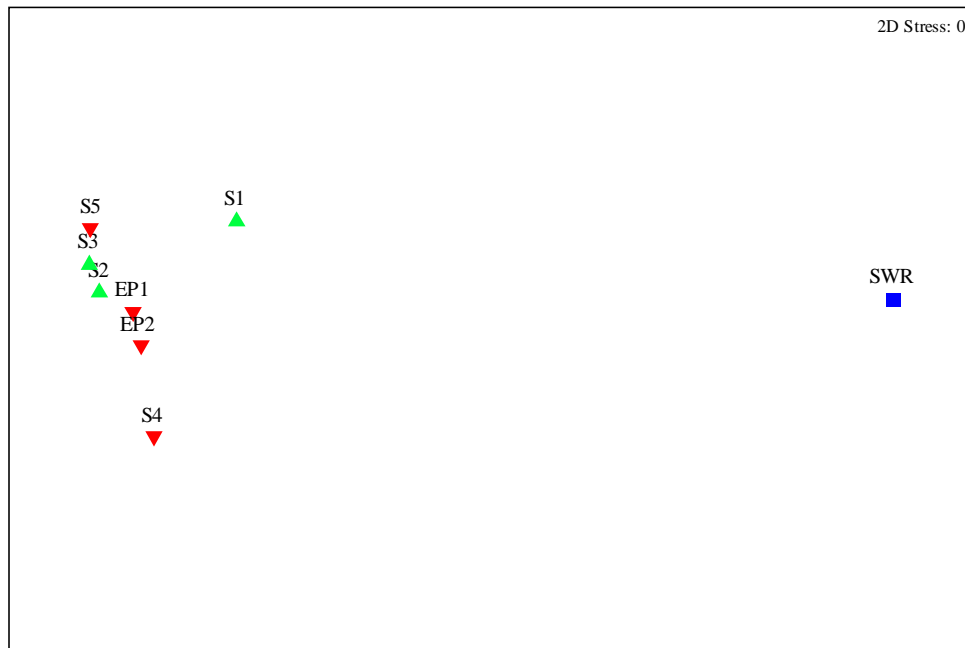
**Figure 6.2:** Diatom percentage abundance in surface core samples (< 5mm), for sites in Lake Yindarlgooda and Swan Refuge (SWR) September 2002.



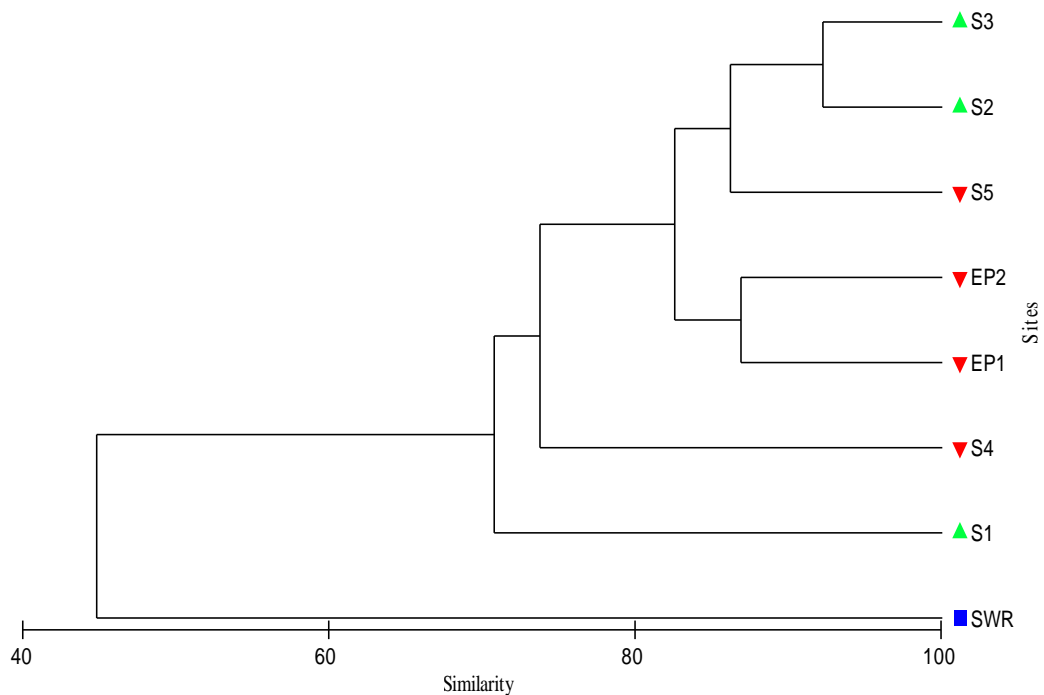
**Figure 6.3:** Non-metric multidimensional scaling (MDS) ordination of the sample sites and diatom abundances for March 2001. Stress = 0.01. MDS obtained from Bray-Curtis similarity after square root transformation. ■ = Wetland site, ▲ = Control sites, ▼ = Impact sites.



**Figure 6.4:** Group-average clustering from Bray-Curtis similarities for diatom abundances and sample sites, March 2001, as shown on MDS ordination. Data square root transformed. ■ = Wetland site, ▲ = Control sites, ▼ = Impact sites.



**Figure 6.5:** Non-metric multidimensional scaling (MDS) ordination of the sample sites and diatom abundances for September 2002. Stress = 0.01. MDS obtained from Bray-Curtis similarity after square root transformation. ■ = Wetland site, ▲ = Control sites, ▼ = Impact sites.



**Figure 6.6:** Group-average clustering from Bray-Curtis similarities for Diatom abundances and sample sites, September 2002, as shown on MDS ordination. Data square root transformed. ■ = Wetland site, ▲ = Control sites, ▼ = Impact sites.

### **6.3.5 Diatom assemblages and environmental parameters: BIOENV analyses**

#### *6.3.5.1 March 2001*

The correlations between the eight environmental variables and the diatom community assemblages were generally weak (Table 6.2). According to the variables selected by BIOENV, salinity and nitrogen (TKN) together had the greatest influence on the community structure in the sites with a correlation coefficient of 0.423. The combination of salinity, TKN and the heavy metals As and Ni were weakly correlated to the assemblages also. All the correlations were positive indicating an influence on their assemblages particularly at the impact sites where these parameters were considered the strongest factors differentiating the sites.

#### *6.3.5.2 September 2002*

For the September 2002 samples, the heavy metal As appeared to have the greatest influence on the differences in community composition (Table 6.3). The correlations were again very weak and salinity did not appear to be affecting the community composition as much as it did in March 2001.

### **6.3.6 Analysis of similarity between sites**

An analysis of similarity between the control and impact sites using an ANOSIM showed significant differences between groups, though the magnitude was not large (global R of 0.322,  $P < 0.01$ ) (at significance level of 0.05). There was significant difference between the control and impact sites, while both groups were significantly different from the wetland site, Swan Refuge (Table 6.4).

**Table 6.2:** Combination of eight environmental variables in the March 2001 water samples that yield the best matches of biotic (diatoms) and abiotic similarity matrices as measured by weighted Spearman rank correlation. Environmental variables = pH, EC, salinity, TKN, As, Ni, TC, TP.

<b>Variables selected by BIOENV</b>	<b>Correlation <math>\rho_w</math></b>
Salinity, TKN	0.423
Salinity, TKN, Ni	0.334
Salinity, TKN, As	0.328
EC, Salinity, TKN	0.318
EC, Salinity, TKN, Ni	0.27
pH, Salinity, TKN	0.262
Salinity, TKN, TC	0.251
Salinity, TKN, As, Ni	0.246
EC, Salinity, TKN, As	0.239
EC, TKN, Ni	0.238

**Table 6.3:** Combination of five environmental variables in the September 2002 sediment samples that yield the best matches of biotic (diatoms) and abiotic similarity matrices as measured by weighted Spearman rank correlation. Environmental variables = pH, TSS, TOC, As and Ni.

<b>Variables selected by BIOENV</b>	<b>Correlation <math>\rho_w</math></b>
As	0.119
TOC, Ni, As	0.103
Ni, As	0.096
TOC, As	0.049
pH, As	0.017
TOC	-0.008
pH, TOC, As	-0.027
TOC, Ni	-0.03
pH, TOC, Ni, As	-0.033
TOC, TSS, Ni, As	-0.062

**Table 6.4:** Analysis of similarities (ANOSIM) for control, impact and wetland sites according to Bray-Curtis similarity indices ( $p < 0.05$ ).

<b>Groups</b>	<b>R statistic</b>	<b>Significance Level</b>
Control, Impact	0.089	0.167
Impact, Wetland	0.776	0.022
Control, Wetland	0.698	0.036

### 6.3.7 Taxonomic notes on the dominant species

6.3.7.1 *Amphora coffeaeformis* (Agardh) Kützing complex: (Plate 6.1, figs 1-5; Plate 6.3, fig. 1). Lit: Archibald 1983 & Ehrlich 1995.

*Dimensions:* L = 15-25  $\mu\text{m}$ ; B = 4-6  $\mu\text{m}$ . Striae (in 10  $\mu\text{m}$ ): dorsal = 22, ventral = 36 ( $n=3$ ).

*Comments:* Greatest morphological variation was observed in the valves of *A. coffeaeformis* complex. The cells were solitary, valves were cymbelloid with a smoothly arched dorsal margin and a straight to slightly concave ventral margin. The poles were rostrate to capitate and the raphe was eccentric. The frustules were weakly silicified, striae were difficult to see under LM, though were visible in a few varieties (Plate 6.1 figs 1 and 2) and SEM (Plate 6.3 fig. 1). The dorsal striae were longer than the ventral striae. The striae appeared to be composed of uniseriate areolae. The specimens recorded from Lake Yindarlgooda matched the description given in Ehrlich (1995) for *A. coffeaeformis* var. *coffeaeformis* and in Archibald (1983) for *A. coffeaeformis*. Measurements of the striae and valves closely matched those given by Archibald (1983) and Ehrlich (1995), though the species from Lake Yindarlgooda, on average, had a smaller size range (in the length of the valve).

The complexity of this group is recognised by both Archibald (1983) and Ehrlich (1995) and there may be varieties within the Lake Yindarlgooda group, though they were not established as the variation in valve morphology was continuous.

*Distribution:* Most abundant in the hypersaline sites near the LRSF ( $<150 \text{ g L}^{-1}$ ), though was also common in the hyposaline waters of Swan Refuge. *A. coffeaeformis* was predominantly epipelagic.

6.3.7.2 *Hantzschia baltica* Simonsen (Plate 6.2, figs 10-13; Plate 6.3 figs. 3 & 4).

Lit: Krammer & Lange-Bertalot 1988; Witkowski, Lange-Bertalot & Metzeltin 2000.

*Dimensions*: L = 30-40  $\mu\text{m}$ ; B = 5-8  $\mu\text{m}$ . Transapical striae (in 10  $\mu\text{m}$ ): 38 ( $n=3$ ).

*Comments*: The valves of this species had better definition, cell walls were heavily silicified and easier to identify in the sediment samples. Cells were solitary, valves dorsiventral, hantzschoid in outline, the dorsal margin curved slightly, and the ventral margin slightly constricted at the central point. The raphe was strongly eccentric, and both raphes placed on the ventral side of the valve. The poles were rostrate or apiculate (Plate 6.3, fig. 14). Little variation was observed in cell size amongst samples. Under LM the striae could not be distinguished, but with SEM biseriate rows of poroids could be resolved. The dimensions of the valves were slightly above those described in the literature and may be better described as *Hantzschia cf. baltica*.

*Distribution*: This is a widespread species, common in benthic samples in saline waters. *H. baltica* was common at all sites in Lake Yindarlgooda, particularly the hypersaline impact sites, but also in the hyposaline waters of Swam Refuge.

6.3.7.3 *Nitzschia pusilla* Grunow (Plate 6.2, fig. 14; Plate 6.3, fig. 2).

Lit: Archibald (1983) & Ehrlich (1995).

*Dimensions*: L = 30 -35  $\mu\text{m}$ ; B = 5-8  $\mu\text{m}$ . Striae (in 10  $\mu\text{m}$ ): 42 ( $n=2$ ).

*Comments*: Cells were solitary and the frustules weakly silicified. The valves were predominantly straight (linear-lanceolate). The poles were obtusely rounded (rostrate to capitate). Under LM the striae were difficult to see, though with SEM parallel rows of simple areolae were distinguished (approximately 25 in 5  $\mu\text{m}$ ) (Plate 6.3, fig. 2). The raphe was located peripheral and on one margin (on opposite margins of the two valves). The measurements fell within those given by Ehrlich (1995) and the valves were slightly than those in Archibald (1983).

*Distribution*: *N. pusilla* was found in small numbers at all sites in salinities ranging from 55 – 140 g L<sup>-1</sup>. Numbers were greater during the wet phase indicating its preference as a periphytic or planktonic species. This species can tolerate a wide range of salinities but is known in Australia as a halobiont species (Gell and Gasse 1994).



#### 6.3.7.4 *Navicula incertata* Lange-Bertalot (Plate 6.2, figs 15-17).

Lit: Krammer & Lange-Bertalot 1986

*Dimensions*: L = 20-25 µm; B = 3-5 µm. Striae (in 10 µm): 10 (*n*=3).

*Comments*: Cells were solitary, valves were linear-lanceolate with obtusely rounded apices. Little morphological variation was observed in the frustules of this species. The transverse striae were clearly visible, slightly radiate in the centre, the raphe was straight, and the terminal fissure of the raphe bending slightly (hooked), axial area was narrow. Dimensions were within that described by Krammer & Lange-Bertalot (1986). The average valve size of this species from Lake Yindarlgooda fell within the larger end of the size range described by Krammer & Lange-Bertalot (1986). It is often confused with *N. durrenbergiana* in Western Australian samples.

*Distribution*: *N. incertata* was well represented in Lake Yindarlgooda at the hypersaline sites. It is often recorded in hypersaline inland waters in Australia (Gell 1997) and overseas (Krammer and Lange-Bertalot 1986; Sabbe *et al.* 2003). Both *N. incertata* and *N. durrenbergiana* are often misidentified and can be easily overlooked in sediment samples because of their weak refraction (Ehrlich 1995).

## 6.4 Discussion

The diatom communities of Lake Yindarlgooda and Swan Refuge consisted of halotolerant, cosmopolitan species, in particular *Amphora coffeaeformis*, *Hantzschia baltica*, *Nitzschia pusilla* and *Navicula incertata*. These taxa have been recorded in secondary salinised wetlands in the Western Australian wheatbelt and are known indicators of hypersaline conditions (Gell and Gasse 1994; Gell 1997; John 1999; John *et al.* 2000; Blinn *et al.* 2004; Taukulis and John 2006). The Pennate diatoms, in particular the genera *Navicula*, *Amphora*, *Nitzschia* and *Mastogloia*, are often the dominant groups in hypersaline environments and usually occur as benthic rather than planktonic forms (John 1994; Segal *et al.* 2006; Cook and Coleman 2007).

The same diatom genera were found to dominate the large salt lakes in the USA such as Mono Lake in California and the Great Salt Lake, Utah (Oren 2002). The microbial community in Mono Lake, like Lake Yindarlgooda, was dominated by benthic diatoms such as *Navicula* and *Nitzschia* species (Kociolek and Herbst 1992) with *A. coffeaeformis* also recorded. In the Great Salt Lake, Utah a diverse diatom community was also recorded in the microbial mats of the shallow south arm, with

some 17 species. *A. coffeaeformis* again is an abundant taxon in waters with salinities above  $100 \text{ g L}^{-1}$  (Felix and Rushforth 1979).

Morphological variation was observed in the diatoms from Lake Yindarlgooda, in particular within the *Amphora coffeaeformis* complex. Differences in the size and shape of the valve is typical for this species, as is their indistinct structure under light microscopy (Archibald 1983; Ehrlich 1995). Examination using SEM revealed greater definition of the striae and all the specimens observed conformed to aspects of their classification as stated in the taxonomic literature. Morphological variation observed in diatoms from inland salt lakes is often associated with high salinities (John 1988, 1994); this phenotypic plasticity not confined to the algae as seen in the differences in ostracod carapace size from inland saline waters (Finston 2000, 2004).

Studies on other inland salt lakes in Western Australia (John *et al.* 2000; Handley 2003; Taukulis and John 2006; Boggs *et al.* 2007) show that the species diversity in both Lake Yindarlgooda and Swan Refuge was comparatively low. Salinity is inversely proportional to species diversity (Williams 1998) and this is true for diatom communities (Clavero *et al.* 2000; Blinn and Bailey 2001; Taukulis and John 2006). Handley (2003) found that differences in the algal flora of inland salt lakes near Kambalda and Esperance were greatest in salinities  $<50 \text{ g L}^{-1}$ , decreasing rapidly as the salinity increased. A similar relationship was found in inland waters of Egypt, waters with salinities of  $40 -50 \text{ g L}^{-1}$  supporting greater species richness with those above  $100 \text{ g L}^{-1}$  having sparse populations (Compere 1994).

In Lake Yindarlgooda a low correlation was found between salinity and diatom diversity. This relationship can be attributed to the high salinity spectrum recorded in the lake; the majority of the sites were classified as hypersaline and dominated by a few halotolerant species. Many diatoms have a preference to particular salinities and often out compete other groups (Clavero *et al.* 2000) as was shown by the high abundance of *A. coffeaeformis* and *N. incertata* at the impact sites.

Other factors may determine the distribution of diatoms such as pH and nutrients. In saline lakes, nutrient concentrations can vary with salinity and anion composition (Saros and Fritz 2000b). Nitrogen (TKN) was found to be correlated, albeit weakly, with the diatom assemblages in Lake Yindarlgooda in March 2001 together with salinity. The TKN levels around the LRSF were the highest in the lake and considered to be a direct influence from the leachate (Chapter 3.0). This may explain

why the diatom assemblages differed slightly around the LRSF compared to the control sites. A strong correlation between diatom assemblages, salinity and its influence on nutrient uptake, was found by Saros and Fritz (2000a, 2002), though the exact mechanisms that determined this were unknown.

Diatoms are able to tolerate higher salinities and desiccation by the secretion of polysaccharide mucilage which insulates the cell (Mosisch 2001). They are also able to withstand extended desiccation by producing resting stages (Round *et al.* 1990), a survival strategy critical in temporary systems (Brock *et al.* 2003). Many of the diatoms in the September samples were recorded as resting cells, the lake bed having been dry for over a year. *Amphora coffeaeformis* is known to produce resting cells (McQuoid and Hobson 1996) which are identified by a thickened cell wall. In contrast, the March 2001 samples showed frustules that were very faint and encystment not apparent. The cells walls of diatoms are made of silica and the utilization of silica is thought to be affected by salinity with less silica per cell found in diatoms from higher salinities (Saros and Fritz 2000a). However, benthic diatoms in less saline environments are able to remain heavily silicified as silica levels are not as readily depleted in the sediment as in the water column (Conley *et al.* 1994). Heavily silicified frustules prevent the dissolution of the cell in the sediment and allows for their preservation (McQuoid and Hobson 1996), essential if they are to remain dormant in the sediment for extended periods.

Of interest was the lack of diatom valves in the sediment samples in Swan Refuge during March 2001. Instead, diatom abundance was higher on the artificial substrate samplers. Substrate type has been indicated as influencing the spatial distribution of diatom assemblages in streams of the Australian wet/dry tropics with similar assemblages found on similar substrate types (Townsend and Gell 2005). The diatom community in Swan Refuge appeared to be dominated by periphytic taxa, the habitat more conducive to epiphytes. The sediment in Swan Refuge was very fine clay sand and easily disturbed, making the water highly turbid. Swan Refuge was not only deeper than Lake Yindarlgooda, it also had extensive macrophyte meadows with the fringing vegetation submerged when the pan was filled (Chapter 4.0). The habitat of Lake Yindarlgooda was noticeably different to that of Swan Refuge. While there was a lack of substrate for epiphytic species, the surface sediment was cohesive and light penetration high, resulting in a dominance of epipellic diatom taxa.

*Brachysira* sp. was absent in Lake Yindarlgooda but formed an important component of the diatom community in Swan Refuge. Along with *Rhopaloida*, *Brachysira* sp. has been recorded as a well known periphyte (Ehrlich 1995) and the high number of these two diatoms show how the difference in habitat are a factor in the structure of the diatom communities in inland waters.

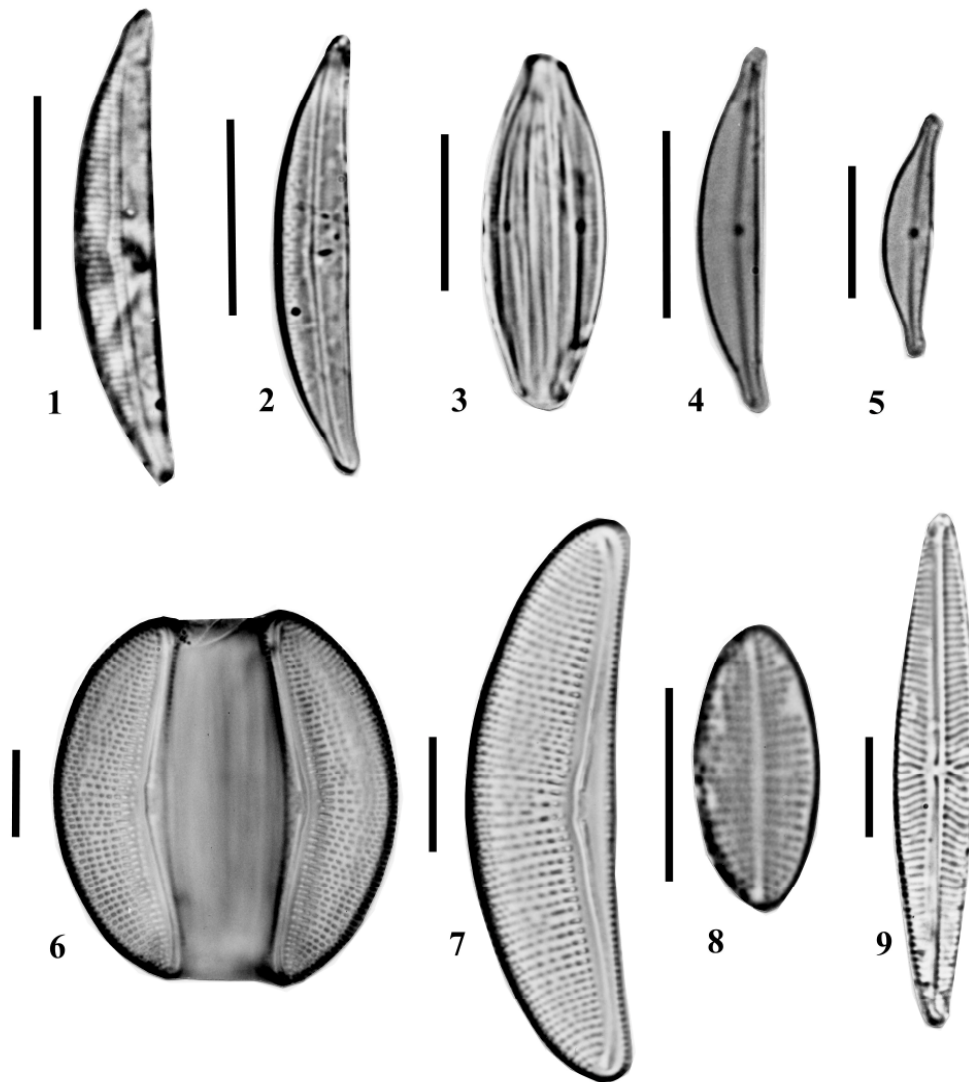
While the impact from the LRSF leachates did not appear to be negative on the diatom diversity in Lake Yindarlgooda, the effects of anthropogenically increased salinity should not be dismissed. Research by Clavero *et al.* (2001) found that many diatom species only produce auxospores after a decrease in salinity. Asexual reproduction in diatoms results in a reduction in cell size, only returned after sexual reproduction and the production of auxospores (Round *et al.* 1990; John 2007). Increases in salinity may prevent sexual reproduction thereby reducing the size of the diatom cells. This, in turn, results in a decline in population size. In an environment such as Lake Yindarlgooda that has a benthic microbial community dominated by a few diatom species, this may eventually reduce the primary productivity of the system.

### **Conclusions**

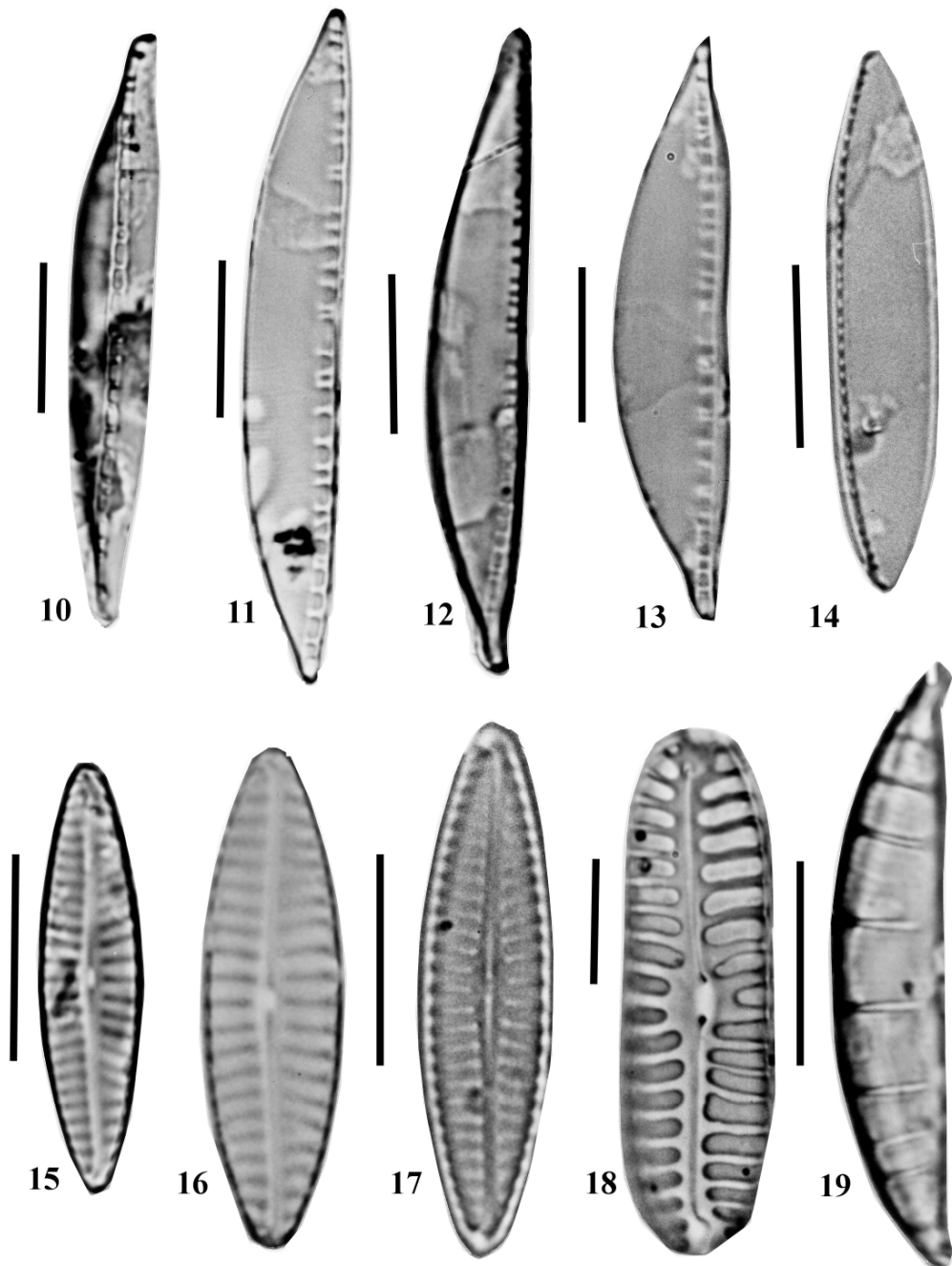
Lake Yindarlgooda and Swan Refuge displayed a low species diversity, dominated by cosmopolitan, halotolerant species, in particular *Navicula incertata*, *Amphora coffeaeformis*, *Nitzschia pusilla* and *Hantzschia baltica*. While a significant difference was found between the clay pan, with extensive macrophytes, and the playa sites, none was found between the control and impacts sites within Lake Yindarlgooda. The salinity recorded in Lake Yindarlgooda at the control sites was hypersaline and the taxa in all sites were restricted to specialised halotolerant species. The salinity spectrum range was hypersaline at all sites and was reflected by little difference in the species diversity between sites. This was confirmed by the low correlation between the abiotic factors, in particular salinity, and the diatom assemblages at the different sites.

While diversity was low compared to other inland waters, diatoms are the dominant primary producers in Lake Yindarlgooda. Like other inland waters in Australia, primary productivity was restricted to the benthic communities as macrophytes are sparse. The dominance of certain taxa around the LRSF indicated a hypersaline environment, tolerated only by specialised taxa. Many of these diatoms had shown

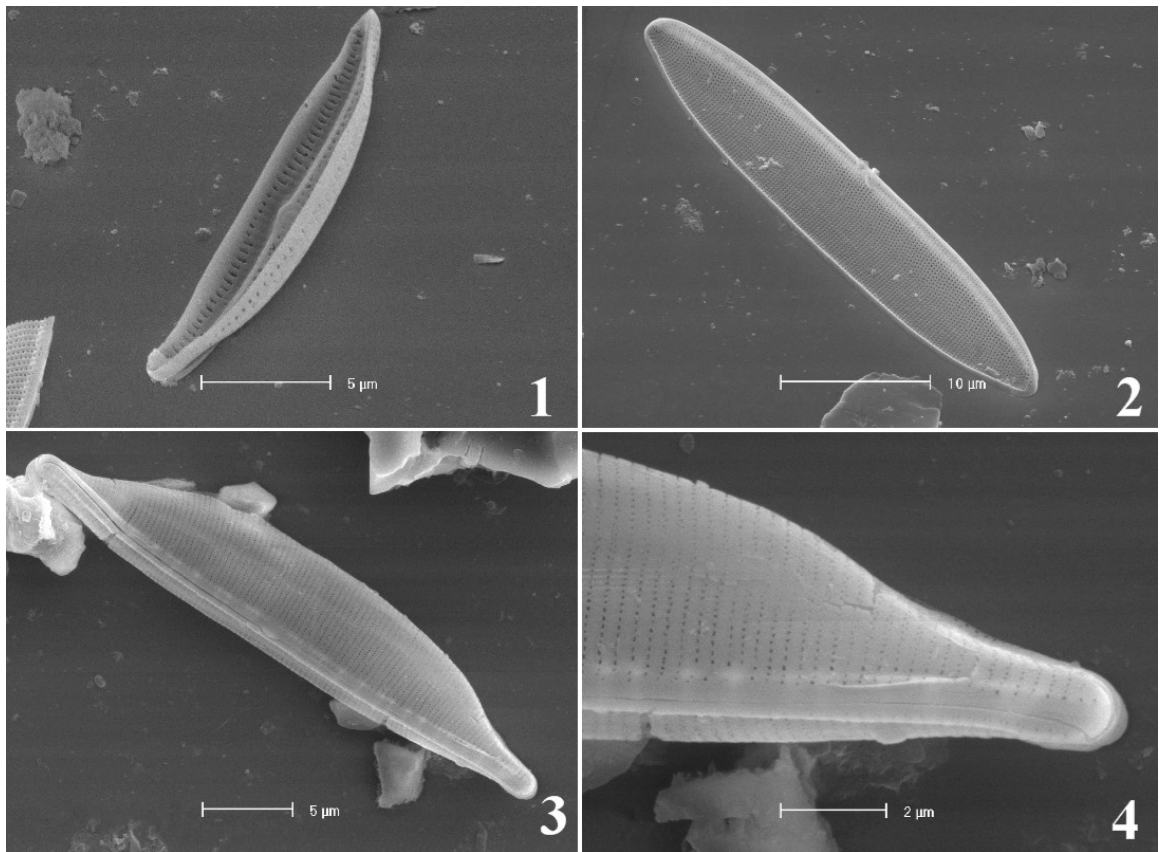
signs of encystment, indicating the importance of resting stages for survival in temporary systems.



**Plate 6.1:** Light micrographs (LM) of diatom species recorded from Lake Yindarlgooda and Swan Refuge, March 2001 and September 2002. Micrographs taken at 1000x magnification. LM scale bars = 10  $\mu\text{m}$ . **Figs 1-5.** *Amphora coffeaeformis* complex. **Figs 6-7.** *Amphora paraveneta*. **Fig 8.** *Cocconeis placentula*. **Fig. 9.** *Navicella pusilla*.



**Plate 6.2:** Light micrographs (LM) of diatom species recorded from Lake Yindarlgooda and Swan Refuge, March 2001 and September 2002. Micrographs taken at 1000x magnification. LM scale bars = 10  $\mu\text{m}$ . **Figs 10-13.** *Hantzschia baltica*. **Fig. 14.** *Nitzschia pusilla*. **Figs 15-17.** *Navicula incertata*. **Fig. 18.** *Pinnularia lata*. **Fig. 19.** *Rhopaloida musculus*.



**Plate 6.3:** Scanning electron micrographs (SEM) of three dominant taxa from Lake Yindarlgooda impact sites. **Fig. 1.** *Amphora coffeaeformis*. Raphe strongly eccentric. (Scale bar = 5 μm). **Fig. 2.** *Nitzschia pusilla*. Striae very faint. (Scale bar = 10 μm). **Fig. 3.** *Hantzschia baltica* (Scale bar = 5 μm). Raphe along ventral margin. **Fig. 4.** Close up of the *H. baltica* terminal nodule showing terminal fissure of raphe, curved toward ventral side. Areolae (pores) visible. (Scale bar = 9 μm).



## Chapter 7.0. *Parartemia* Sayce 1903 (Crustacea: Anostraca):

### Morphology

#### Abstract

The morphology of *Parartemia* n. sp. d from Lake Yindarlgooda is described for both the males and females. Detailed examination of the secondary sexual characteristics and the resting egg has been included, including the ultrastructure of the egg shell. Non-formal taxonomic descriptions of *Parartemia* n. sp. g from Lake Miranda have been included and comparisons made with *Parartemia* n. sp. d.

Obvious morphological differences in the resting eggs of the two *Parartemia* species were observed using both SEM and light micrographs. The egg diameters were similar for the two species, though the egg of *Parartemia* n. sp. g had a thicker appearance. Closer examination revealed hair-like extensions on the external cortex of *Parartemia* n. sp. g, while *Parartemia* n. sp. d was glabrous and similar to the eggs of *Artemia*. SEM of the shell showed the alveolar layer of *Parartemia* n. sp. g to be thicker with two layers, the vesicles larger and rounder, while *Parartemia* n. sp. d had a more compact alveolar appearance.

Examination of thin sections of *Parartemia* n. sp. d resting eggs showed that they are identical to *Artemia* eggs. The similarity of the *Parartemia* resting eggs to those of *Artemia* suggests that they may be as resilient.

### 7.1 Introduction

The aquatic biota of Lake Yindarlgooda was described in Chapter 4.0 and *Parartemia* was identified as the dominant invertebrate, particularly in the northern impact sites around the LRSF. This chapter is the first of three that discusses the *Parartemia* of Lake Yindarlgooda, ranging from their morphology (Chapter 7.0), and ecology (Chapter 8.0), to the use of their resting stages to assess the effects of increased salinity (Chapter 9.0). This chapter includes non-formal descriptions of *Parartemia* n. sp. g from Lake Miranda and makes comparisons between the resting egg morphology of the two species.

The Anostraca are a primitive order of extant crustaceans belonging to the Class Branchiopodiidae. They have a primitive segmented body comprising of a head, thorax and abdomen, covered in a thin, flexible chitinous exoskeleton rather than a

rigid carapace. Attached to the thoracic segments are foliaceous limbs in which the first antennae and the first and second maxillae are reduced in size (Hessler 1982). The Anostraca, within Australia, comprise of *Artemia*, *Branchinella*, *Streptocephalus* and *Parartemia*, the last being the only endemic genus. It is thought that *Parartemia* evolved from *Artemia*, diverging some 85 million years ago with the geological isolation of Australia in the late Mesozoic (Coleman *et al.* 1998), molecular analyses now confirming their phylogenetic relationship (Remigio and Hebert 2000).

The classification of *Parartemia* is under review by Savage and Knott (2004) in which three genera within the Parartemiidae are proposed. For the purpose of this investigation, the current classification is that used by Timms (2004b), the only available key. Daday first established the Parartemiidae in 1910 and regarded it as a subfamily of the Branchiopodiidae until Weekers *et al.* (2002) placed it in a family of its own using DNA analysis. At present, there are eight described and eight undescribed species of *Parartemia*, with a new species, *Parartemia* n. sp. x, collected from Lake Carey in 2004 (Timms *et al.* 2006).

With the exception of greater morphological variation of the males within the species, *Parartemia* species are similar to *Artemia* species in many respects. They are an elongate animal varying from 11 to 40 mm in length and lack a carapace. They have a clearly defined head with visible stalked eyes, a thorax with 11 foliaceous appendages, and an abdomen with eight segments. The genitalia are contained on the genital segments, located posterior to the thorax on two partly fused thoracic segments (Williams 1980).

*Parartemia* are bisexual and sexually dimorphic. The males display large second antennae modified into claspers for amplexing the female during copulation. They are distinct in having the basal third segment of the second antennae fused to form a clypeus. This is made up of a pair of dorso-ventrally flattened rectangular, or short blade-like, frontal processes and a pair of digitiform dorsal processes (Timms 2004b). *Parartemia* possess a single pair of penes, or gonopods, located on the ventral surface of the genital segments. The penes are composed of a rigid, proximal basal part and a retractable distal part. The morphological features of anostracan penes are often used a taxonomic tool (Brendonck and Belk 1997), though for the *Parartemia* the obvious secondary sexual characteristics are easier to apply.

Generally, the females are smaller than the males with less distinctive morphological features. The most noticeable is the brood pouch (ovisacs) located ventrally on the genital segments of mature females. The brood pouch may extend laterally or posteriorly, with lateral lobes or as a single ventrally protruding pouch. At the distal end of each pouch is the gonopore, an opening that allows for the insertion of the penis and the expulsion of the eggs (Timms 2004b).

While the females lack obvious secondary sexual characteristics, there are morphological features within the amplexial region, or groove, which are species specific. The amplexial groove, also known as the pregenital segment by Timms (2004b), is the region between the base of the brood pouch and the last pair of legs (thoracic segments 8–11). Modifications to these segments such as bulges and ridges enable the male to clasp the female during copulation (amplexus). The amplexial region of the female complements the ornamentation of the male's second antennae, creating a "lock and key" fit (with regard to the secondary sexual characteristics) that is unique to each species (Rogers 2002).

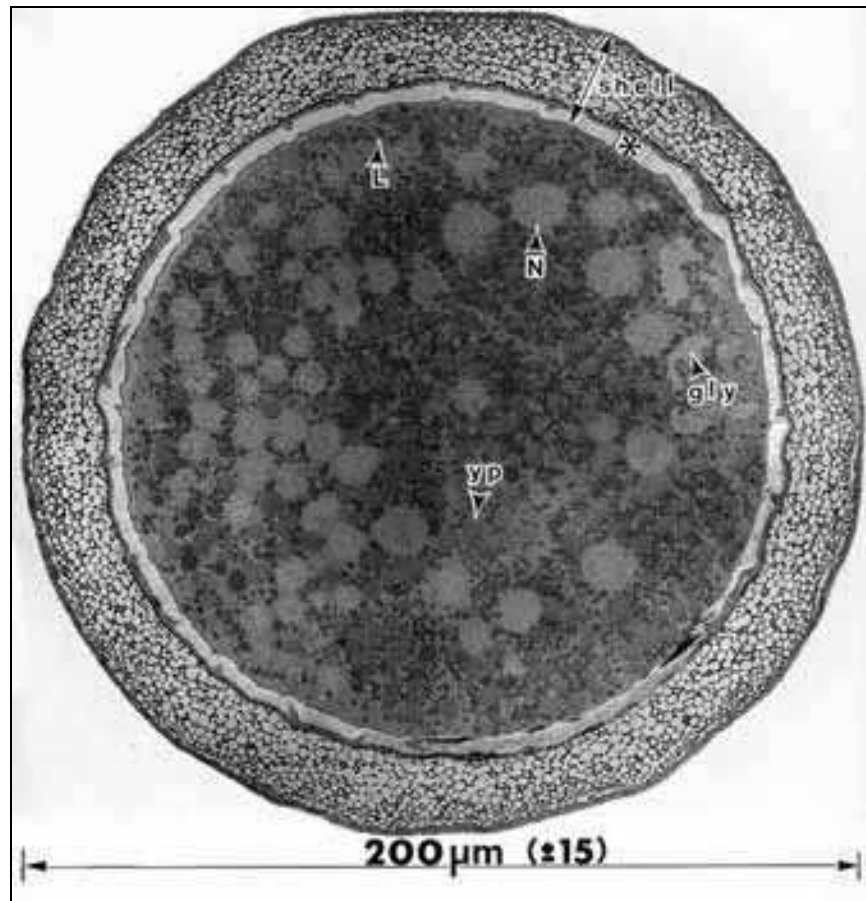
*Parartemia*, like *Artemia*, follow two modes of reproduction (Geddes 1981); ovoviviparity with the release of free swimming nauplii from the females, or oviparity, with the embryo encysting and released as dormant, or resting stages (Jackson and Clegg 1996). The dormant eggs of anostracans are often referred to simply as cysts (Dumont *et al.* 2002; Timms *et al.* 2004; Clegg and Campagna 2006; Varo *et al.* 2006) and their morphological characteristics considered important inclusions in descriptions of taxa (Brendonck and Coomans 1994; Hill and Shepard 1997; Shepard 1999; Mura 2001; Timms *et al.* 2004).

There is still little published information on the morphology of *Parartemia* resting eggs, the only published work being Timms *et al.* (2004) and Hill and Shepard (1997). In contrast, there is much published work on other anostracans (Mura 1991; Brendonck and Coomans 1994; Brendonck and Riddoch 1997; Hill and Shepard 1997; Thiery 1997; Mura 2001; Dumont *et al.* 2002; Sugumar and Munuswamy 2006). Increasing information on anostracan egg morphology has provided sufficient data that may be useful for species identification (Hill and Shepard 1997). Descriptions of new species now include the morphological features of the egg with keys based solely on their structure (Brendonck and Coomans 1994). Due to the urgency for information on the distribution of endangered anostracan species in

California, USA, the use of egg banks as a tool for the rapid and accurate assessment of their presence in temporal habitats was adopted and a large scale program into the gathering of information on egg morphology was commenced (Shepard and Hill 2001).

The internal egg wall structure of the Anostraca is defined as consisting of three layers by Hill and Shepard (1997). They are the outer layer (the cortex - surface of the egg), the inner layer (called the tertiary base), and the middle layer (the alveolar). According to Criel and MacRae (2002) and Drinkwater and Clegg (1991), the cryptobiotic egg shell of *Artemia* is made of three layers: the tertiary layer (chorion), the outer cuticular membrane, and the embryonic cuticle (Figure 7.1). The tertiary layer consists of an outer membrane (cortex), which is relatively thin, and the alveolar layer, which is thicker and may have various distinct layers. The alveolar layer is often highly vacuolated with the vacuoles separated by curved, or straight, solid struts of varying length (Timms *et al.* 2004). Below the tertiary layer is the outer cuticular membrane (OCM). The embryonic cuticle consists of the fibrous layer and the inner cuticle membrane. Below this is the embryonic membrane, which develops into the membrane encasing the prenauplii on their release from the resting egg. Decapsulation using hypochlorite removes the tertiary layer (chorion) allowing for quicker and easier hatching of the nauplii. The function of the chorion is to protect the embryo from UV radiation and mechanical disruption. It is the outer cuticle membrane that is impermeable to volatile solutes (Drinkwater and Clegg 1991) and the inner cuticular membrane that is impermeable to non-volatile solutes (Clegg and Conte 1980).

As stated by Williams and Geddes (1991) over a decade ago there was little interest in *Parartemia* outside of Australia and unfortunately this still is the case. The habitats of this group are temporary and episodic, collection of adult specimens is difficult, the sampling locations often isolated and inaccessible after rainfall. The success rate of rearing to adulthood of many *Parartemia* species is low. All these factors contribute to the necessity of incorporating their resting stages in ecological investigations of *Parartemia*. Studies of the dormant egg banks are now considered an important means of fully understanding the ecology of aquatic systems (Brendonck and De Meester 2003; Hulsman *et al.* 2006), both permanent and temporary.



**Figure 7.1:** The ultrastructure of *Artemia franciscana* encysted embryo. The shell is shown consisting of the different layers (cortex, alveolar and cuticular membrane). Embryo shown within the shell. L = lipid; N = nucleus; gly = glycogen; yp = yolk platelet. \* = embryonic cuticle (cuticular membrane). Reprinted with permission from Clegg *et al.* (1999).

### Objectives

The objectives of this chapter are to:

- Investigate and describe the morphology of the *Parartemia* species from Lake Yindarlgooda and Lake Miranda,
- Investigate and describe the morphological characteristics of the resting eggs of the two *Parartemia* species,
- Investigate the internal structure of the egg shell of *Parartemia* n. sp. d from Lake Yindarlgooda and compare it with that of *Artemia*.

## 7.2 Methods

### 7.2.1 Field collection

Specimens from Lake Yindarlgooda were collected in the field by isolating a column of water and removing the *Parartemia* as stated in Chapter 4.0. Specimens were fixed in 4% formalin. *Parartemia* specimens from Lake Miranda were collected in the field by Fiona Taukulis and Erin Thomas. Collection and preservation followed the same procedure.

### 7.2.2 Identification of *Parartemia* specimens

Specimens were identified following Timms (2004b). Staining of the preserved specimens with Toluidine Blue (B) Stain enabled easier microscopic examination of the female pregenital segments and the body segments. With the aid of a Leica MZ6 stereomicroscope, measurements of the specimens were made using calibrated Vernier callipers and a calibrated ocular micrometer. All specimens were photographed with an Olympus SC35 camera mounted on the Leica MZ6 stereomicroscope using Kodak ProImage Colour negative film.

### 7.2.3 Morphology and ultrastructure of the resting eggs

Sediment for the examination of the *Parartemia* resting eggs was collected and treated as described in Chapter 4.0. A sub-sample of this sediment from each of the study sites was then sieved through stacked 500  $\mu\text{m}$  and 180  $\mu\text{m}$  Endecott<sup>®</sup> brass sieves. The material retained in the 180  $\mu\text{m}$  sieve was then washed through a plastic 125  $\mu\text{m}$  sieve and immediately oven dried for at least 30 mins. Intact resting eggs were hand picked from this sediment with the aid of a Leica MZ6 stereomicroscope.

#### 7.2.3.1 Measurements of the resting eggs

Measurements of the diameters of up to 20 cysts from various sites in both Lake Yindarlgooda and Lake Miranda were made with the aid of a Leica MZ6 stereomicroscope using a calibrated ocular micrometer.

#### 7.2.3.2 Thin sections of *Parartemia* n. sp. d resting egg

Dried intact resting eggs (encysted embryos) from Lake Yindarlgooda were prepared for ultrastructure examination according to Clegg *et al.* (2000). Eggs were placed in 4% glutaraldehyde (diluted from 25% in Buffer K: 40 mM HEPES, 70 mM potassium gluconate, 15 mM sorbitol, 5 mM MgSO<sub>4</sub>, 5 mM NaH<sub>2</sub>O at pH 7.4). Each egg was pierced with a 28G dissecting needle and transferred to centrifuge tubes

where fixation in glutaraldehyde was continued for 24 h. Samples were centrifuged for 10 s at 2000 *g* to remove the fixative. Eggs were then washed three times, 10 mins each time, in Sørensen's phosphate buffer (pH 7.4). The embryos were dehydrated through a graded series of ethanol: 30, 50, 70, 90, and 100 (x2) % stages. The eggs were mounted in GMA polymerized in UV light and N gas at 23 °C for 12 h. Specimens were then orientated and 1.0 µm thin sections cut on a Sorvall® Ultracut Microtome. A selected number of the thin sections were stained with Toluidine Blue (B).

#### *7.2.3.3 Examination and measurement of Parartemia egg shell: ultrastructure*

With the aid of light micrographs, measurements were taken of the width of the tertiary layer of each of the eggs from Lake Yindarlgooda. Eggs were collected from control (Site 1) and impact (EP1 and EP2) sites during two sampling periods (March 2001 = wet; September 2001 = dry).

Differences in the alveolar thickness of the *Parartemia* egg shell between the control and impacts sites were analysed using the one-way analysis of variance procedure in Minitab (V14).

#### *7.2.3.4 Resting egg morphology - SEM*

Dried *Parartemia* eggs hand picked from the sieved sediment were mounted on SEM stubs using double-sided carbon tape. Certain eggs were dissected using a scalpel for internal examination. The eggs were gold coated and details of the external and internal morphology of the shell examined with a Philips XL30 SEM.

Representative specimens of the eggs were placed in glass vials and stored in the Museum collection of the Wetland Research Group, Dept of Environmental Biology, Curtin University of Technology, Western Australia.

## 7.3 Results

It should be clearly noted that the description of the two *Parartemia* species in this study are *not* formal and this is not a taxonomic document. The following descriptions follow those of Timms (2004b) and have been included to prevent confusion of the species, which are, to date, unnamed.

### 7.3.1 Description of *Parartemia* n. sp. d (Lake Yindarlgooda)

*Location:* Specimens were collected from Lake Yindarlgooda, March 2001. Other specimens were hatched in the laboratory from sediment collected from 2001 – 2002.

*Voucher specimen:* LYParaS4MAR01, deposited at Wetland Research Group, Dept of Environmental Biology, Curtin University of Technology, Perth, Western Australia.

To date, this species is unnamed and the classification adopted is that of Timms (2004b), identifying this species as *Parartemia* n. sp. d and is referred to as such throughout this study.

*Habitat:* Specimens were collected from a salinity range of 50 g L<sup>-1</sup> to 140 g L<sup>-1</sup> and a pH ranging from 6.01 to 8.23 (the higher salinity and lower pH were from the sites impacted by decant water from the LSRF). Vegetation was sparse at the collection sites and the lake floor composed of red clay. The water levels were <10 cm and water temperature was close to ambient air temperature (approximately 22 - 29 °C at time of collection).

#### *Male*

*Description:* (Figure 7.2a). Clypeus with anterior medial process broad and triangular, < 0.5 height of frontal process; second antennae long and smooth with no curves as in other species; basal segment of second antennae narrow, projecting laterally; frontal processes anterior margin forming an apex, dorsal process broad based (Figure 7.2b & c); the penes with lateral swelling in the basal part, distal part not observed (Figure 7.2c). Body was delicate and soft body, the base of the head relatively narrow across the basal segment of the antennae. Compound eyes positioned laterally at the base with large mandibles.

*Size:* 10 – 19 mm (from distal end of second antennae to end of distal abdominal segment) (average = 13.58 mm ± 2.78; n = 12). All males measured were mature.



### *Female*

*Description:* (Figure 7.3a). Amplexial groove with dorso-lateral bulges on thoracic segment 9 (T9), no sclerotised ridges, T10 and T11 appear to taper rapidly posteriorly (Figure 7.3b), laterally paired brood pouch with rounded posterior-lateral margins (Figure 7.3c & d), abdomen more cylindrical than tapered. Specimens hatched from sediment (*in vitro*) contained white eggs located in the ventral section of the brood pouch and the mass of brown oocytes were present on the dorsal side (Figure 7.3e). Ovigerous females collected in the field carried brown eggs (Figure 7.3a).

*Size:* 5 - 8 mm (average = 7.44 mm  $\pm$  2.53; n = 16). All females measured were ovigerous.

The males were larger than the females, with male to female ratio from field collections: 2.2:1.

### **7.3.2 Description of *Parartemia* n. sp. g (Lake Miranda)**

*Location:* Specimens were collected live from Lake Miranda during 2001 and 2003.

*Voucher specimen:* LMParaC1(1)Apr03, deposited at the museum collection of the Wetland Research Group, Department of Environmental Biology, Curtin University of Technology, Perth, Western Australia.

To date, this species is unnamed and classification follows that of Timms (2004b), identifying this species as *Parartemia* n. sp. g and will be referred to as such throughout this study.

*Habitat:* Specimens were collected at different sites around Lake Miranda with an average salinity of 70 g L<sup>-1</sup> and a pH of 8.46 (data E. Thomas and F. Taukulis, 2003). Large number of *Lamprothamnium* oospores were recorded from the sediment which consisted of mostly of coarse sandy quartz. Lake Miranda is a shallow playa located in the Carey Palaeoriver in the northern Goldfields, filling less frequently than Lake Yindarlgooda.

### *Male*

*Description:* (Figure 7.4). Clypeus with anterior medial process narrow and digitiform, present as a single, nipple-like projection. Dorsal processes visible.

Prominent frontal processes, forming an apex toward centre. Basal segment of second antennae segment broad, projecting laterally (Figure 7.4b & c).

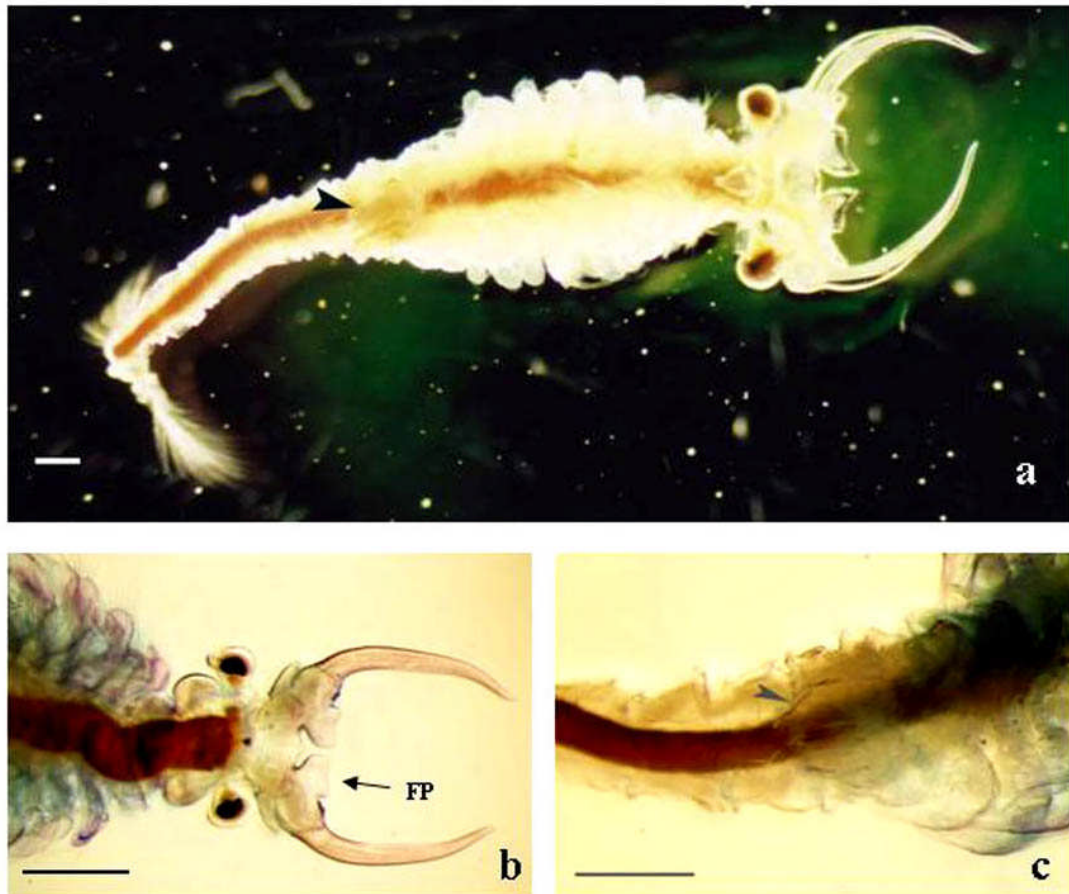
*Size:* 18.8 -23 mm (top of head to end of distal abdominal segment, length of second antennae included) (average = 20 mm  $\pm$  1.59; n = 10). All males measured were mature.

#### *Female*

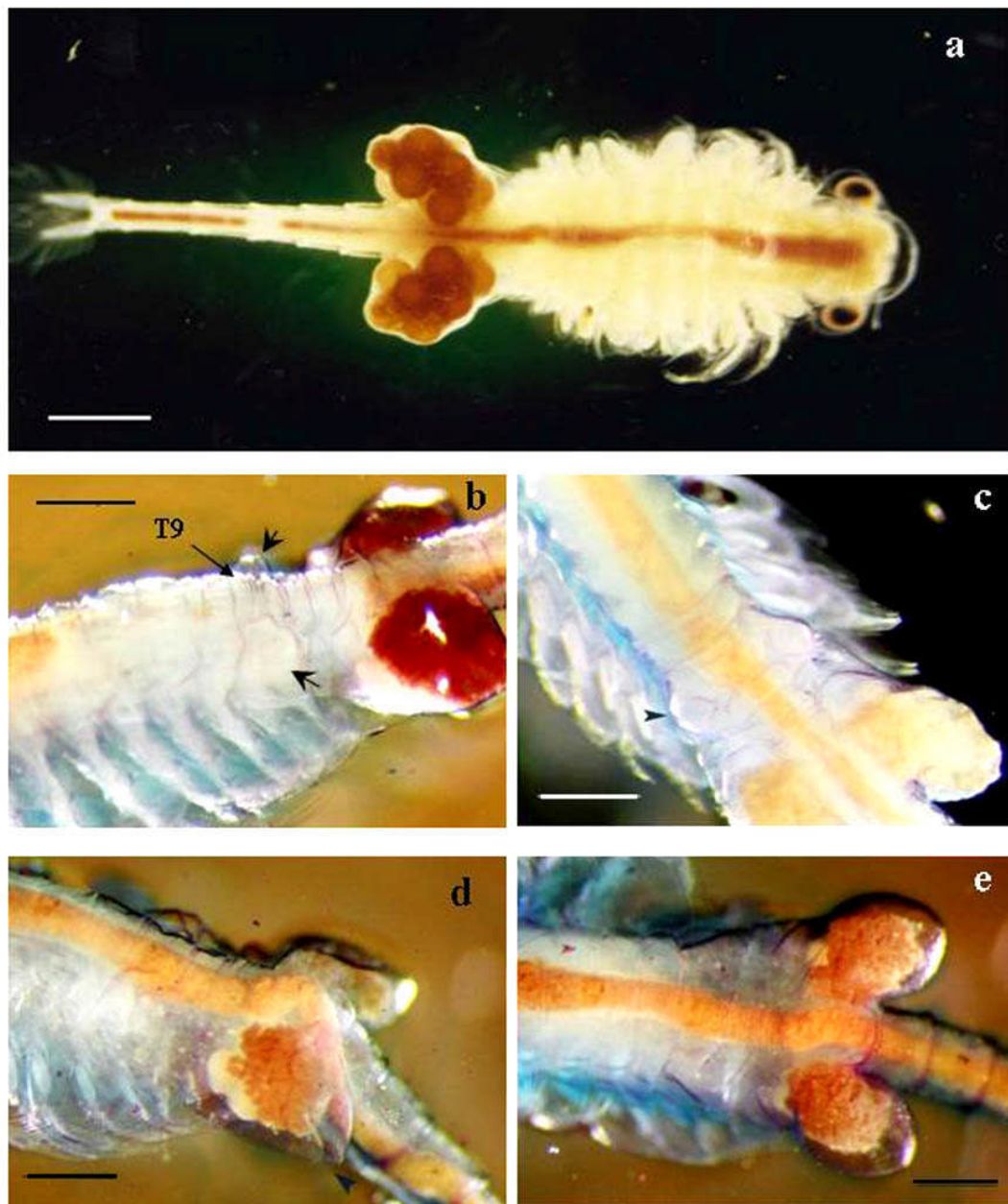
*Description:* (Figure 7.4a). Dorso-lateral bulges on T9, smaller central bulge and larger lateral bulges either side; T10 reduced and T11 expanded (Figure 7.4d & e). Anterior abdominal segments broad and tapering rapidly posteriorly, distinctly dorso-ventrally flattened and broad. Brood pouch, evenly rounded, extending posteriorly and laterally away from the body.

*Size:* 8.3 – 12 mm (average = 11 mm  $\pm$  1.41; n = 10). All females measured were ovigerous.

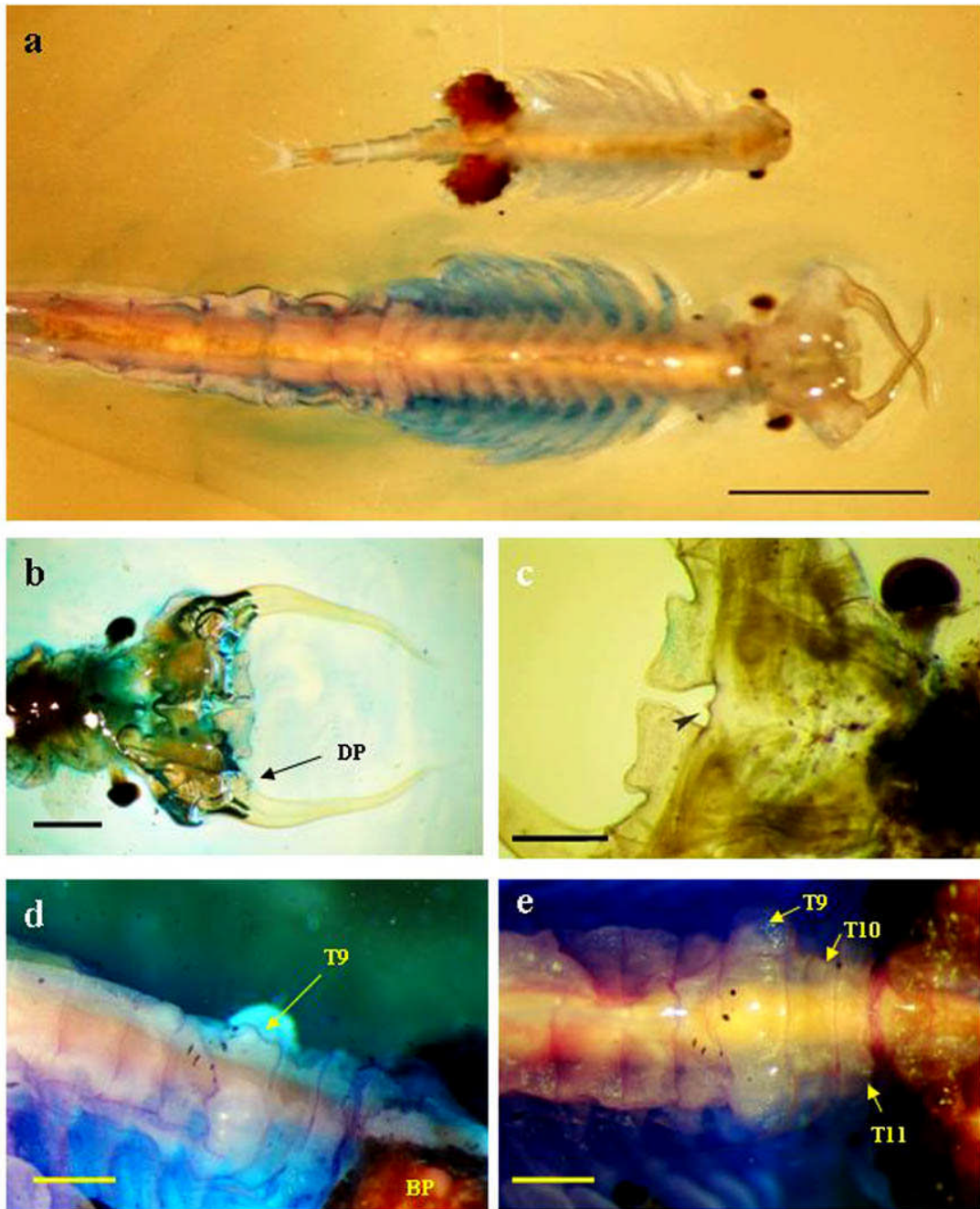
The males were much larger than the females, the male to female ratio 2:1 (Figure 7.4a). Compared to *Parartemia* n. sp. d from Lake Yindarlgooda, the male *Parartemia* n. sp. g were quite robust. Many specimens were collected from the field whilst amplexing (Figure 7.5), this species matured two weeks after hatching with mating observed in the third week, couples amplexing for more than 24 h.



**Figure 7.2:** Male *Parartemia* n. sp. d (Lake Yindarlgooda) morphology: **a)** Whole male, ventral view, arrow pointing to penes. **b)** Head: dorso view, frontal processes (FP) shown; labrum seen below compound eyes at base of the head. **c)** Genital region: ventral view, arrow pointing to penes on genital segment between posterior thoracic segments and anterior abdominal. Scale bars = 1 mm.



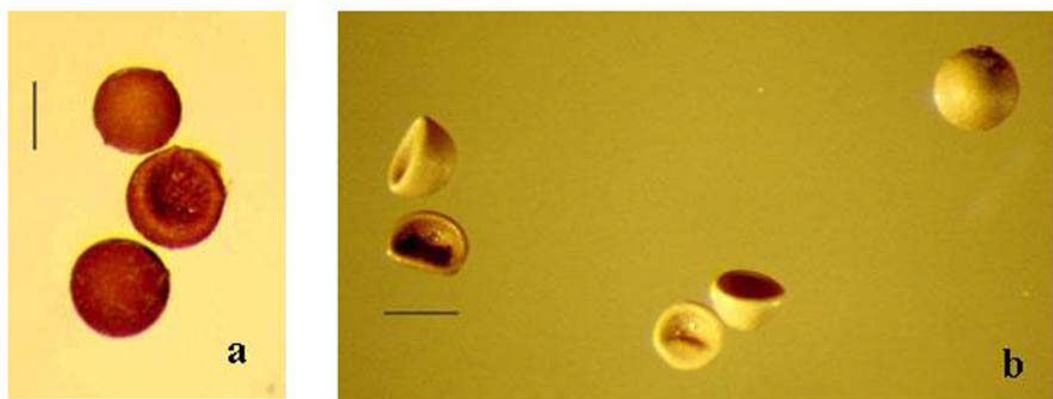
**Figure 7.3:** Female *Parartemia* n. sp. d (Lake Yindarlgooda) morphology: **a)** Whole ovigerous specimen collected live, dorso view. Brown eggs seen in brood pouch. **b)** Thoracic segments: latero-dorso view, arrows pointing to lateral bulges at T9. **c)** Pregenital segments: dorsal view, arrow shows lateral bulges. **d)** Lateral view: arrow pointing to gonopore in lateral brood pouch. Opaque oogonia (eggs) in ventral section of the brood pouch toward the anterior appendages. **e)** Dorso view of brood pouch, brown granular section of brood pouch (oocytes), possibly prior to fertilisation. **(b - e)** Specimens hatched from sediment *in vitro*. Scale bars = 1 mm.



**Figure 7.4:** *Parartemia* n. sp. g (Lake Miranda) morphology: **a)** Female, ovigerous (above) & male (below); dorso view of whole specimens collected live (scale bar = 5mm). **b)** Male head, dorso view; DP = dorsal process of clypeus. **c)** Male head, dorso view; arrow points to medial clypeus in between the frontal processes. DP can be seen between the second antennae and FP (next to right side of scale bar). **d)** Female: thoracic segments, dorso-lateral view (arrow at T9 points to lateral bulges); BP = brood pouch. **e)** Female pregenital region: dorso view (T9 – T11), large lateral bulges at T9. **(b – e)** Scale bars = 1 mm.



**Figure 7.5:** *Parartemia* n. sp. g: Copulation. Male second antennae bent inwards for amplexing, each penes inserted into gonopore of brood pouch (ovisac). Amplexing may last for up to a day or more for this species. Male detached from amplexing female pregenital region when preserved. Ovisacs containing brown and opaque oocytes. Scale bar = 4 mm.



**Figure 7.6:** *Parartemia* resting eggs collected from surface sediment. **a)** *Parartemia* n. sp. g, Lake Miranda. External surface of the egg has coarse appearance. Scale bar = 280  $\mu$ m. **b)** *Parartemia* n. sp. d, Lake Yindarlgooda. External surface of eggs, glabrous. Variation in egg colour is typical for this species. Scale bar = 300  $\mu$ m. Inpocketing in the eggs indicate anhydrobiotic state. The inpocketing in *Parartemia* sp. d is much deeper than that in *Parartemia* n. sp. g.

### 7.3.3 Resting egg morphology

The ultrastructure of the *Parartemia* resting egg follows a similar structure to that of *Artemia*, consisting of three layers: the tertiary layer, the outer cuticular membrane, and the embryonic cuticle. SEM revealed morphological variation in the eggs of *Parartemia* n. sp. d and *Parartemia* n. sp. g. (Figures 7.7 and 7.8).

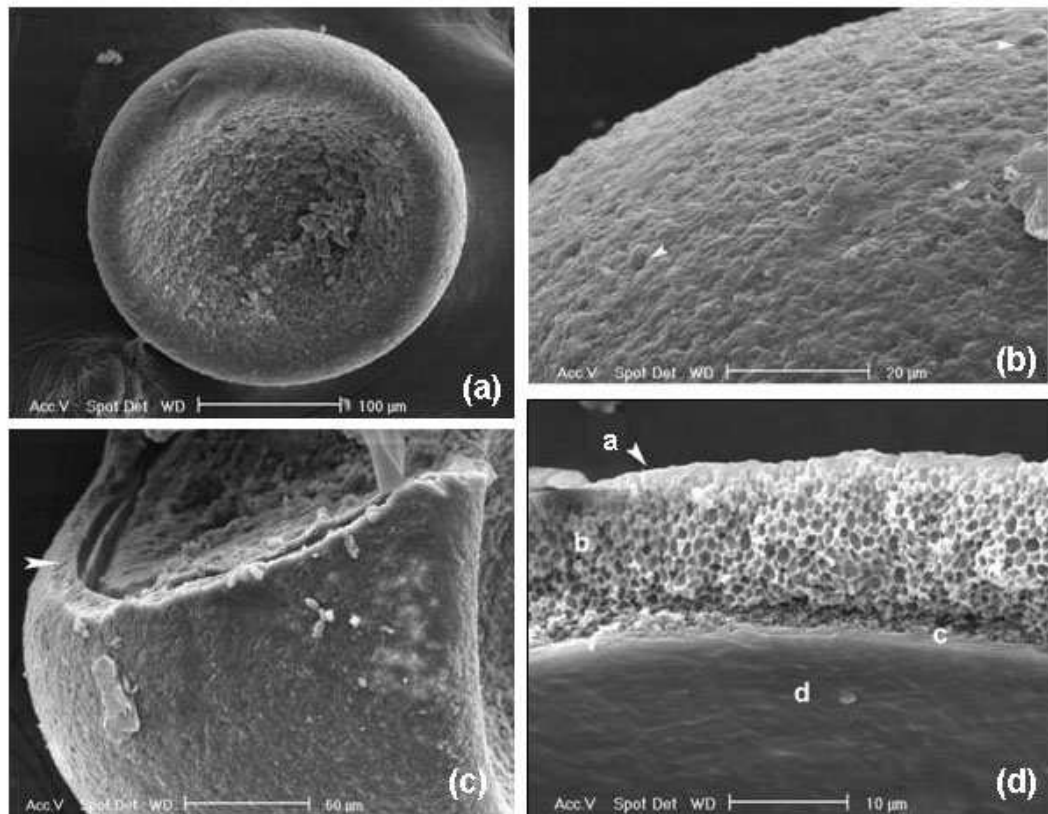
#### 7.3.3.1 *Parartemia* n. sp. d (Lake Yindarlgooda)

Eggs are spherical, depressed on one face (in-pocketing), with a deep depression (approximately half the diameter of the sphere), they are light brown (tan) in colour (Figure 7.6b; Figure 7.7a). Egg size: 285 - 322  $\mu\text{m}$  (average = 302.5  $\mu\text{m} \pm 22.27$ ; n=58). External surface of cortex is smooth, glabrous, with pores only just visible, cortex solid and thin (Figure 7.7b). Alveolar layer was uniform, with small rounded subequal vesicles compressing into a thinner layer just before the outer cuticular membrane (Figure 7.7c-e). The inner cuticular layer is smooth, fibrous layer is visible in Figure 7.7c and d. The thickness of the shell of *Parartemia* n. sp. d was approximately 20 – 30  $\mu\text{m}$ .

The encysted embryo appeared to sit loosely within the shell, not occupying the entire volume circumscribed by the shell (Figure 7.7c).

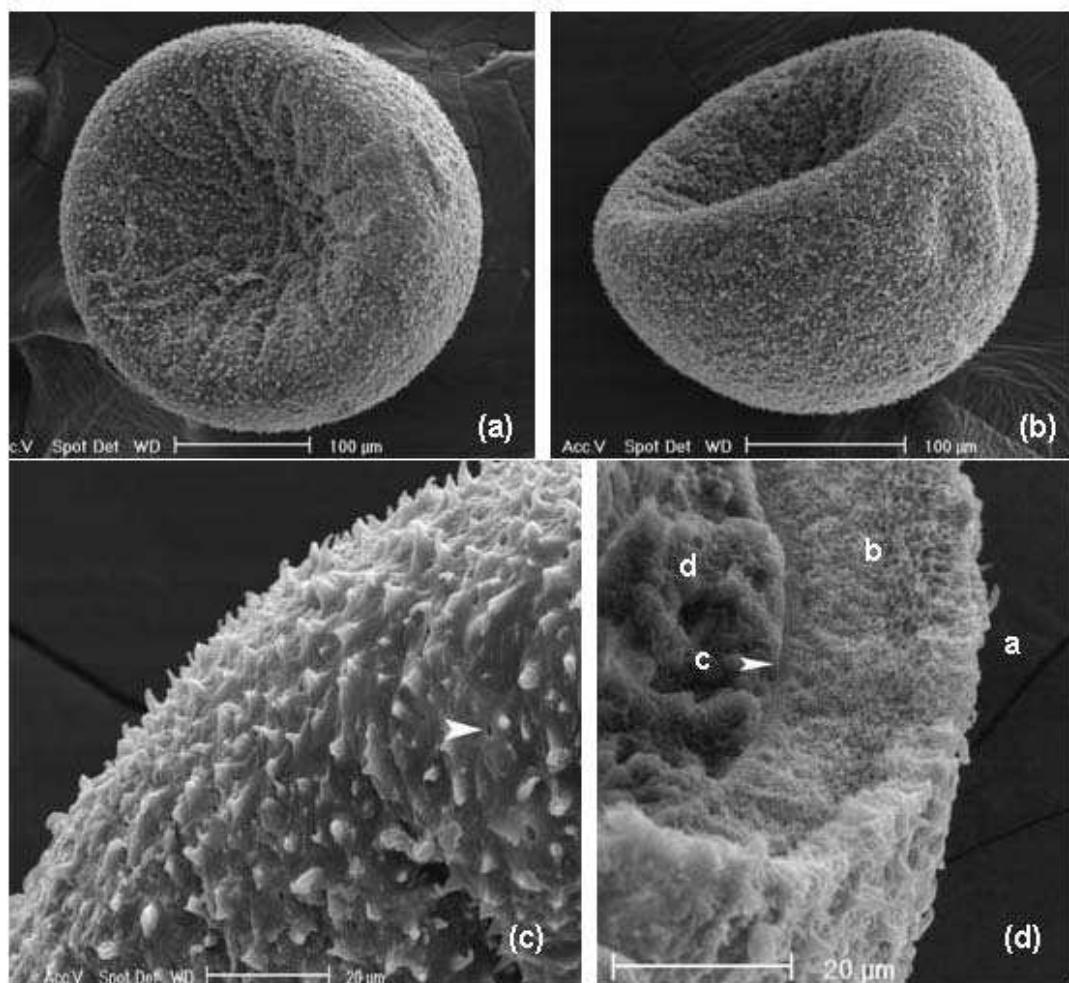
#### 7.3.3.2 *Parartemia* n. sp. g (Lake Miranda)

Resting eggs are spherical with in-pocketing on one side, ropy folds visible and some eggs slightly pinched on one side (Figure 7.8a & b). The eggs of this species were darker brown than the eggs of *Parartemia* n. sp. d (Figure 7.6a). The egg diameter ranged from 260 - 320  $\mu\text{m}$  (average = 289  $\mu\text{m} \pm 20.70$ ; n = 11). External surface layer of cortex covered in “hair-like” extensions (not smooth like *Parartemia* n. sp. d), with larger pores (Figure 7.8c). The cortex was thick and vacuolated with vertically aligned vesicles (Figure 7.8d). The alveolar layer contained two sub-layers (lamellate) with unequal vesicles decreasing in size and compacting toward the cuticular membrane (Figure 7.8d). The vesicles of the alveolar were aligned perpendicular to those of the cortex. The thickness of the shell of *Parartemia* n. sp. d was approximately 22  $\mu\text{m}$ .



**Figure 7.7:** *Parartemia* n. sp. d resting egg structure: **a)** Whole egg showing in-pocketing. **b)** External surface, arrows pointing to pores. **c)** Close up of shell wall, small white arrow on left pointing to shell. Below shell, embryonic cuticle can be seen pulling away from shell, embryo seen in cavity in the centre. **d)** Internal structure of the shell: **a** = cortex; **b** = alveolar layer showing rounded subvesicles; **c** = embryonic cuticle made up of OCM (outer cuticular membrane), fibrous layer, ICM; **d** = ICM (inner cuticular membrane).





**Figure 7.8:** *Parartemia n. sp. g* resting egg structure: **a)** Egg showing furrowing of in-pocketing with ropey folds, rough external surface layer. **b)** Egg with indentations on side (pinching), rough surface clearly visible, in-pocketing shallow, with thick edges. **c)** Outer surface of the shell with hair-like extensions; white arrows point to large pores. **d)** Internal structure of egg shell: **a** = cortex; **b** = alveolar layer (lamellate); **c** = inner cuticular membrane (ICM); **d** = embryo.

### 7.3.4 Ultrastructure of the resting egg: *Parartemia n. sp. d*

Observations of the thin sections made through the prepared *Parartemia* eggs from several sites around Lake Yindarlgooda showed the ultrastructure to be similar to those of *Artemia*. All the sections of the egg shell were visible in Figure 7.9a-d. The tertiary layer, clearly outlined in Figure 7.9b, consisted of a thin, solid cortex (a) and the vacuolated alveolar layer (b). Below this was the outer cuticular membrane (OCM) (c) separated from the inner cuticular membrane (ICM) (d) by a thick fibrous layer. The tertiary layer and the cuticular membrane that make up the shell were distinct sections, detaching from the shell (Figure 7.9c). Characteristic of the *Parartemia* egg was the inpocketing of the shell as seen in Figure 7.9d, indicated by the arrow.

Held within the shell was the encysted gastrula embryo, surrounded by the thin embryonic membrane (Figure 7.9c) and detached from the shell. The embryo did not fill the entire volume of the shell (Figure 7.9a), though it appeared to in Figures. 7.9c and d. The various thin sections made through the embedded eggs show the embryo sitting in different positions and hence in some micrographs the embryo appears to fill the cavity while in others it does not. Figure 7.9d shows a transverse section through the inpocket. The other figures (a-c) are transverse sections perpendicular to the inpocket.

The tertiary layer was the thickest section of the *Parartemia* shell and therefore the most reliable for comparison of eggs from different sites in Lake Yindarlgooda. Allowing for mechanical distortions when embedding, measurements indicated the thickness of the tertiary layer to be uniform within the eggs sectioned, with some variation in thickness between the eggs from the different sites (Table 7.1). The size of the alveolar layer ranged from approximately 15 to 28  $\mu\text{m}$  from one side of the embedded egg to the other. The thickness of the cuticular membrane was measured as approximately 6  $\mu\text{m}$ .

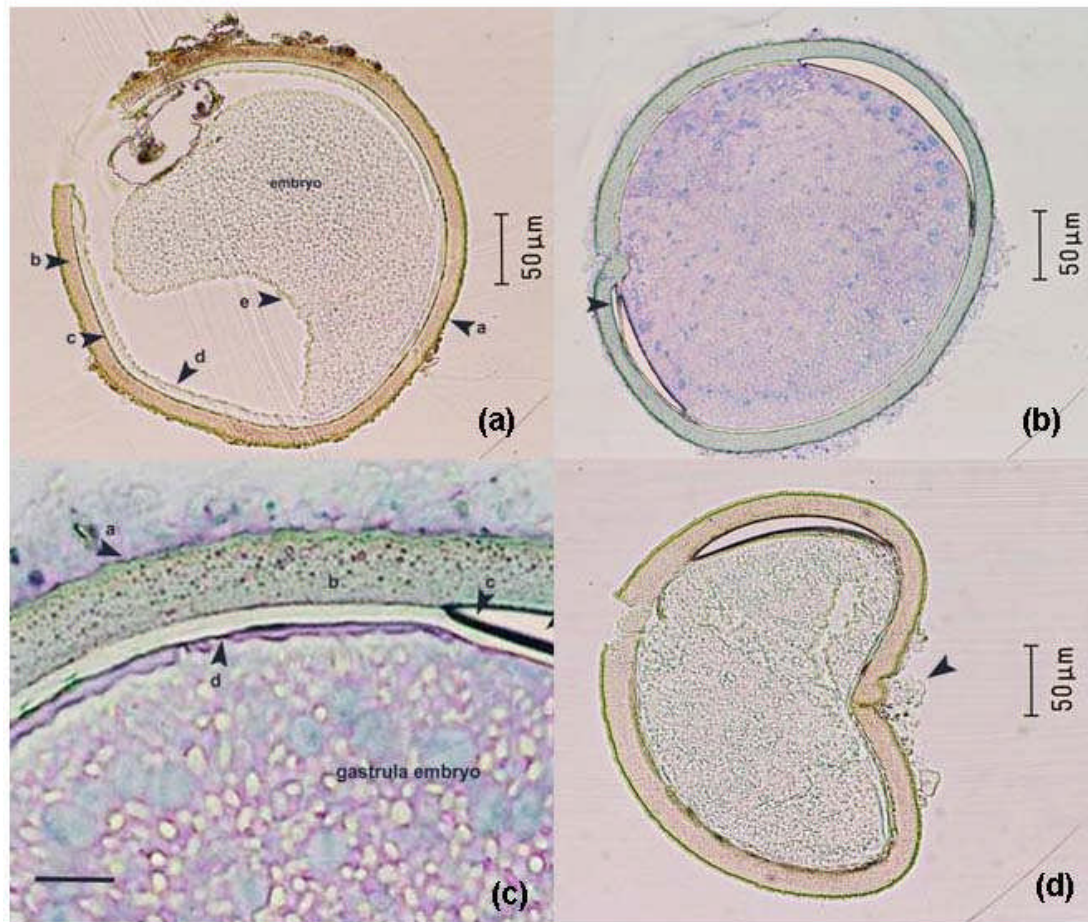
The thickness of the alveolar layer of the eggs from the three different sites, control and impact, were found to be significantly different ( $p = 0.000$ ) (Table 7.2). Whether this is an environmental adaptation or genotypical it cannot be determined from this study.

**Table 7.1:** Alveolar thickness of *Parartemia* resting eggs from Lake Yindarlgooda ( $\mu\text{m}$ ). Measurements taken from just below the inner section of the cortex and the start of the cuticular membrane at various positions around the egg using light micrographs. Sites used were Site 1 - control site (1(2)MAR01); EP1 - impact site (EP1(2)SEP01); and EP2- impact site (EP2(2)MAR01).

Layers	Slide Label		
	1(2)MAR01	EP1(2)SEP01	EP2(2)MAR01
1 (outer)	20.07 $\pm$ 0.99	16.53 $\pm$ 1.31	30.67 $\pm$ 3.01
2 (middle)	18.45 $\pm$ 1.39	14.31 $\pm$ 1.16	29.44 $\pm$ 2.17
3 (middle)	N/A	17.19 $\pm$ 1.54	23.78 $\pm$ 2.62
4 (outer)	N/A	13.46 $\pm$ 0.68	N/A
Average	19.26 $\pm$ 1.19	15.37 $\pm$ 1.175	27.93 $\pm$ 2.6

**Table 7.2:** One-way analysis of variance table ( $H_0$ : no difference in thickness of the alveolar layer between resting eggs from impact and control sites). Data normalized using Johnson's transformation. R-Sq = 74.22% R-Sq(adj) = 73.00%. A *post hoc* test (LSD) found all sites to be different from each other.  $P_{\text{critical}} = 0.05$ .

Source	d.f.	SS	MS	F	P
Site	2	34.098	17.049	60.47	0.0000
Error	42	11.842	0.282		
Total	44	45.939			



**Figure 7.9:** Light micrographs of the ultrastructure of *Parartemia* n. sp. d (Lake Yindarlgooda) resting eggs from dried surface sediment. **a)** Egg ultrastructure, whole, unstained (Site 1, March 2001). Gastrula embryo in centre of the shell, not filling cavity entirely, and easily pulling away from the shell. **b)** Whole eggs, stained with Toluidine Blue (B), arrow pointing to embryonic cuticle pulling away from tertiary layer. (Site EP1, September 2001). **c)** Shell wall, stained with Toluidine Blue (Site EP1, September 2001) showing layers (scale bar=15 µm). **d)** In-pocketing of egg (indicated by arrow) (Site 6, September 2001 – unstained). For all slides: **a** = cortex; **b** = alveolar layer; **c** = OCM; **d** = ICM; **e** = embryonic membrane.

## 7.4 Discussion

Despite the increase in research on Australian inland waters and their unique biota, published information on *Parartemia* is still sparse, especially compared to that on *Artemia*. Previous information on *Parartemia* published in the 1980s is restricted to unpublished dissertations. Prior to this, studies were confined to only a few *Parartemia* species, in particular the extensive work by Geddes (1975a; 1975b; 1975c; 1981) and Marchant (Marchant and Williams 1977) on *Parartemia zietziana*. The information presented in this chapter will be incorporated into Chapter 9.0 to understand the effects of increased salinity on the hatching of the eggs from the sediment and the protective role of the shell.

In contrast to *Artemia*, there is a high degree of morphological variation among the different species of *Parartemia* (Williams and Geddes 1991; Van Stappen 2002) displayed strongly by the secondary sexual characteristics of the adult males. While the female features are less obvious, on closer inspection the differences in the pregenital segments easily identified *Parartemia* n. sp. d and *Parartemia* n. sp. g.

The “lock and key” feature observed in many anostracans (Rogers 2002) was displayed in the *Parartemia* species from Lakes Miranda and Yindarlgooda. While it is generally accepted that *Parartemia* are not sympatric with other species and occurrence with other anostracans is rare (Williams and Geddes 1991; Timms 2004b), recent studies have shown otherwise. A new species, *Parartemia* n. sp. x was recorded as occurring with *Branchinella simplex* in seven collections from Lake Carey (Timms *et al.* 2006). *Parartemia* n. sp. d has also been recorded as sympatric with *P. serventyi* in the Johnston Lakes (Timms 2004b), while both *Parartemia* n. sp. d and *Parartemia* n. sp. g have been collected from Lake Way in the northern Goldfields (Campagna and Taukulis 2006). The presence of *Branchinella* eggs in the sediment of Lake Yindarlgooda (Chapter 4.0) and in the sediment of Lake Miranda, indicate the possibility of co-occurring anostracans, though it appears that salinity ensures sympatric existence is avoided.

Rogers' (2002) study of *Parartemia minuta* found that the dorsal bulges on the female fit directly into the medial and anterior clefts of the male's clypeus. Applying this to the *Parartemia* from Lake Miranda and Lake Yindarlgooda, observations of their mating behaviour suggested that the second antennae bent inwards clasping the

female in the pregenital segments. The medial margin of *Parartemia* n. sp. g should fit over the bulge on the amplexial groove at T9 of the female allowing the male to attach and thereby amplex for an extended period as observed *in vitro*. *Parartemia* n. sp. d does not have this bulge on T9 to grasp, though the flattened frontal processes may allow the male to hold the female with his head bent forward as he clasps with his second antennae. The complimentary features of the male and female secondary sexual characteristics play an obvious role in assisting the males to grasp the female during copulation.

The morphological differences between the males of the two *Parartemia* species were obvious, with *Parartemia* n. sp. g the larger and more robust of the two with at least a 5 mm difference in size. The females of *Parartemia* n. sp. g were also larger than the females of *Parartemia* n. sp. d. The differences in the appearance of the brood pouches were also obvious for both species, with *Parartemia* n. sp. g appearing to carry a greater number of eggs than *Parartemia* n. sp. d. The rapid maturity observed in *Parartemia* from Lake Miranda and the large number of eggs they produce may be a reflection of their habitat. The differences in the ecology of the biota from temporary lakes that fill predictably to those that fill episodically is discussed further in Chapter 9.0.

Increasingly, the morphology of anostracan eggs is included in the description of new species, with details of both external and internal features. Studies conducted by Timms *et al.* (2004), Shepard and Hill (2001), and Hill and Shepard (1997) found sufficient differences between certain genera to justify the use of egg morphology in ecological investigation in the absence of adults. Timms *et al.* (2004) noted that the external morphology of the resting eggs of the *Parartemia* species were similar to *Artemia* resting eggs, both with a smooth outer cortex. Comparison of the SEM images of *Parartemia* n. sp. d eggs and those of *Artemia franciscana* in Hill and Shepard (1997) showed similarities. While *Parartemia* n. sp. d eggs appeared similar to *Artemia* and the four *Parartemia* species in Timms *et al.* (2004), *Parartemia* n. sp. g egg morphology was quite different. Mura (2001) found the taxonomic use of resting egg morphology to be less successful for the anostracan genus *Chirocephalus*. Variation within population in the resting egg morphology was high and different species difficult to distinguish. Whilst morphological

differences between species have proven difficult, the use of ootaxonomy should not be dismissed for identification of different genera (Hill and Shepard 1997; Timms *et al.* 2004), particularly for ecological studies in environments where the absence of water is an issue.

It is recognised in larger permanent systems that the egg bank is an important component of any aquatic system and avoiding it can lead to erroneous interpretations on the analysis of the community structure (Brendonck and De Meester 2003). The examination of sediment for palaeolimnological information is not a recent phenomenon, with extensive use of diatom frustules (Gell 1997; Fritz *et al.* 1999; John 2000) and ostracods tests (De Deckker *et al.* 1988) to determine habitat changes.

To date, Timms *et al.* (2004) is the only other published description of the egg shell morphology of different *Parartemia* species. This study, unlike previous work, records obvious differences in the egg shell morphology, both external and internal, of two *Parartemia* species for the first time, allowing for detailed identification.

The need for comparisons on the thickness of the anostracan egg shell was stated by Dumont *et al.* (2002). The shell of *Parartemia* n. sp. g from Lake Miranda had a thicker alveolar layer and larger vesicles than that of *Parartemia* n. sp. d from Lake Yindarlgooda, though the egg diameters were similar. These differences may be due to abiotic parameters. Lake Miranda is a naturally less saline system than Lake Yindarlgooda. The thicker alveolar layer and larger pores may facilitate the greater uptake of fresh water and therefore initiate faster hatching. Research on *Artemia* by Anderson *et al.* (1970) suggested that the thickness of the shell wall may control the permeability of the shell and therefore regulate diapause.

The cells of the encysted gastrula embryos of *Artemia franciscana* are among the most resistant of all known animal cells (Clegg *et al.* 2000). In addition to the chorion (the tertiary layer) secreted by the shell gland, there is the outer cuticular membrane which is formed by the blastoderm cells (Morris and Afzelius 1967). It is the outer cuticular membrane that is impermeable to substances such as lead and hyperchlorite and the inner cuticular membrane to non-volatile solutes (Criel and MacRae 2002a).

The ultrastructure of the *Parartemia* n. sp. d eggs were identical to that of *Artemia franciscana*. All the characteristic features of the anostracan eggs were identified in the *Parartemia*. The *Parartemia* shell consisted of three distinct layers: the tertiary layer (cortex and alveolar), the outer cuticular layer (OCM and fibrous layer) and the inner cuticular membrane, which delineates the embryo from the fibrous layer. Research by Abatzopoulos *et al.* (2006) and Sugumar and Munuswamy (2006) on the cysts of different *Artemia* species found them all to be similar in structure.

The thickness of the shell was uniform for each egg, though there was a significant difference in the thickness of the egg shell between samples from different sites. The implications of this are difficult to ascertain, as there is little literature on the role of shell thickness between species. Studies by Abatzopoulos *et al.* (2006) found differences in the thickness of *Artemia urmiana* egg shell, though did not discuss the implications of their findings. Variation in egg diameter is common for the anostracans (Mura 2001; Shepard and Hill 2001) as has been shown for the two *Parartemia* species in this study, and this may extend to the thickness of the alveolar layer within the same species.

### **Conclusions**

Differences in the morphology of *Parartemia* n. sp. g and *Parartemia* n. sp. d were demonstrated, including the morphological characteristics of their resting eggs, for the first time. Distinct morphological differences in the *Parartemia* resting eggs were found, for the first time. This finding indicates the usefulness of ootaxonomy as a tool for ecological studies.

The ultrastructure of the *Parartemia* egg was found to be identical to *Artemia*, structurally. The *Parartemia* shell consisted of three distinct layers: the tertiary layer (cortex and alveolar), the outer cuticular layer (OCM and fibrous layer) and the inner cuticular membrane. This finding indicates that the *Parartemia* resting egg may be as resilient as that of *Artemia*. Mechanisms that control the hatching of *Parartemia* eggs may be studied using the available information on *Artemia* as a reference.

The differences in the resting egg morphologies of the two *Parartemia* species were presented at the 9<sup>th</sup> International Salt Lake Society Conference. The paper is awaiting publication (Campagna and John, *in press*).



## Chapter 8.0. The ecology of *Parartemia* in Lake Yindarlgooda

### Abstract

The distribution patterns in relation to salinity, the population structure and dynamics of *Parartemia* n. sp. d in Lake Yindarlgooda were investigated. From field observations, this species was found to be halotolerant and was collected from salinities spanning 50 to 140 g L<sup>-1</sup>. It is bisexual with a male to female sex ratio of approximately 1:1.5. During the study, this species followed an oviparous mode of reproduction and recruitment to the population was from dormant eggs. The distribution of the species within Lake Yindarlgooda ranged from the southern control sites to the northern impact sites with the egg bank becoming sparser in the north eastern arm of the lake. The impact sites around the LRSF recorded the highest number of live individuals and the richest egg bank. This is the first investigation on the dormant egg bank and the specific distribution in relation to salinity of *Parartemia* n. sp. d species and extends the distribution record for this species in Western Australia.

### 8.1 Introduction

In general, *Parartemia* inhabit the large inland playas. Their overall distribution in Australia is summarised in Timms (2004b) with records of individual species from a few publications (for e.g. Linder 1941; Geddes 1976; De Deckker and Geddes 1980). With the increase in research on these systems, new discoveries of this and other species, such as *Parartemia* n. sp. x in Lake Carey (Timms *et al.* 2006), have been recorded. As *Parartemia* are exceptional osmoregulators they are often collected in waters of varying salinity (Geddes 1975a, 1975b, 1975c; Timms 2004b). Seldom are *Parartemia* species sympatric with other *Parartemia* species (Williams and Geddes 1991; Timms 2004b), though some of the larger systems may contain more than one species inhabiting distant sections of the lake, such as in Lake Way (Campagna and Taukulis 2006), Lake Carey (Timms *et al.* 2006) and Lake Johnstone (Timms 2004b). Co-occurrence is also rare and often dictated by salinity levels. For example, the genus *Branchinella* was found to dominate the clay pans, while *Parartemia* were restricted to the large, more saline lakes of the Paroo (Timms and Sanders 2002). This was observed in the Western Australian interior (Timms 2002; Timms *et al.* 2006).

The absence of *Artemia* in Australian inland salt lakes is enigmatic. Australia is the only continent where *Artemia* is not the dominant anostracan and it appears that *Parartemia* occupy the less saline, temporary waters while *Artemia* inhabit the permanent coastal salterns (Van Stappen 2002). However, recent studies by McMasters *et al.* (2007) recorded *Artemia parthenogenetica* Bowen & Sterling from inland playa lakes in the south-west Wheatbelt region of Western Australia, indicating an expansion of its range. They suggested birds to be the vectors for a metapopulation originating from Lake Hayward on the coastal south-west region, rather than human agencies as in other parts of Australia (Mitchell and Geddes 1977). In addition to these findings, a group of *A. parthenogenetica* has been identified from a treated effluent pond at a mine site in Lake Carey in 2007, further extending the range of distribution of *Artemia* (*pers. obs.*, 2007). The increase in suitable habitats away from the coast of Western Australia because of secondary salinisation of the Wheatbelt wetlands, plus the creation of permanent saline ponds in mining centres, may have assisted the dispersal of *Artemia*. However, the ecological consequences of this recently discovered distribution are unknown. Unlike the resting eggs of *Artemia*, those of *Parartemia* sink once released (Van Stappen 2002), limiting their dispersal by vectors such as wind or animals.

All *Parartemia* species are obligately sexual and may follow two modes of reproduction, ovoviviparity and oviparity (Geddes 1981). Like *Artemia*, the females release free-swimming nauplii (ovoviviparity) or encysted embryo (oviparity) (Jackson and Clegg 1996). The mode of reproduction appears controlled maternally and may switch from one mode to the other according to the environmental conditions. *Artemia* species reproduce ovoviviparously when the rearing conditions are favourable such as moderate salinity, high oxygen levels, and an abundance of food. When conditions are adverse, the oviparous reproduction is chosen, in which resting eggs are released and undergo periods of desiccation, entering diapause (Clegg and Trotman 2002). Geddes (1976) noted that the switch in reproductive modes in *Parartemia* appeared to be associated with rising salinity levels, accompanied by falling oxygen concentrations.

The ovoviviparously produced embryos are enclosed within a thin membrane and develop in the brood pouch of the female prior to their release as instar I. In oviparous reproduction, the shell glands, located medially and antero-laterally in the

ovisacs, produce a secretion inserted into the fertilisation membrane of the arrested gastrula developing into the tertiary envelope (Criel and MacRae 2002b). Upon release, the encysted embryo enters a state of dormancy, in which endogenous factors arrest the metabolism and development of the embryo, commonly called diapause (Lavens and Sorgeloos 1987). After a period of desiccation, the embryo may be activated and develop into the larval stage. If unfavourable conditions prevail, the growth of the larvae is again arrested and enters quiescence - a cryptobiotic stage. This is an example of exogenous control of metabolism and development.

Inhabitants of temporary system rely on the production of dormant eggs for survival during dry periods (Caceres 1997), and *Parartemia* is no exception. Belk (1998) promoted the importance of understanding their characteristics for the conservation of branchiopods and this led to studies on their dynamics and characteristics (for e.g. Maffei *et al.* 2002; Mura 2005; Hulsman *et al.* 2006). The dormant egg banks of temporary systems can be seen as an archive. They provide information on of the occurrence and distribution of a species and provide information on their habitats (Brendonck and De Meester 2003). The fact that they are better preserved within these habitats allows for their use in the absence of water (Belk 1998).

Ecological studies on *Parartemia* species are limited and the focus has been on species found in other states of Australia (Geddes 1975a, 1975b, 1975c). Little information is available on their population structure or dynamics. This chapter continues from Chapter 7.0 and examines the ecology of *Parartemia* n. sp. d in Lake Yindarlgooda as one of the dominant crustaceans, studying their distribution within the lake according to varying salinities and examines their population dynamics. The differences in the population structure between the control and impact sites are presented. The findings of this chapter lead into Chapter 9.0, which investigates further the *Parartemia* egg bank and the factors that control its resilience.

### **Objectives**

The objectives of this chapter are to:

- Investigate the distribution pattern of *Parartemia* in Lake Yindarlgooda, according to environmental factors,

- Investigate the population structure of the *Parartemia* in Lake Yindarlgooda and understand their mode of reproduction,
- Use the egg bank of *Parartemia* to identify their distribution pattern in Lake Yindarlgooda.

## **8.2 Methods**

### **8.2.1 Study sites**

Samples were collected from the study sites stated in Chapter 2.0 (Figure 2.2). The wetland sites were not included in this study as *Parartemia* were not recorded from these sites.

### **8.2.2 Field collections of *Parartemia***

During the March 2001 field trip, observations of *Parartemia* activity were recorded from each of the sites in Lake Yindarlgooda. *Parartemia* were collected at all sites with sufficient water, > 5 cm (sites 1-5 and EP1) as described in Chapter 4.0.

### **8.2.3 Identification and enumeration**

*Parartemia* specimens were identified following Timms (2004b). *Parartemia* counts were performed with the aid of a Leica MZ6 stereomicroscope. The total *Parartemia* present in each sample were counted and the number of individuals per litre of water calculated (Gannon 1971). Ratios of males, to females and the number of juveniles present in each population were recorded. The number of females in the population with mature brood pouches was also recorded.

### **8.2.4 Dormant *Parartemia* egg bank (resting stages)**

#### *8.2.4.1 Collection of surface sediment*

Three random 50 x 50 cm scrapings of the first three centimetres of the surface sediment were collected from within each of the sampling sites in Lake Yindarlgooda (sites 1 -7, EP1 and EP2). This was the area considered to be the “active” area for the dormant egg bank according to Caceres and Hairston (1998). Each sample was stored in calico bags and returned to the laboratory for examination.

#### 8.2.4.2 Examination and enumeration of *Parartemia* resting eggs

Sediment samples were oven dried at 30 °C and each dried sample was weighed and transferred to plastic sample bags for storage. A sub-sample of the sediment from each site was sieved through stacked 500 µm and 180 µm Endecott® sieves. The material retained in the 180 µm sieve was then washed through a plastic 125 µm sieve, immediately oven dried for half an hour and weighed.

Sub-samples of up to a gram of the dried material were examined manually under a Leica MZ6 stereomicroscope at high magnification (×64). Only intact *Parartemia* eggs were counted and the final calculation recorded as number of resting eggs per cm<sup>2</sup> of sediment.

### 8.3 Results

#### 8.3.1 Field observations

During the March 2001 field trip, *Parartemia* were recorded from all sites, the exception being EP2, where water levels were too low to collect a zooplankton sample. While *Parartemia* were observed *in situ* at Site 2, they were sparse and none were recorded from the zooplankton net samples collected (Figure 8.1). The behaviour of the *Parartemia* varied between the southern control sites and the northern impact sites, as did the structure of each community. No *Parartemia* were recorded from sites 6 and 7, as they were dry in March 2001.

##### 8.3.1.1 Southern control sites

In general, *Parartemia* numbers were relatively sparse in the southern control sites 1-3, averaging below two individuals per litre of water. Of the control sites, Site 1 recorded the highest number of *Parartemia*. Aggressive mating behaviour was observed at this site with multiple males attempting to amplex a single female. The salinity range during collection was 54.7 g L<sup>-1</sup>, 73.6 g L<sup>-1</sup> and 67.4 g L<sup>-1</sup> at sites 1, 2 and 3 respectively.

##### 8.3.1.2 Northern impact sites

*Parartemia* numbers were higher in the northern impact sites around the LRSF, particularly at EP1 (Figure 8.1). A large stand of dead *Parartemia* was observed along the shoreline at Site 4. *Parartemia* were seen swimming in the surface water, indicating a second recruitment. Examination of samples of the dead *Parartemia*

found the majority of females with full brood pouches carrying dark brown eggs. The salinity at Site 4 on collection was  $134.4 \text{ g L}^{-1}$ . Large numbers of dead *Parartemia* were also observed along the trench at EP2 which had been dug to release the hypersaline decant water from the new LRSF. No live individuals were visible in the surrounding water at EP2. During March 2001, Site EP2 recorded the highest salinity of  $140 \text{ g L}^{-1}$ .

The highest number of *Parartemia* were recorded from EP1 and confined to a few isolated pools as the area was covered in a thick salt crust. A number of dead *Parartemia* were visible and many of the live females had bright yellow ovisacs, the salinity recorded at this site was  $125.3 \text{ g L}^{-1}$ . The *Parartemia* numbers at Site 5 were half that recorded from EP1. The salinity recorded was  $125.7 \text{ g L}^{-1}$ .

### **8.3.2 *Parartemia* n. sp. d population structure**

Microscopic examination of the zooplankton samples revealed differences in the *Parartemia* population structure at the different sites. The population in the southern sites appeared less mature later than those in the northern sites.

#### *8.3.2.1 Southern control sites*

The southern control sites had a more even distribution of males to females and juveniles in the population than the northern impact sites. At Site 1, approximately 46% of the population was juveniles, 23% were adult males and 31% females, with 34% of these females ovigerous (carrying brown eggs) (Figure 8.2). The sex ratio of males to females was 1:1.3. Site 3 recorded a higher proportion of females to males, with 15% of the females ovigerous. The sex ratio was 1:1.6 (male: female). The number of juveniles collected was lower than at Site 3 making up approximately 10% of the population. These findings corresponded to the behaviour recorded in the field.

#### *8.3.2.2 Northern impact sites*

The *Parartemia* populations of the northern impact sites EP1 and 5 were more mature than the southern sites with a lower percentage of juveniles at sites EP1 and 5 and a higher percentage of ovigerous females (Figure 8.2). The population at Site 5 had 100% of the females carrying mature brood pouches and fewer males. The ratio of males to females was of 1:8, while at EP1 it was 1:1.2.

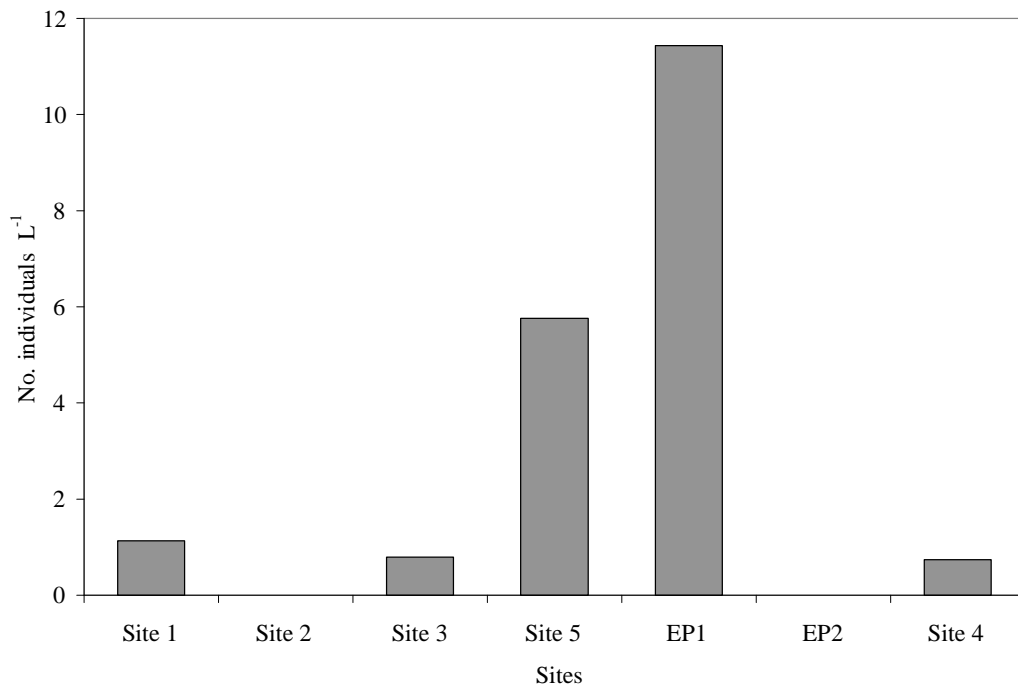
The high percentage of juveniles at Site 4, the lack of mature males and immature females indicated that this site may have undergone a second recruitment from the egg bank. The large number of dead mature *Parartemia* observed on the shoreline supported this. The dead *Parartemia* at EP2 may have been translocated from Site 4 by the movement of the surface water, or may have been killed by the release of the decant water from the LRSF. This may have also been the case for Site 4 as the salinity levels were similar.

### **8.3.3 Characteristics of the dormant egg bank**

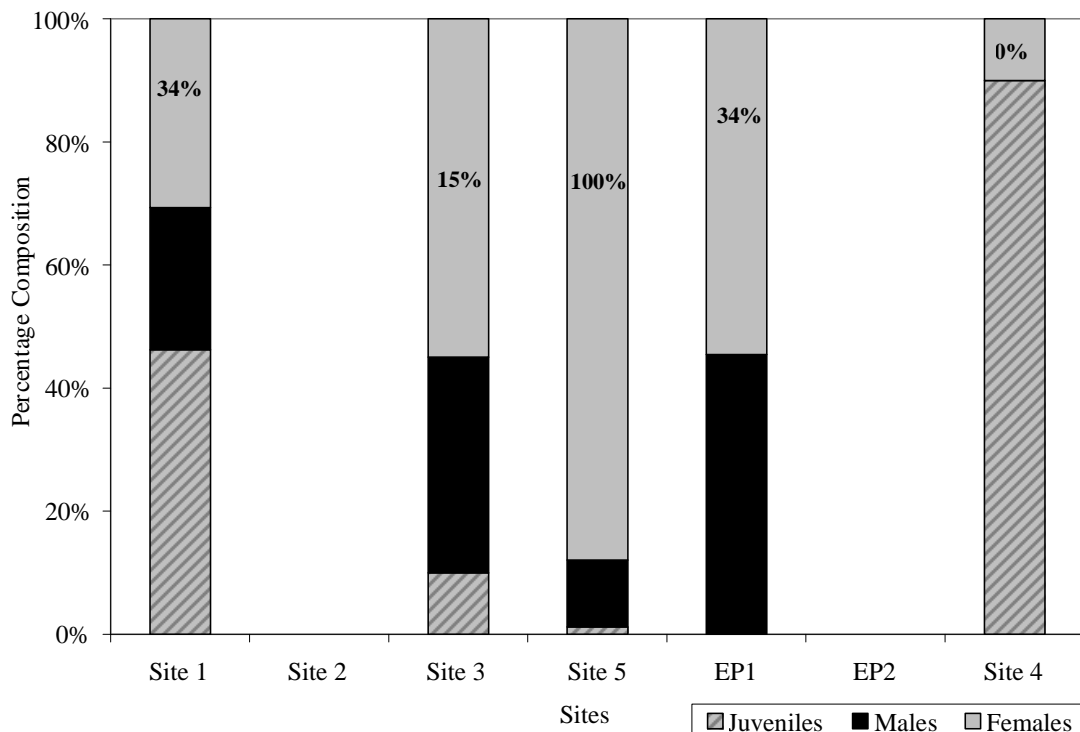
The active dormant egg bank of *Parartemia* was considered to be in the first 3 cm of the sediment. Examination of the sediment showed spatial variability in egg numbers per cm<sup>2</sup> between sites with the highest numbers recorded at the impacted sites (Figure 8.3). Variation within sites was also observed.

#### *8.3.3.1 Southern and northern control sites*

Average egg numbers in the sediment ranged from 3 to 44 eggs per cm<sup>2</sup> at sites 3 and 1, respectively (Figure 8.3). Site 2 recorded 15 eggs per cm<sup>2</sup> in the sediment confirming the presence of *Parartemia* at this site, despite the absence of specimens from the zooplankton samples. The spatial distribution of the eggs varied in each collection. Site 3, for example, recorded eggs only in the sediment from the March 2001 field trip while in subsequent collections none were recorded. From the northern control sites, 6 and 7, low numbers were recorded. Site 6 had only 4 eggs per cm<sup>2</sup> while Site 7 recorded none, consistently.

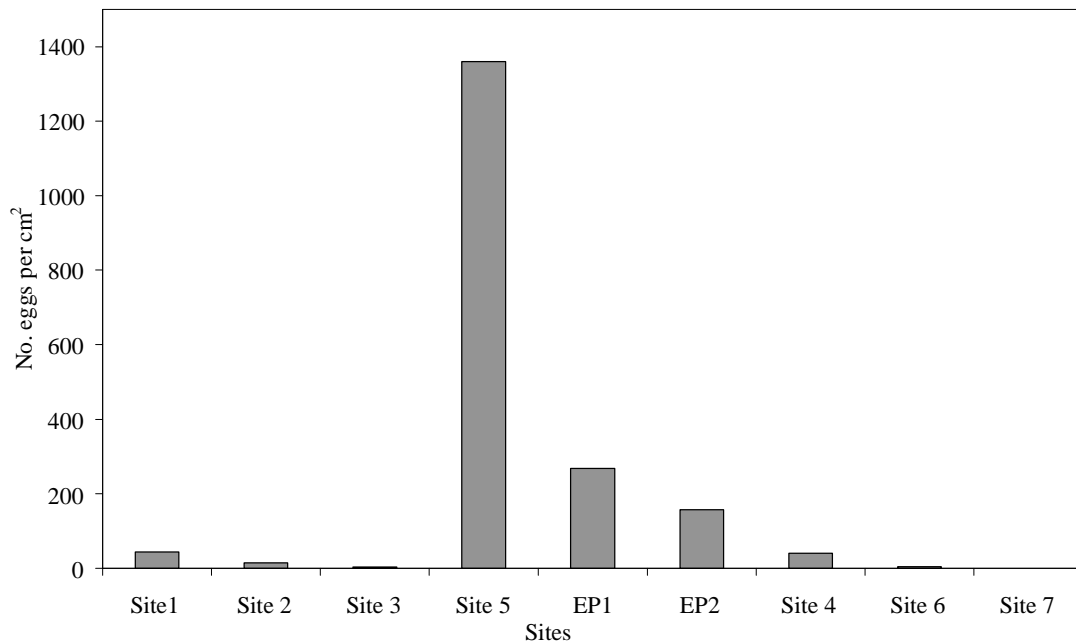


**Figure 8.1:** *Parartemia n. sp. d* abundance in the surface water in Lake Yindarlgooda, March 2001. No *Parartemia* were recorded in the samples from Site 2 and EP2. Individuals were calculated per Litre.



**Figure 8.2:** Percentage composition of *Parartemia n. sp. d* populations, March 2001. Percentage figures inserted on the bars indicate the percentage of ovigerous females. Site 2 and EP2 did not record any live *Parartemia* from the samples.





**Figure 8.3:** Average number of *Parartemia n. sp. d* resting eggs in the surface sediment (first 3 cm) around Lake Yindarlgooda (2001-2002). No eggs were recorded from Site 7.

## 8.4 Discussion

*Parartemia n. sp. d* from Lake Yindarlgooda was a halotolerant anostracan, inhabiting shallow saline temporary waters in inland Western Australia. It was the only Parartemiidae in Lake Yindarlgooda, observed as both adult and juvenile stages. It was not the only anostracan in the lake with resting eggs of *Branchinella* (Anostraca) were recorded in the sediment. The distribution range of this species appears to be widespread in the Goldfields. It has been identified from the southern Eastern Goldfields in the Johnston Lakes (Chaplin 1998), where it is sympatric with *Parartemia serventyi* (Timms 2004). It has also been recorded in Lake Way in the Northern Goldfields, where it occupies the open playa while *Parartemia n. sp. g* inhabits smaller creeklines (Campagna and Taukulis 2006).

The three lakes from which this species has been recorded are each located on different palaeorivers. Lake Way in the north is the head water of the ancient Carey Palaeoriver (Morgan 1993). Lake Yindarlgooda, in the eastern Goldfields, forms part of the Yindarlgooda Palaeoriver and the Johnston Lakes are on the Lefroy Palaeoriver, in the southern Goldfields. Considering the age of the Parartemiidae and the presence of an extensive permanent to semi-permanent lacustrine

environment throughout the Yilgarn Craton prior to the late Cenozoic (Zeng *et al.* 1998), early migration of this species may have been possible, the salt lakes being interconnected during fluvial times (Timms 2007). With evolution theoretically occurring in predictably filled localities and episodic waters having little value as evolutionary loci (Williams and Geddes 1991), further evolution in this species may have ceased prior to the late Miocene. The lack of dispersal mechanisms and the sinking nature of their resting eggs make the chance dispersal of *Parartemia* eggs by animal vectors low, though transport via gut content of birds cannot be ruled out (Green and Figuerola 2005). Whilst wind dispersal is considered a major dispersal agent of branchiopod resting eggs, studies on the African fairy shrimp *Branchipodopsis wolffi* showed limited dispersal by wind. The maximum distance the eggs were recorded from the source was 50 cm with no more than 2% of the population dispersing (Brendonck and Riddoch 1999). Migration amongst the clam shrimp in Western Australian rock pools was also found to be limited, with pools only 20 m apart displaying significant difference in size and sex ratios, indicating minimal gene flow (Weeks *et al.* 2006).

Spatial distribution of *Parartemia* within Lake Yindarlgooda was highly variable. The northern impact sites around the LRSF had greater numbers than the southern control sites in both live adult collections and the dormant egg bank. The wind pattern in the Kalgoorlie region is predominantly from the east-south east during winter, when the lake is seasonally inundated. This and the buffering effect of the islands in the centre of the lake, may explain differences in *Parartemia* numbers between the southern and northern sites in Lake Yindarlgooda and the high number of eggs near the LRSF. In many Western Australia playas *Parartemia* are often found in high concentrations around areas where barriers such as causeways have been built, preventing movement across the lake. As the distribution of the adults can be governed by the movement of the surface water, so too is oviposition.

Horizontally, invertebrate egg banks generally have a patchy distribution (Brendonck and De Meester 2003). This may be caused by the direction of the dominant wind, granularity of sediment, depth and morphometry (Thiery 1997). It may also be due to preferential habitat selection by the depositor as in *Chirocephalus ruffoi* (Mura 2005), or in *Triops numidicus* which stick their eggs to gravel along peripheral zones (Thiery 1997). Viable aquatic invertebrate eggs are restricted to the top 2 - 6 cm of

surface sediment in both permanent and temporary systems (Thiery 1997; Maffei *et al.* 2002; Brendonck and De Meester 2003).

*Parartemia n. sp. d* is bisexual and oviparous. The colour of the eggs in the brood pouch may be an indicator of oviparity. Investigation on the shell glands in *Artemia* were not conclusive as to whether brown eggs were definitely oviparous, though the production of white eggs occurred only in ovoviviparous *Artemia* or in eggs that were released but do not enter diapause (Criel and MacRae 2002a). Only brown eggs were observed in ovigerous females collected from Lake Yindarlgooda. *Parartemia n. sp. d* was also studied in the Johnston Lakes by Chaplin (1998) and found to reproduce oviparously. Recruitment was only from hatched diapausing eggs after rainfall had decreased salinity levels in the lake.

Literature on the reproductive biology of *Parartemia* is limited and field studies on different species have been contradictory with regard to population recruitment. Studies by Geddes (1976) recorded only oviparity in *Parartemia zietziana* while observations made in the same area by Marchant and Williams (1977) found *P. zietziana* reproducing ovoviviparously. De Deckker and Geddes (1980) concluded in other studies that *P. cylindrifera* only reproduced oviparously regardless of abiotic factors. The number of cohorts in a *Parartemia* population is also not well documented, again a possible reflection of the temporary nature of the lakes, with oviparous reproduction producing only a single cohort as displayed by *P. cylindrifera* and more than one in the ovoviviparous *P. zietziana*. The limited wet sampling in this study was restrictive and sufficient observations on the lifecycle of *Parartemia n. sp. d* may not have been achieved. This species may also reproduce ovoviviparously with multiple cohorts under different conditions, particularly in longer filling stages of the lake.

Variation was observed in the structure of the *Parartemia* populations around Lake Yindarlgooda, the southern sites having a less mature population than the northern sites. Hatching in diapausing *Artemia* eggs is controlled by environmental factors such as pH, temperature, salinity and dissolved oxygen (Lavens and Sorgeloos 1987). Laboratory experiments by Chaplin (1998) found that in *Parartemia n. sp. d* hatching was reduced at lower pH (< 7), and higher salinities (> 50 g L<sup>-1</sup>). Similar conditions were present in the northern impact sites where *Parartemia* were

collected. Large numbers of juveniles were present at the impact sites at salinities which exceeded those stated by Chaplin (1998) to be conducive to successful hatching.

*Parartemia* are well known osmoregulators, able to withstand high salinity fluctuations (Geddes 1975a, 1975b, 1975c). The salinity range for *Parartemia* n. sp. d in Lake Yindarlgooda was 54.7 g L<sup>-1</sup> in the southern sites to 125.4 g L<sup>-1</sup> in the impacted sites, all with ovigerous females. Salinity ranges in the Johnston Lakes were also high from 126 to 225 g L<sup>-1</sup> (Chaplin 1998), confirming the osmoregulatory ability of the adults of this species.

### **Conclusions**

*Parartemia* n. sp. d is a halotolerant species, recorded from a salinity range of 50 – 140 g L<sup>-1</sup> in Lake Yindarlgooda. This species is bisexual and follows an oviparous mode of reproduction, though ovoviviparity cannot be ruled out. The population structure was found to be one male for every two females.

*Parartemia* n. sp. d is widespread in the Western Australian Goldfields. Although sympatry was not observed in Lake Yindarlgooda, this species has been recorded with other *Parartemia* in two other lakes, though the habitats differed slightly.

Examination of the sediment indicated a well-established *Parartemia* egg bank in Lake Yindarlgooda. The highest concentration of eggs was found in the northern section of the lake around the impacted area of the LRSF.

## **Chapter 9.0. The effects of salinity on the dormant *Parartemia* egg bank**

### **Abstract**

The highest number of *Parartemia* n. sp. d resting eggs were recorded around the LRSF, with lower numbers at control sites. Sediment samples from Lake Yindarlgooda were rewetted with deionised water in the laboratory. The salinity measured in the cultures was comparable to that measured in the field. The impact sites EP1 and EP2 had the greatest egg numbers in the sediment and the highest salinities in the cultures. Hatching numbers at these sites were minimal or none. When the sediment salinity was reduced through sieving, hatching of *Parartemia* nauplii was highly successful. The characteristics of the egg bank in Lake Yindarlgooda were examined and *Parartemia* n. sp. d was found to adopt the survival mechanism of delayed hatching or bet-hedging.

The techniques adopted in the hatching trials were tested on sediment collected from Lake Miranda, containing *Parartemia* n. sp. g. For both lakes the salinity measured in the cultures was found to be comparable to the environmental conditions, indicating the salinity levels required for successful hatching in both species. These trials showed that *Parartemia* n. sp. d eggs require salinities of  $< 80 \text{ mS cm}^{-1}$  to hatch. A protocol for the use of the dormant egg bank in the assessment of anthropogenic impacts was developed.

### **9.1 Introduction**

This chapter is the third investigating the dominant aquatic invertebrate in Lake Yindarlgooda, *Parartemia* n. sp. d. In Chapter 8.0 well established *Parartemia* egg banks were identified at the northern impact sites adjacent to the LSRF and salinity identified as the one of the main factors differentiating control sites from impact sites (Chapter 3.0). Using this information, hatching trials on sediment collected from the control and impacts sites were run examining the effects of increased salinity on the dormant *Parartemia* egg bank.

Organisms that live in unpredictable environments have survival mechanisms that include short lifecycles, the production of desiccation resistant stages and life history strategies which include risk-spreading (bet-hedging) strategies (Simovich and Hathaway 1997). Risk-spreading is the idea that unpredictable environments will

favour genotypes which have developed a physiology or behaviour that spreads the risk in time or space. There are two types; conservative risk-spreading, where a single phenotype avoids risks, or diversified risk-spreading where a single genotype displays phenotypic variation (Hopper 1999). Bet-hedging has been used to explain the trade-off between the mean and variance of fitness (an organisms ability to adapt to environmental pressures) for a genotype. The term was coined from a commentary by Slatkin (1974) entitled “Hedging one’s evolutionary bets” (Philippi and Seger 1989). Bet-hedging has been adopted by many anostracans that inhabit temporary or vernal pools, such as populations of *Chirocephalus diaphanus* studied by Maffei *et al.* (2005). Without any possibility of prior knowledge of the environmental conditions these populations will face, their reproductive strategies are therefore modified to ensure the survival of their progeny. The dynamics of the dormant egg bank is of great importance for the persistence of a given species in highly variable habitats and hatching characteristics should be particularly sensitive to local conditions. The dormant egg bank can reflect the effectiveness of the hatching and reproductive characteristics of a species for successful replenishment (Hulsman *et al.* 2006).

The ability of an organism to create a cryptobiotic state during its lifespan is a vital adaptation in unpredictable environments (Lavens and Sorgeloos 1987). Much work has been published on the resilience of *Artemia* resting eggs (“cyst”) (Abatzopoulos *et al.* 2002). As stated by Clegg and Trotman (2002) it “is arguably the most resistant of all animal life history stages to extremes of environmental stress”. The ability of the encysted embryo to survive long periods of desiccation, continuous anoxia and extreme temperatures is due partly to the structure of the egg. The shell has a layer impermeable to all non-volatile solutes (Criel and MacRae 2002) and the encysted embryo is protected by the presence of the stress proteins p26, artemin, and HSP-70 (Trotman 1991; Clegg and Trotman 2002).

Studies on *Artemia* have shown that activation, a break in quiescence, occurs through permissive environmental cues such as salinity, ionic composition, temperature, pH, light and dissolved oxygen (Lavens and Sorgeloos 1987). Genotypic factors have also been suggested through studies by Browne *et al.* (1984) who found hatching in 12 *Artemia* strains was more strongly correlated with environmental factors than within the genotypes.

Once activation has occurred and environmental conditions remain favourable, metabolism is recommenced in the encysted gastrula embryo and development proceeds. The resting egg is hydrated allowing water to traverse to the alveolar and cuticle regions of the shell, rehydrating the embryo. The accumulating glycerol in the egg becomes the osmotic gradient and eventually the inelastic alveolar layer is fractured, rupturing the shell and propelling the instar from the shell (Trotman 1991).

Published work on comparative effects of salinity on the hatching of *Parartemia* is limited to work by De Deckker and Geddes (1980) and Geddes (1976). Measurements were taken in the field and high intra-species variability was observed. To date, there is no published work on controlled laboratory studies on the effects of salinity and the hatching of *Parartemia* nauplii from dormant eggs.

## **Objectives**

The objectives of this chapter are:

- To investigate the effects of increased salinity on the hatching of *Parartemia* n. sp. d nauplii from their resting eggs in the surface sediment (egg bank),
- To investigate the characteristics of the egg bank in Lake Yindarlgooda,
- To assess the effectiveness of the hatching technique using sediment from Lake Miranda containing *Parartemia* n. sp. g eggs.

## **9.2 Methods**

### **9.2.1 Sample collection**

Two sediment samples were collected from all sites in Lake Yindarlgooda and prepared as stated in the methods section of Chapter 4.0. Only samples collected during September 2001, May 2002 and September 2002 were used for the hatching trials. The lake was dry during these collections and this ensured that the samples had been exposed to uniform conditions. Only sites 4, 5, EP1 and EP2 were sampled in May 2002. Samples from Lake Miranda were collected by Fiona Taukulis and Erin Lowe. The sediment was prepared for the trials in the same manner as the Lake Yindarlgooda samples.

## 9.2.2 Sample preparation

Sediment samples collected from Lake Yindarlgooda and Lake Miranda were oven dried at 30 °C. Drying the sediment allowed for easier sieving of the samples and ensured complete desiccation of the sediment and therefore the eggs.

## 9.2.3 Dormant egg bank: identification and enumeration

Identification and enumeration of *Parartemia* eggs in the samples was required to assess possible impacts on the hatching of the dormant egg bank at each site. The hypothesis that a high number of eggs in the sediment would result in a high number of nauplii in the culture was tested.

Identification and enumeration was carried out as detailed in Chapter 8.0. Egg numbers were calculated per gram for these trials enabling comparison with the amount of sediment used in the hatching trials. Sediment samples with no *Parartemia* eggs were not included in the trials.

## 9.2.4 Hatching trials

Salinity was identified as one of the main factors influencing the biotic community in Lake Yindarlgooda and differentiated control from impact sites (Chapter 3.0). Trials were set up to determine the effects of increased salinity on the hatching of *Parartemia* resting eggs from the sediment (Figure 9.1). The protocol for this technique is presented in Appendix 9.1.

### 9.2.4.1 Sieved sediment (reduced salinity)

The effects of reduced salinity on the hatching of the *Parartemia* resting eggs in Lake Yindarlgooda, and therefore the viability of the eggs was tested using 20 g of sieved sediment. Sieving removed a large portion of the sediment reducing the salinity. Approximately 20 g of unsieved dried surface sediment, two samples collected from each site, was placed in rectangular plastic containers (18 x 12 x 6 cm). To each container 200 ml of deionised water was added. Samples were exposed to natural light near the laboratory windowsill (approx. 9-11 h day<sup>-1</sup>).

Daily measurements of temperature and dissolved oxygen (DO = ppm) were taken using a Windaus Winlab<sup>®</sup> DO-Sensor and electrical conductivity (EC = mS cm<sup>-1</sup>) measured with a Windaus Dataline<sup>®</sup> Conductivity Meter for each of the cultures. The number of nauplii present in the culture was counted each day and the



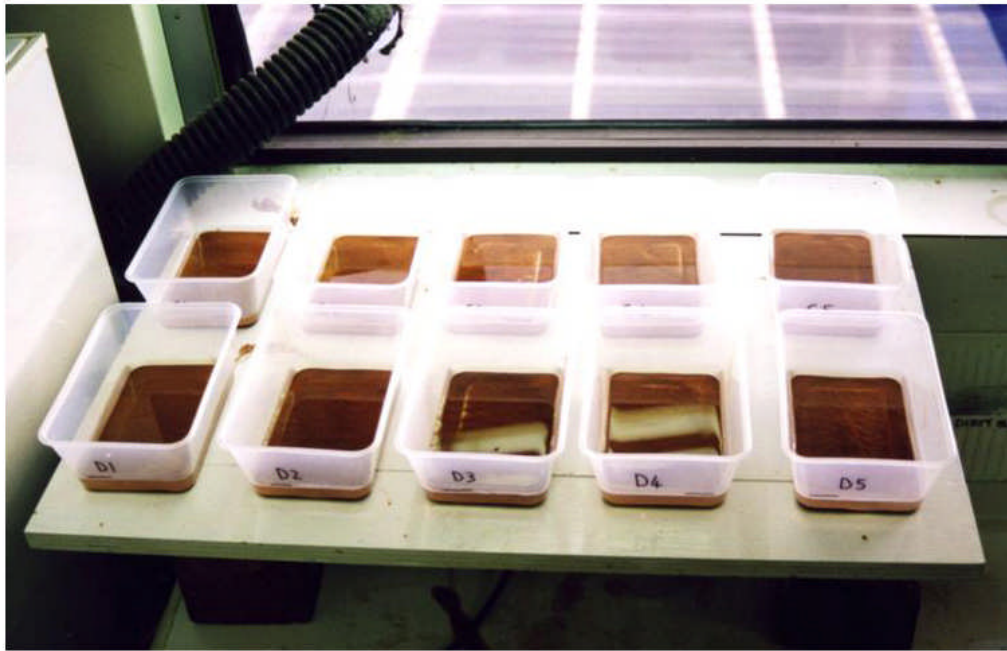
experiment was terminated after 14 days. Conductivity was used as a surrogate measurement of salinity.

#### *9.2.4.2 Unsieved sediment (impact of increased salinity)*

To test the effects of increased sediment salinity the above trials were repeated with raw sediment. Approximately 100 g of unsieved dried surface sediment, two samples collected from each site, was placed in rectangular plastic containers (18 x 12 x 6 cm). To each container, 500 ml of deionised water was added and the cultures were maintained at room temperature (18 - 22 °C). Samples were exposed to natural light near the laboratory window sill (approximately 9 - 11 h day<sup>-1</sup>).

Daily measurements of temperature, dissolved oxygen, and electrical conductivity were taken. The number of nauplii present in the culture was recorded each day and the experiment was terminated after 14 days.

At the end of each trial the sediment was air-dried, the container covered with a lid and stored. These trial samples were then rehydrated after a resting period of approximately 60 days, repeating the above procedure. This technique mimicked the drying and wetting of the lake, allowing for the strategy of delayed hatching to be investigated. When nauplii numbers in each consecutive rewetting began to decline the samples were no longer rewetted. For the majority of samples this was after two rehydrations. The entire experiment for the three sampling periods was completed over a period of 6 months (allowing for the resting period).



**Figure 9.1:** Arrangement of *Parartemia* salinity hatching trials. Each container held 100 g of unsieved surface sediment, rehydrated with deionised water with 9-11 hours of natural light per day. Trials ran for 14 days, allowed to air dry and lids placed over each container for later rehydration.

## 9.2.5 Treatment of data

### 9.2.5.1 Salinity groups

The salinity (electrical conductivity) recorded daily from each of the Lake Yindarlgooda cultures of the unsieved sediment was graphed using box and whisker plots, to identify salinity ranges. Because of high variation in the salinity ranges of the sediment samples from Lake Yindarlgooda, salinity groups were used for comparison instead of strict control and impact sites. The range in which the greatest number of hatchings occurred determined the salinity group of that site. This would indicate the salinity ranges preferential to hatching of *Parartemia*. Salinity groups were established for each of the trials: September 2001, May 2002 and September 2002. The relatively consistent salinity ranges in the Lake Miranda cultures did not require the establishment of salinity groups for those trials.

### 9.2.5.2 Statistical analyses

Non-parametric data were ranked using the statistical package Minitab (v14.0). The Spearman-rank order test ( $p$  critical = 0.05) was used to determine the following associations:

A high number of *Parartemia* resting eggs in the samples would yield a high number of nauplii in the cultures.

At low salinities viable eggs would hatch from the sieved sediment.

The Kruskal-Wallis test was used to test the  $H_0$ : there were no differences between the salinity groups. A Mann-Whitney  $U$  test was then used to determine which of the groups were significantly different.

To assess if there was a relationship between the different salinity levels in the unsieved sediment cultures and the number of *Parartemia* hatchlings, the Spearman Rank-order correlation test ( $p$  critical = 0.05) was applied to ranked hatching data. This test was also used to see if the dissolved oxygen and temperature of the cultures had an effect on the number of hatchings.

## 9.3 Results

### 9.3.1 Lake Yindarlgooda

#### 9.3.1.1 Dormant egg bank numbers

As identified in Chapter 8.0 the majority of the eggs in the sediment were concentrated in the northern sites around the LRSF at sites 5, 4, EP1 and EP2 (Figure 9.2). Variation in the egg numbers was observed between sampling periods with eggs recorded as absent from some of the control sites. Samples from sites 2 and 3 had very low to no eggs in the sediment, while samples from Site 1 recorded eggs in September 2001 and 2002. Site 7 in the northern arm of Lake Yindarlgooda recorded no eggs and was removed from the hatching trials.

#### 9.3.1.2 Sieved sediment

The salinity levels of the cultures of the sieved samples ranged from 10 mS cm<sup>-1</sup> in the control sites (1-3) to 15 mS cm<sup>-1</sup> in the impact sites. No cultures had salinities above 25 mS cm<sup>-1</sup> at the termination of the trials. The number of nauplii that hatched from the sieved sediment was high with nauplii present in the cultures 24 hours after the addition of deionised water. After five days, the number of nauplii hatching had

stabilised, with minimal new hatchlings recorded each day after. Samples with no hatchlings recorded no eggs in the sediment sub-sample used for enumeration. In several of the trials hatchlings were observed in the cultures though no eggs were detected in the samples.

A strong positive correlation between the number of eggs in the sediment and the number of nauplii that hatched in the sieved sediment was found, particularly in the September 2001 trials. The May 2002 trials, though positive correlation, the  $p$  value indicated that there was insufficient strength to determine a significant association (Table 9.1).

Correlations between the number of nauplii hatched and the lower salinities for the September 2001 and May 2002 were positive and significant while that of September 2002 were not (Table 9.2). The low  $r_s$  values may be due to the minimal salinity ranges for the cultures.

Samples with minimal egg numbers and little, or no, hatching were removed from the salinity trials, as salinity was no longer considered a factor in the poor hatching rates of the *Parartemia* nauplii. These were Site 2 (samples 2.1 and 2.2) and Site 3 (samples 3.1 and 3.2).

**Table 9.1:** Spearman rank-order correlation coefficients for the number of *Parartemia* resting eggs and the maximum number of *Parartemia* nauplii that hatched from 20 g of sieved sediment in the sieved hatching trials for the three sampling periods (September 2001, May 2002 and September 2002).  $P_{\text{critical}} = 0.05$ .

<b>Trial</b>	<b>Correlation coefficient (<math>r_s</math>)</b>	<b>P- value</b>
September 2001	0.866	0.0000
May 2002	0.349	0.2210
September 2002	0.529	0.0200

**Table 9.2:** Spearman rank-order correlation coefficients for the number of hatched *Parartemia* nauplii and the electrical conductivity in the hatching trials (sieved sediment) for the three sampling periods (September 2001, May 2002 and September 2002).  $P_{\text{critical}} = 0.05$ .

<b>Trial</b>	<b>Correlation coefficient (<math>r_s</math>)</b>	<b>P- value</b>
September 2001	0.288	0.001
May 2002	0.247	0.005
September 2002	0.031	0.724

### 9.3.1.3 Unsieved sediment

During the salinity hatching trials (unsieved sediment), the dissolved oxygen levels and temperature remained constant, the DO not falling below 6 ppm. As a result, the correlation of hatching numbers and these parameters showed no relationship and they were not considered to impede the hatching.

#### *Salinity groups*

The salinity ranges of the cultures were graphed and three salinity groups per trial established (Figure 9.3; Table 9.3). As a result the impact sites 5 (5.1, 5.2) and 4 were placed in the same group as the control Site 1 and 6 for the September 2001 and 2002 trials. The salinity ranges toward the end of the trials (14 days) recorded values similar to those measured *in situ* in Lake Yindarlgooda during the March 2001 field trip (Chapter 3.0, Table 3.2).

#### *Hatching trials*

For all three sampling periods, Group 1 (lowest salinity ranges) recorded the highest number of nauplii hatchlings in each trial (Figure 9.4). Group 2 recorded few or no nauplii and Group 3, none. The Kruskal-Wallis test indicated significant differences between the groups. A Mann-Whitney  $U$  test showed a significant difference between Groups 1 and 2 for the September 2001 and 2002 samples. There was no significant difference between groups during May 2002 with only impact sites sampled (Table 9.4).

A correlation between nauplii numbers in the culture and the salinity levels showed that the increase in salinity had a negative effect on the number of nauplii that hatched from the sediment. This was significant for the September 2001 trials with Group 2 and 3 and for the May 2002 trials (Table 9.4). The lower salinity ranges in September 2002 trials for Group 1 resulted in a positive relationship with the number of nauplii increasing in the lower salinities.

#### 9.3.1.4 Characteristics of the egg bank

Nauplii began to appear in the culture four to five days after the sediment rehydration with minimal hatchings after eight days. During the trials, the addition of deionised water in some samples was required to prevent drying of the sediment prematurely. The subsequent decrease in salinity resulted in new hatchings.

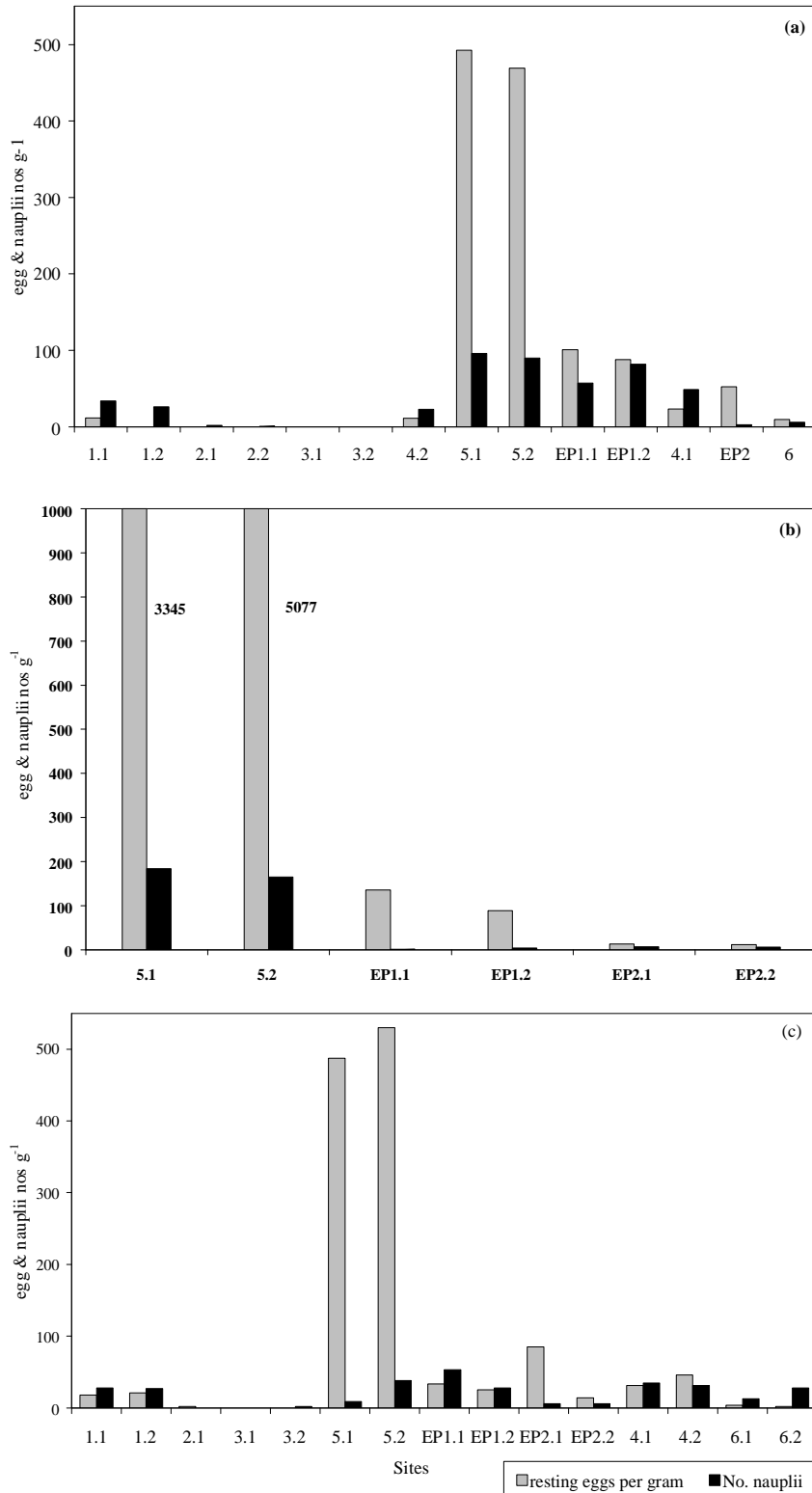
In all the salinity trials, the majority of the hatchings occurred in the first sediment rehydration (Figure 9.5). The exception to this was site 5.1 for the September 2001 trials. This site recorded delayed hatching with higher numbers recorded in consecutive hydrations, up to four. After the second rehydration number became progressively less.

**Table 9.3:** Salinity groups established according to the electrical conductivity (EC =  $\text{mS cm}^{-1}$ ) of the cultures for the hatching trials (unsieved sediment) from the three sampling periods (September 2001, May 2002 and September 2002).

<b>Trial</b>	<b>Salinity group</b>	<b>Electrical conductivity (<math>\text{mS cm}^{-1}</math>)</b>
September 2001	1	0 – 60
	2	60 – 100
	3	> 100
May 2002	1	0 – 80
	2	80 – 150
	3	> 150
September 2002	1	0 – 85
	2	85 – 125
	3	> 125

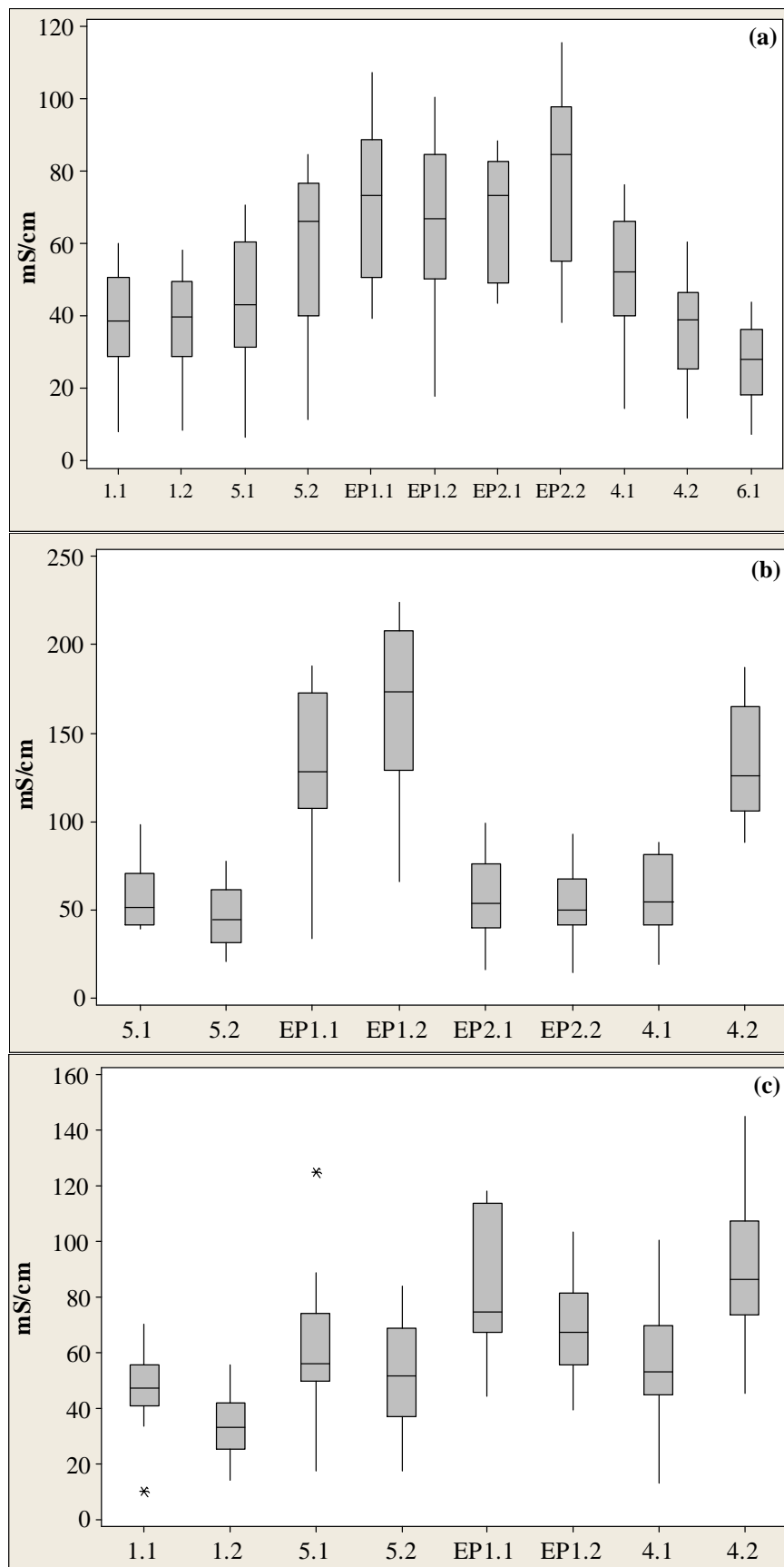
**Table 9.4:** Spearman rank-order correlation coefficients for each of the salinity groups (after Kruskal-Wallis test) for each of the three hatching trials (September 2001, May 2002 and September 2002). No statistical difference was found between the three salinity groups in May 2002 and they were placed as one group.  $P_{\text{critical}} = 0.05$ .

<b>Trial</b>	<b>Salinity group</b>	<b>Correlation coefficient (<math>r_s</math>)</b>	<b><i>P</i>- value</b>
September 2001	1	-0.14	0.2630
	2 & 3	-0.342	0.0100
May 2002	All same group	-0.214	0.0260
September 2002	1	0.496	0.0000
	2 & 3	-0.096	0.3330

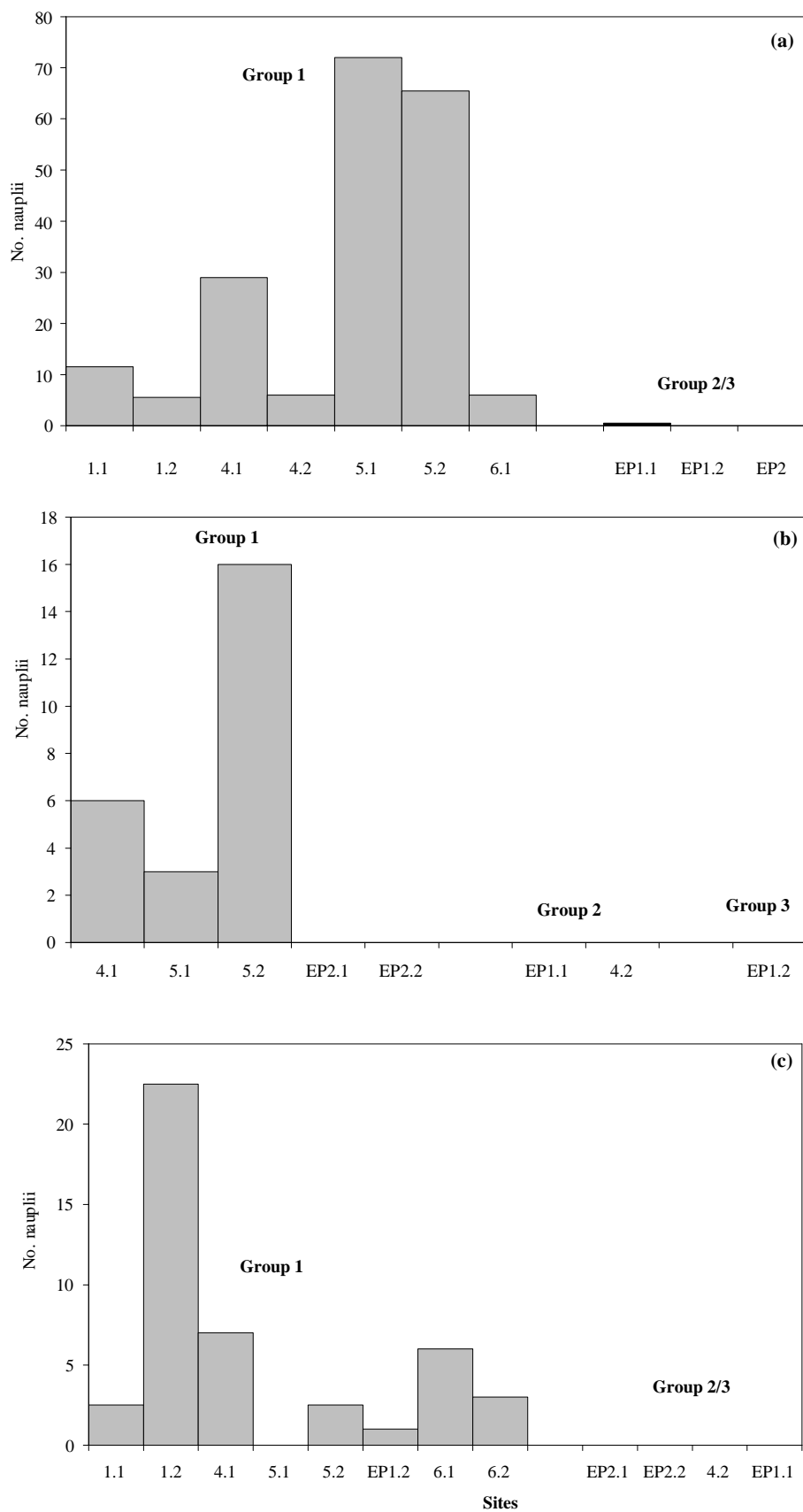


**Figure 9.2:** The number of *Parartemia* resting eggs in the sieved sub-samples and the number of nauplii that hatched from the sieved sediment. Eggs and nauplii are represented per gram of sieved sub-sample for the (a) September 2001, (b) May 2002 and (c) September 2002 trials.

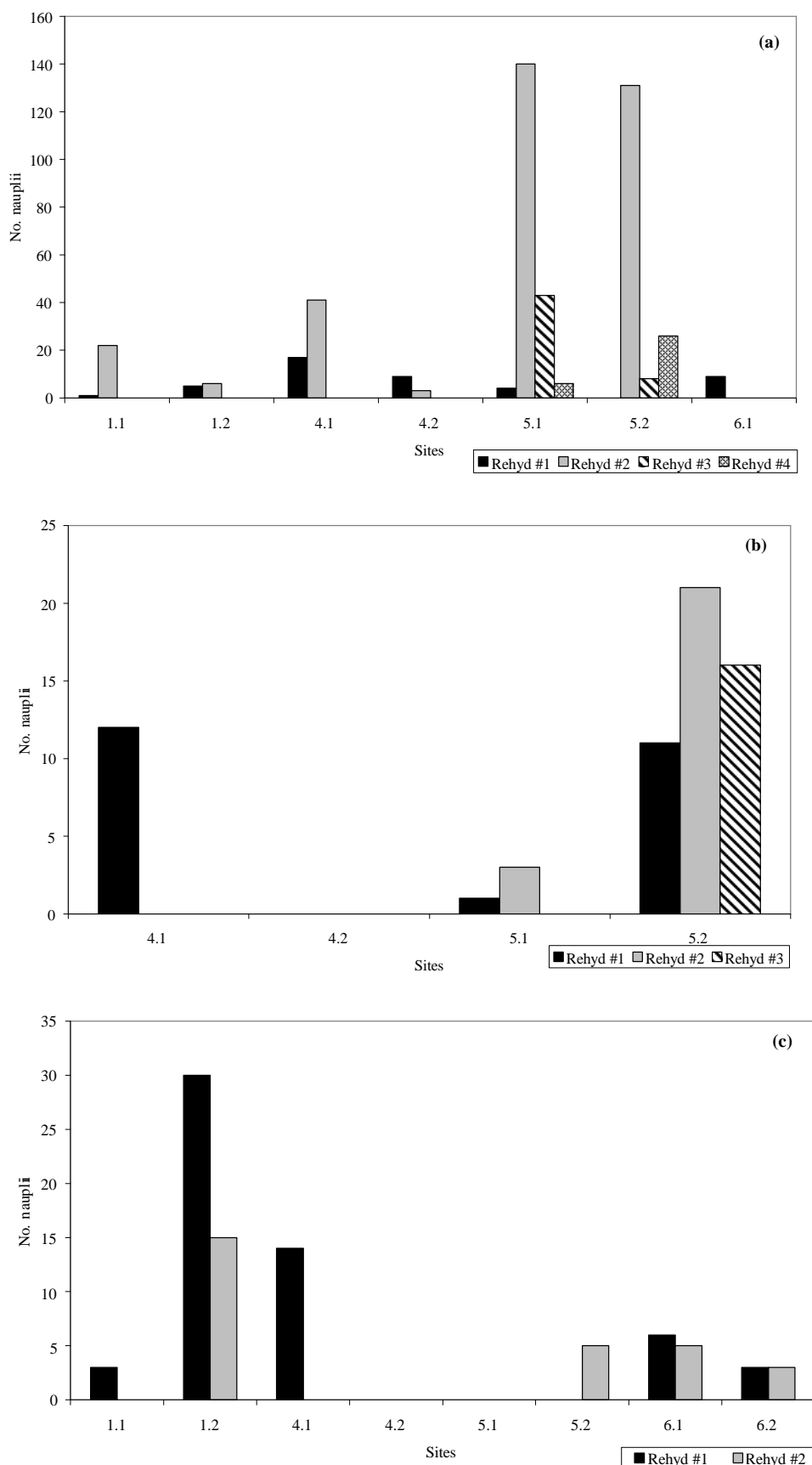




**Figure 9.3:** Box and whisker plots of electrical conductivity levels recorded in the cultures during the three hatching trials **(a)** September 2001, **(b)** May 2002 and **(c)** September 2002. Samples are shown on x-axis. \* indicates outlier.



**Figure 9.4:** Maximum number of *Parartemia* nauplii (y-axis) hatching from 100 g of unsieved sediment. Sites (x-axis) arranged into the different salinity groups for the three trials (a) September 2001, (b) May 2002 and (c) September 2002.



**Figure 9.5:** Number of *Parartemia* nauplii in the samples after repeated rehydration for the three sampling periods (a) September 2001, (b) May 2002 (c) September 2002.

### 9.3.2 Lake Miranda

Samples collected from Lake Miranda were used to test the hatching trial methods on the *Parartemia* egg bank from different lakes. Specific water quality data for these samples at collection was only provided for the 2003 sampling period (Table 9.5). Sites were inundated at the time of collection with adult *Parartemia* n. sp. g present in the surface water samples.

**Table 9.5:** Water quality data for Lake Miranda collected in 2003. No data were collected for site A3. F1 is included as it was a new site not affected by increased salinity from the mining activity at the time of collection and may indicate normal salinity levels for the lake.

Parameter	Sites			
	B1	C1	E1	F1
pH	8.83	8.46	9.09	8.27
Conductivity (mS cm <sup>-1</sup> )	40.2	113	104.6	45.3
Salinity (g L <sup>-1</sup> )	23.8	75.4	68.8	27.1
Dissolved Oxygen (mg L <sup>-1</sup> )	9.77	9.25	7.76	6.89
Temperature (°C)	27.5	20.1	27.9	18.6
Water Depth (cm)	28	7	7.5	4.5

#### 9.3.2.1 Salinity ranges in cultures

The box and whisker plots show that the salinity ranges for each of the trials remained consistent (Figure 9.6). The sites with the highest salinity were site B1 in 2001 and E1 in 2003. The average salinity for the sites was 40 mS cm<sup>-1</sup>, which may be considered the normal salinity for Lake Miranda, as indicated by the water quality data collected at site F1. The salinity values for site B1 cultures also reflected that collected in the field. Repeated rehydrations did not show much variation in salinity levels in the cultures.

#### 9.3.2.2 Egg bank numbers

The majority of the sites contained resting eggs of *Parartemia* n. sp. d, with minimal numbers in B1 in the 2001 samples and none in the 2003. The sites with the greatest number of eggs were C1 and E1 for both sampling periods, 2001 and 2003 (Figure

9.7). Observations of the sediment found a high number of *Branchinella* sp. resting eggs in the Lake Miranda sites.

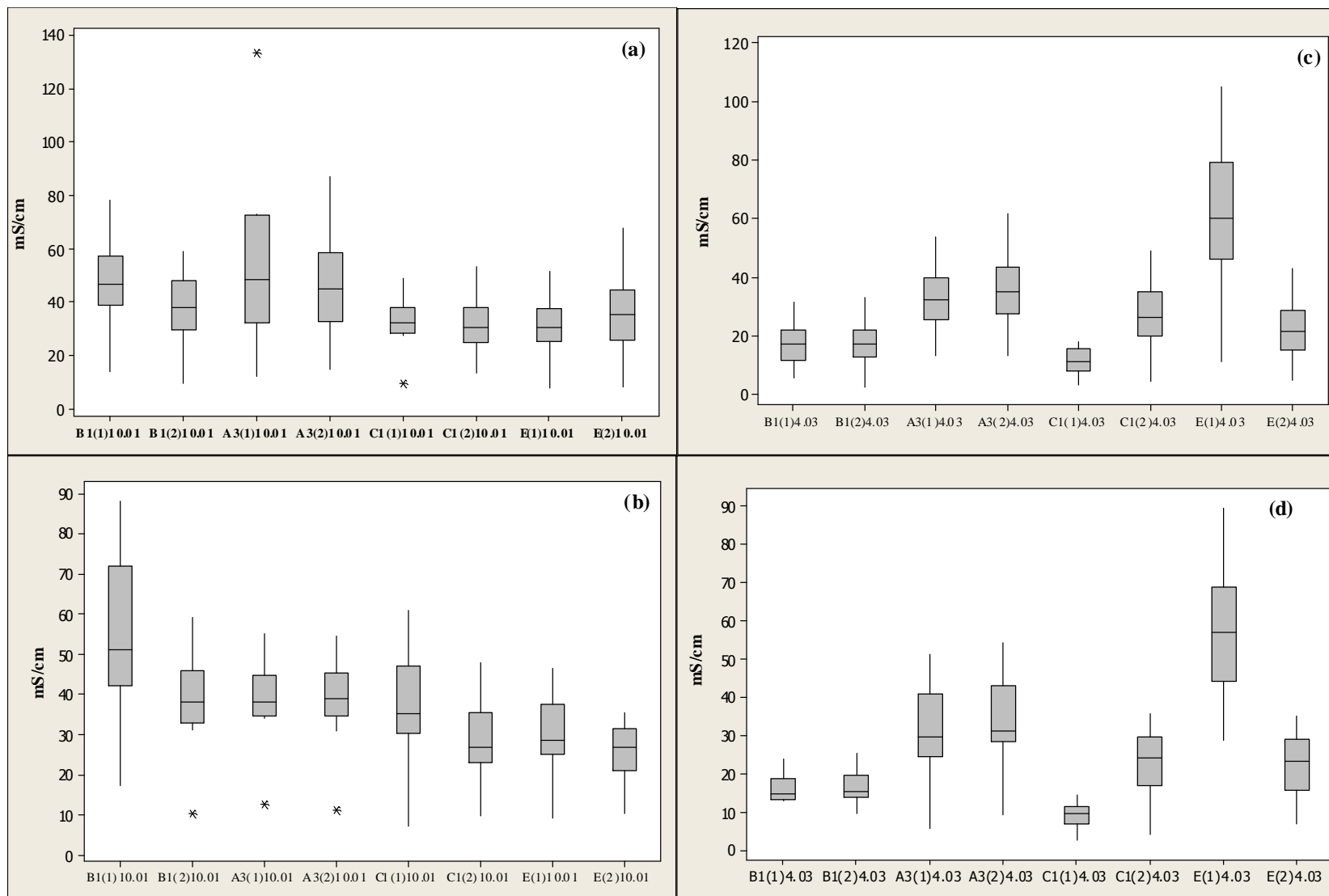
#### 9.3.2.3 *Hatching from rehydrated sediment*

The sites with the high egg numbers in the sediment also had the highest number of nauplii hatching (Figure 9.8). The exceptions were sites A (2001) and E (2003). The salinity levels in the culture were higher in these samples. The low salinity in the C1 (2003) cultures resulted in a high number of hatchings. Correlations between the number of hatchings and the salinity levels all showed strong positive correlations, particularly at site C1 in 2003 (Table 9.6). The site with the highest salinity levels, E1, had the lowest  $r_s$  value, though still positively correlated.

#### 9.3.2.4 *Characteristics of the egg bank*

Samples from Lake Miranda had nauplii hatching two to four days after rehydration. Hatchings continued steadily up until termination of the trials at day 14. Consecutive sediment rehydrations (after a period of sediment dehydration) resulted in repeated hatching from only a few samples. Site C1, 2003 (samples C1.1 and C1.2) were the only samples in which a second rehydration resulted in increased hatchings (Figure 9.8).

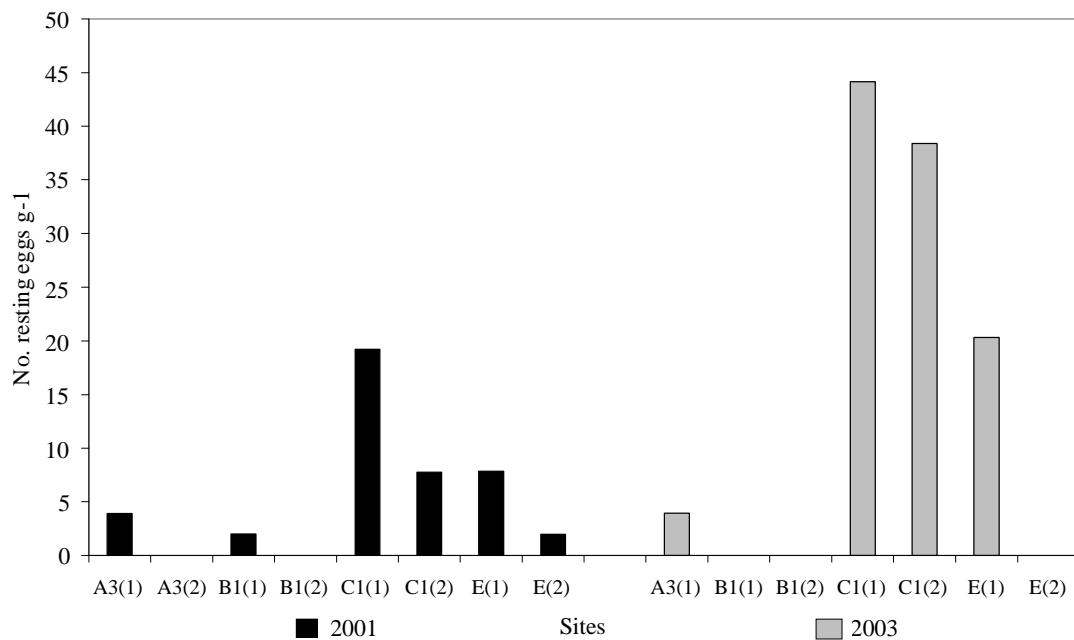
Of interest was the maturity rate of the *Parartemia* n. sp. g in Lake Miranda samples. In the samples from site C1 (2003) ovigerous females and adult males were observed within 10 days of the sediment rehydration. Copulation was also recorded in the cultures with males amplexing females for over 24 hours.



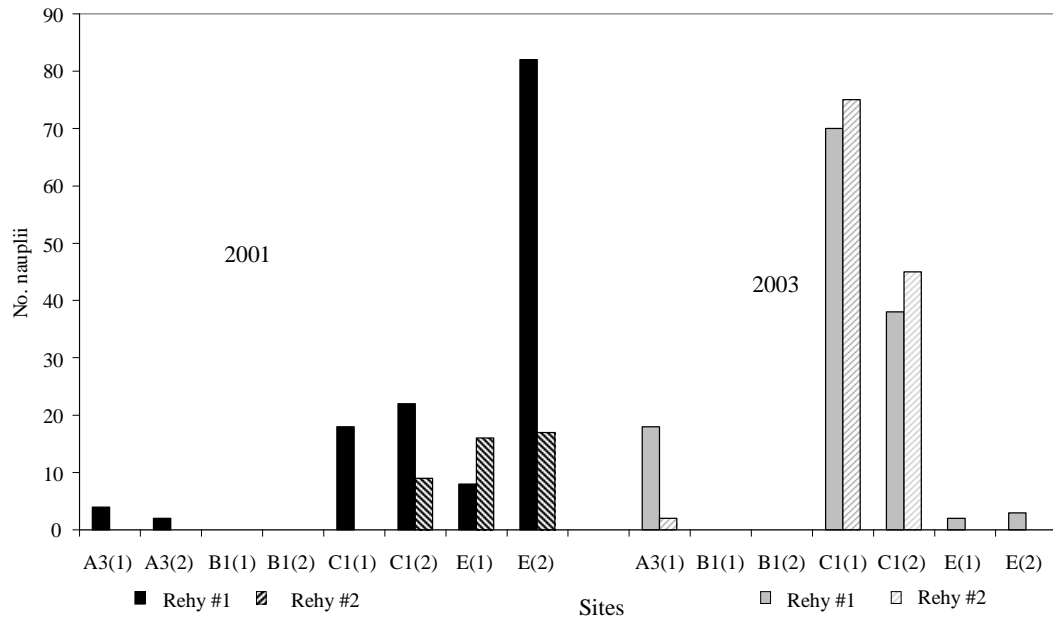
**Figure 9.6:** Box and whisker plots of electrical conductivity levels recorded in the cultures during the hatching trials for Lake Miranda **(a)** Trial 1 2001 **(b)** Trial 2 2001 **(c)** Trial 1 2003 **(d)** Trial 2 2003. \* = outliers.

**Table 9.6:** Spearman rank-order correlation coefficients for Lake Miranda hatching trials 2001 and 2003.  $P_{\text{critical}} = 0.05$ .

Trial	correlation coefficient ( $r_s$ )	$P$ -value
2001		
A3	0.527	0.0170
C1	0.728	0.0000
E1	0.738	0.0000
2003		
A3	0.807	0.0000
C1	0.96	0.0000
E1	0.787	0.0070



**Figure 9.7:** *Parartemia* resting egg numbers for Lake Miranda sediment for 2001(left) and 2003 (right) trials. Sediment was sieved and 1 g samples counted.



**Figure 9.8:** Total number of *Parartemia* nauplii that hatched from the sediment for Lake Miranda for 2001(left) and 2003 (right) trials. Graph shows repeated rehydration.



## 9.4 Discussion

The temporary nature of Lake Yindarlgooda dictates that the aquatic biota adopts life stages that enable them to survive extended periods of desiccation, including the premature drying of the lake. *Parartemia* n. sp. d has adapted to such conditions by the production of resting stages, a well established egg bank in the northern section of the lake, and the risk spreading strategy of diversified bet-hedging.

The adults of this species were able to tolerate salinity ranges of 74 to 170 mS cm<sup>-1</sup>. Chaplin (1998) also recorded the same species in the Johnston Lakes living with a range of 126-225 g L<sup>-1</sup> (EC = 79 - 140 mS cm<sup>-1</sup>). Studies on the osmoregulatory capabilities of *Parartemia* have shown it to be exceptional (Geddes 1975a, 1975b, 1975c), like those of *Artemia* (Geddes 1981). Field observations on the hatching rate in different salinities found high intra-species variability (Geddes 1976; De Deckker and Geddes 1980). Laboratory studies by Chaplin (1998) on the effects of salinity on *Parartemia* n. sp. d hatching did not reflect environmental conditions. Kefford *et al.* (2004) found uncertainty in the degree to which salinity tolerances reflected the field distributions of freshwater biota and changes in other water quality variables, such as ionic proportions, were often not reflected in these laboratory studies. The retention of the egg bank in its entirety, including the sediment, for laboratory trials may overcome these problems. The increase in sediment salinity caused by the LRSF had a negative effect on the hatching of *Parartemia* n. sp. d. Hatching was more successful in salinities less than 80 mS cm<sup>-1</sup>. With each decrease in salinity more nauplii hatched from the sediment. Geddes (1976) also found subsequent recruitment of *Parartemia* in field studies when there was a decrease in salinity levels after rainfall.

While a number of factors induce dormancy in crustaceans, for anostracans the cues appear to be more strongly related to the absence of water (Maffei *et al.* 2005). Anostracans from environments with predictable filling show high initial hatching while those from less predictable habitats often have low, or incomplete, initial hatching with subsequent rehydrations resulting in higher numbers (Simovich and Hathaway 1997). This display of diversified bet-hedging ensures the subsequent survival of the progeny (Maffei *et al.* 2005) and was displayed in the *Parartemia* species in Lake Yindarlgooda. The strongest example of bet-hedging was in the September samples from Site 5. Repeated rewetting of the sediment resulted in a

substantial increase in hatchings and this continued for up to four sediment rehydrations. Simovich and Hathaway (1997) found that hatching of eggs over three rehydrations continued in species of *Branchinecta*.

The resilience of the *Parartemia* resting egg is vital to the survival of the species. Like *Artemia*, the two *Parartemia* species in this study contained the stress proteins p26 and artemin (Clegg and Campagna 2006). These proteins are essential in maintaining the integrity of the encysted gastrula embryo which undergoes complete desiccation (Clegg and Trotman 2002) and can survive years of continuous anoxia (Clegg 1997). Protection from the elements is also provided by the shell of the *Parartemia* resting egg. Examination of the shell (Chapter 7.0) found it to be identical to that of *Artemia*, containing the impermeable outer cuticular membrane. The degree of permeability may be controlled by the thickness of the shell or the density of the layers (Anderson *et al.* 1970). The shell of *Parartemia* n. sp d was not as thick as that of *Parartemia* n. sp g from Lake Miranda. The alveolar layer of the *Parartemia* n. sp. d was compact and the cortex had smaller pores. These features suggest environmental adaptation, premature hatching being minimised in an unpredictable environment such as Lake Yindarlgooda.

The salinities, on average, of Lake Miranda were lower than the salinities of the Lake Yindarlgooda control sites (Chapter 3.0). Examination of the sediment from Lake Miranda found a large number of resting stages of known hyposaline taxa, such as fairy shrimp eggs, *Branchinella* sp., and *Nitella* sp. oospores. These suggest an environment less saline than Lake Yindarlgooda. *Parartemia* n. sp g hatched within a few days of sediment rehydration, it was quick to mature with ovigerous females observed by the tenth day. Amplexing between males and females was seen at the termination of the trials. This lake is situated in the Northern Goldfields where the underlying palaeorivers are less saline than those in the Eastern Goldfields (Morgan 1993). These suggest that Lake Miranda has a brief, yet less predictable hydroperiod compared to that of Lake Yindarlgooda, salinities only increasing toward the drying phase. This would favour a reproductive strategy of quick hatching, facilitated by an egg that is easily hydrated, rapid growth and early reproduction.

While the *Parartemia* resting egg is resilient, physiological similarities to *Artemia* suggest that extended periods of desiccation can lead to a decrease in the viability of the eggs (Lavens and Sorgeloos 1987). Less viable eggs and a reduction in the

replenishment of the egg bank by healthy adults may be detrimental in a system naturally low in species diversity.

The hypersaline water that is released onto the lakes by mine dewatering often contain high levels of heavy metals. These exist either as a result of the processing techniques or due to the use of palaeochannel water in which the minerals are concentrated. Lake Yindarlgooda recorded nickel levels at the impact sites exceeding the background levels at the control sites. Heavy metals are known to inhibit the emergence of nauplii from the resting eggs (MacRae and Pandey 1991). The effects of Ni on the hatching of *Parartemia* n. sp. d should not be overlooked, but it was outside the scope of this study.

Estimation of the egg bank size in these types of studies has always proven difficult. The distribution of eggs in lake sediment is often patchy and can be related to a number of ecological factors such as wind patterns, morphometry of the lakes, granularity of the sediment and the behaviour of the ovipositor (Thiery 1997; Mura 2005). The patchiness of the *Parartemia* eggs in Lake Yindarlgooda also limited the collection of uniform sediment samples, with variation observed not only around the lake but within sites. While the techniques adopted in this study underestimate the egg bank size in the lake, examination of the sediment prior to the trials enables the detection of this error. The technique of sieving the sediment allows for the viability of the dormant eggs to be tested. Removal of the majority of the sediment particles reduces the salinity. This allows for faster hydration of the eggs and ensures the recommencement of embryo metabolism and the hatching of the eggs.

## **Conclusions**

The methods adopted in this study proved successful in understanding the impact of increased salinity on the dormant *Parartemia* egg bank. The conditions in the culture were found to be similar to the environmental conditions found in the lake in terms of salinity.

While the adult *Parartemia* n. sp. d were efficient osmoregulators and easily survived salinities up to  $150 \text{ g L}^{-1}$ , the resting eggs require lower salinities to hatch. The impact sites around the LRSF recorded the highest number of eggs in the sediment. Hatching in the unsieved sediment was poor at the sites EP1 and EP2 which recorded the highest salinities. Reducing the salinity by sieving resulted in a

high number of eggs hatching from these sites and verified the viability of the eggs. The trials found the hatching of *Parartemia* n. sp. d eggs from the sediment was more successful in salinities less than 80 mS cm<sup>-1</sup>.

Because of the patchy distribution of eggs in the lake uniform samples are difficult to obtain. The technique of sieving a sub-sample of the sediment proved useful. Not only did it allow for the presence of the eggs to be verified, by reducing the salinity the viability of the eggs could also be tested. This study found a positive correlation between the number of eggs in the sediment and the number of nauplii hatchlings. While errors occurred in accurately calculating the egg bank size, calculations of eggs per gram provided an estimate and a basis for assessing impacts.

These trials found a difference in the ecology of the two *Parartemia* species. *Parartemia* n. sp. d had adapted to environments with higher salinities than *Parartemia* n. sp. g. This was deduced by their hatching traits coupled with the characteristics of their resting eggs as discussed in Chapter 7.0.

## **Appendix 9.1.**

### **Protocol for assessing impacts on the dormant egg bank of *Parartemia* species.**

This protocol outlines the methods for setting up hatching trials for assessing impacts on the dormant egg bank of *Parartemia* species. Theoretically it can also be applied to studies on other anostracans from temporary systems.

#### **Sample collection**

Observations at each of the collection sites should be made initially to identify areas conducive to establishment of an egg bank. Due to the spatial distribution of eggs in the lake collect several samples from various sites.

Collect samples by scraping the first centimetre of the sediment within a 50 x 50 cm quadrat using a PVS halfpipe. Place each sample in calico bags.

#### **Sample preparation**

Oven dry each of the samples at 30 °C, especially if the sediment is still wet or damp. This will allow for easier manipulation of the sediment and to ensure the eggs have become anhydrobiotic.

Weigh the entire sample. Sub-sample the dried sediment and weigh.

Sieve the known sub-sample through stacked 500 µm and 180 µm Endecott® brass sieves. Retain the sieved material > 180 µm for enumeration of the eggs.

#### **Identification and enumeration**

Weigh a gram of the sieved material and place the amount on a glass petri dish. Using a stereo microscope examine the material for the presence of resting eggs. Count and record eggs per gram of material. This process will identify the dominant species and verify the presence of eggs in the sediment.

#### **Viability of the eggs**

Weigh an amount of the sieved material in which the presence of eggs has been established (20 g for example). Scatter the sediment evenly in rectangular plastic containers (18 x 12 x 6 cm). To each container add 200 ml of deionised water.

Expose the containers to sufficient light to induce hatching, such as near a natural light source or in a growth cabinet, ensuring constant air flow and appropriate temperature. The temperature required for the breaking of dormancy by different species can be determined by their natural environment. Some lakes are inundated during winter months while others in summer.

Take daily measurements of the dissolved oxygen, salinity, temperature and pH of the cultures, ensuring the sediment is not disturbed. Record the number of new nauplii that hatch each day.

A positive correlation between high egg numbers and high hatchings indicate a viable egg bank.

### **Unsieved sediment (impact of increased salinity)**

Once the samples with viable egg banks have been identified weigh 100 g of raw (unsieved sediment) from the original dried sample. Repeat the above procedure, again taking daily measurements of the dissolved oxygen, salinity, temperature and pH and the number of new nauplii that appear in the cultures.

Allow the trials to run for at least 14 days. If the sediment dries out prior to 14 days, add more deionised water.

After 14 days, allow the sediment to air dry. Once it has dried place a lid on the containers and allow them to rest for a period. Rewet the sediment and re-run the trials. This technique mimics the dry and filling of the lakes and will account for any delayed hatching typical of anostracans in temporary systems. Often the first rehydration of the sediment may not yield a high number of hatchings and the results could be misinterpreted.

Once the number of new nauplii in each rewetting begins to decline from the previous hydrations, the trials can be terminated. Usually two to three rehydrations will suffice. This will ensure the majority of the resting eggs have hatched.

## Chapter 10.0. Conclusions and recommendations

The principal objective of this study was to understand the limnology and aquatic ecology of Lake Yindarlgooda, an inland salt lake in the semi-arid zone of Western Australia. By adopting an integrated approach, the physical and chemical limnology and all the biological aspects of the lake, including the riparian vegetation and the use of the lake by waterbirds, were examined, albeit during a restricted hydrocycle. Once the baseline data had been established the anthropogenic impacts from the LRSF could be determined. In the process, information on the unique biota of inland salt lakes was revealed, some for the first time.

The following major findings were made in this study:

- Lake Yindarlgooda is an example of an extreme environment. The lake has high salinities, experiences high temperatures and remains dry for much of the year, the area often exposed to prolonged drying events. It is typical of Western Australian inland salt lakes. Heterogeneity of the salinity within the lake was common.
- The biota, dominated by diatoms and crustaceans specifically *Parartemia*, have adapted to the extreme environmental conditions by developing survival strategies such as desiccation resistant dormant spores and eggs capable of remaining viable for extended periods.
- In temporary inland waters, the monitoring of the spore or egg bank in the surface sediment has proven to be a reliable method of assessing the resilience of such systems and their ability to recover after a disturbance such as a prolonged dry phase.
- Added to the extreme environmental conditions, anthropogenic activities such as mining and to an extent, grazing, have impacted on the biota of Lake Yindarlgooda. The impact from the leaching of hypersaline water from the LRSF though this work has demonstrated the adverse affects on the viability of the *Parartemia* eggs. Control sites were easily differentiated from impact sites according to the LRSF leachate. While the increase in salinity did not appear to decrease species diversity, it was associated with distinct

community structures within the lake as it altered the water and sediment quality.

- Habitat types around the lake were homogeneous with the riparian zones displaying similar vegetation types, consisting of sparsely distributed halophytic plants. Biological soil crusts, though limited to certain sites, form an important component associated with certain riparian vegetation. The functional role of the crusts was also displayed by the extensive physical crusts observed at sites not disturbed by livestock.
- Investigations of the ultrastructure of the resting egg of *Parartemia* n. sp. d showed it to be identical to the resting egg of *Artemia*. The *Parartemia* shell consisted of three distinct layers: the tertiary layer, the outer cuticular layer and the inner cuticular membrane. These findings indicated that the *Parartemia* resting egg may be as resilient as that of *Artemia* and has implications for the use of *Parartemia* in the monitoring of temporary systems.

Other findings recorded for the first time were:

- Differences in the morphology of the resting eggs of the two *Parartemia* species.
- The presence of biological soil crusts in the riparian zone of a salt lake dominated by the cyanobacteria *Microcoleus* sp. and *Bryum* sp..

The findings in each of the chapters contributed to an understanding of the ecology of the lake and helped to assess the possible impacts caused by the LRSF.

Salinity was found to be the major factor influencing the structure of the biotic communities in Lake Yindarlgooda. The biota identified in Lake Yindarlgooda were all halotolerant forms typical of large saline playas, the low diversity attributable to the episodic nature of the lake (Timms *et al.* 2006; Timms 2007). Diversity was not strongly affected by the salinity spectrum in the lake as the taxa were all halotolerant species. Instead, the community structure for each of the biotic groups differed according to the different salinities.

Salinity was shown to be most important factor in the hatching of resting stages. Salt lakes have a biota that is hidden in the surface sediment as resting stages (Brendonck



and Williams 2000) and the true diversity of these systems may not be apparent during wet phases especially if reduced rainfall only permits a hypersaline phase. Many large salt lakes have a hyposaline phase expressed only after exceptional rainfall (Timms 2005) and this is when the less saline species, such as *Branchinella*, emerge. This species was recorded as resting stages in the hypersaline sediment adjacent to the LRSF in Lake Yindarlgooda. The rewetting of the sediment revealed algal taxa that were typical of less saline environments. While the diatoms were dominated by halotolerant taxa such as *Amphora coffeaeformis* and its different forms, a number of other species were mesosaline forms that occurred in lower numbers. These indicated that Lake Yindarlgooda may have a lower salinity phase when the lake is fully inundated and in the early stages of the hydrocycle.

The dominant invertebrates in Lake Yindarlgooda were the ostracods and the *Parartemia*. The former are known to be dispersed by vectors such as birds and the families found in Lake Yindarlgooda were typical of other Western Australian salt lakes. Ostracods are the most widely distributed halobiont invertebrate in the state (Halse 2002). *Parartemia*, on the other hand, show no dispersal mechanisms (Geddes 1981). While *Parartemia* n. sp. d was found to be widespread their dispersal may have occurred at a time when the Western Australian interior was more fluvial and the lakes interconnected (Timms 2007).

The restricted fauna in salt lakes has been attributable to habitat homeogeneity (Timms 2007). Lake Yindarlgooda did not contain a variety of different habitats, the exception being the adjacent wetland. This was confirmed in Chapter 5.0 with the riparian vegetation types similar for the all sites, except the wetlands. Differences in the invertebrate and diatom communities were observed between Swan Refuge and Lake Yindarlgooda. The riparian zone of Swan Refuge, while having similar flora to Lake Yindarlgooda, had a slightly different structure. The fringing vegetation enclosed the lake and the samphire zone was inundated in March 2001. The clay pan supported large meadows of *Ruppia* sp. in contrast to the sparse growth of macrophytes observed in Lake Yindarlgooda. Not only did the difference in habitat reflect the structure of the invertebrate and algal communities, it also supported a variety of functional waterbird groups. The lack of extensive sand flats as seen in Lake Yindarlgooda resulted in the absence of foragers such as the plovers, the only two species recorded around the LRSF in Lake Yindarlgooda. Different aquatic

habitats in inland water have been found to support different functional waterbird groups (Kingsford 1998) and this was true for this study.

Lake Yindarlgooda is surrounded by a mosaic of wetlands that when inundated are highly productive and indicative of “boom” periods when wet and “bust” when dry (Roshier *et al.* 2002). Swan Refuge was an important site for the waterbirds that foraged from Lake Yindarlgooda as it provided drinking water and supplemented their diet. The dense riparian vegetation also provided protection for nesting birds. Lake Penny was also found to be as important as Swan Refuge. While much information could not be collected on the biota of Lake Penny, observations of the lake when dry indicated that it was a highly productive system when wet and an important wetland for birds, supported by the many Black Swan nests recorded at the lake. From this and other studies it is apparent that the mosaic of wetlands that form around inland salt lakes is collectively important for waterbirds as they rely on the variety of habitats to fulfil their different needs. Many of the nomadic birds in Australia’s interior move between the numerous wetlands throughout the year, rather than migrate to them collectively once they have filled (Roshier *et al.* 1999).

In the absence of consecutive wet cycles, hatching trials were adopted to determine the impact from the LRSF on the egg bank that is vital to the resilience of Lake Yindarlgooda. Field collections rarely show the salinity ranges required for the hatching of invertebrates. *Parartemia* are excellent osmoregulators as adults, though hatching from the egg bank was shown to be more successful at lower salinities. The egg shell of *Parartemia* was found to be identical to that of *Artemia* and therefore its resilience also considered similar. Hatching viability in *Artemia* is reduced when dormancy has been extended (Lavens and Sorgeloos 1987). The increase in salinity of the sediment around the LRSF had a negative effect on activation of the *Parartemia* resting eggs. A continued reduction in the hatchings from the egg bank has the potential to decrease the viability of the eggs and prevent the replenishment of the bank which is vital for the resilience of the lake. Heavy metals also inhibit the emergence of *Artemia* nauplii from their resting eggs (MacRae and Pandey 1991) and may have been a factor preventing hatching from the sediment at the impact sites in Lake Yindarlgooda.

Invertebrates have been known to adapt to elevated levels of nickel, often bioaccumulating to no adverse affect (Peterson *et al.* 2003). Lake Yindarlgooda has high background levels of nickel as a reflection of the geology. The levels around the LRSF, however, exceeded the average background levels of the control sites. Nickel is an element that has low bioavailability from the water column (Munksgaard and Parry 2002), yet it is in clay particles that heavy metals readily bind (ANZECC 2000). The invertebrates in Lake Yindarlgooda are sediment feeders and therefore susceptible to the ingestion of heavy metals.

The role of the riparian vegetation in salt lakes is often overlooked. While they do not provide as much terrestrially derived carbon as in temperate environments (Bunn *et al.* 2003), their structural role as soil stabilisers is acknowledged (Barrett 2006). Biological and physical soil crusts fill the large open spaces between the vascular plants and their stabilising properties are unique (Belnap and Lange 2003). While biological soil crusts were only found at one site, their function along with that of the extensive physical crusts in stabilising the low dunes around the lake is acknowledged in this study. Aeolian or fluvial erosion is a major transport of sediment in arid zones, much being deposited in the salt lakes. In an environment where excessive siltation is detrimental to the aquatic biota (Williams 2005) a reduction can only be beneficial in maintaining the integrity of the salt lake.

This study has shown that large inland salt lakes have a number of components that all contribute to the ecological functioning of Lake Yindarlgooda. None of the components are isolated; all interact with each other enabling them to survive in a hostile environment. Diversity in Lake Yindarlgooda is low, but abundance can be high enough to support a number of consumer groups. Because Lake Yindarlgooda is a closed system disturbances in the form of increased salinity and heavy metals can be detrimental to an environment that has evolved under specific conditions.

The findings of this study were limited due to the lack of rainfall permitting only one wet sampling event. “One-off “collections are not desirable in ecological studies and the true diversity of Lake Yindarlgooda is yet to be fully revealed. This is a situation that is common in the study of temporary inland waters and in the absence of water other techniques must be adopted. The presence of a well established egg/seed bank proved useful in examining not only the biological communities and their distribution in Lake Yindarlgooda, but also in assessing impacts on the biota. While

the technique of using resting stages is not new its incorporation in studies on salt lakes in Western Australia is in its infancy and as yet, not widely used, though its potentials are large. The findings of this study strengthen the use of resting stages in monitoring programs and provide valuable data that can be incorporated in the study of other large temporary salt lakes and can assist in the rehabilitation and conservation of these lakes, particularly as they are under increased threat from human activities such as mining and pastoralism.

### **Recommendations**

A number of the findings in this study require further investigations. Studies on inland salt lakes are few with distance a serious problem. Lake Yindarlgooda is located nearly 630 km from the Curtin University laboratory limiting the number of field trips, in terms time and available finances. The sheer size of the lake presented further problems limiting the number of sites that could be established logistically and when the lake was inundated many were simply inaccessible. The heterogeneity of water quality displayed in Lake Yindarlgooda during this study, such as the salinity, temperature, and depth of the surface water, did not allow for variation in temporal or seasonal cycles to be investigated. The drought that occurred in Western Australia from 2000 to 2004 was, undeniably, the biggest hurdle faced during this research.

This study has provided a reference point for inland salt lakes allowing for future investigations on this unique environment. The following recommendations are made:

- Extend the study to further hydrocycles, allowing for more sampling to cover temporal and seasonal variation.
- Perform studies on the effects of heavy metals in the hatching of *Parartemia* eggs. This study examined only the effects of increased salinity and the role of heavy metals was outside the scope. The information that the *Parartemia* resting egg is structurally identical to that of *Artemia* and can be used as a basis for toxicological studies.
- Perform more extensive research on the biological soil crusts found in the riparian zone of salt lakes. Personal observations from other playas in the Salinaland have shown that there may be an association between the

halophytic shrub *Lawrenzia helmsii* and the biological soil crust examined in this study. The various factors that affect the growth and colonisation of biological soil crusts require further investigation as their application in the monitoring and rehabilitation of disturbed soils has enormous potential in the arid zones of Western Australia.

- Diatoms, being the predominant primary producers, are vital to the resilience of these inland salt lakes and their resting spores are poorly understood. Further studies on the diatoms including the effect of heavy metals on their growth would add to their role as a valuable monitoring tool for temporary waters.

## References

- Abatzopoulos, T. J., Baxevanis, A. D., Triantaphyllidis, G. V., Criel, G. R. J., Pador, E. L., Van Stappen, G. and Sorgeloos, P. (2006) Quality evaluation of *Artemia urmiana* Gunther (Urmia Lake, Iran) with special emphasis on its particular cyst characteristics (International Study on *Artemia* LXIX). *Aquaculture* 254: 424 - 454.
- Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S. and Sorgeloos, P. (ed.) (2002). *Artemia: basic and applied biology*. Kluwer Academic Publishers.
- Adamus, P. and Brandt, K. (1990) Impacts on Quality of Inland Wetlands of the United States: A survey of indicators, techniques and applications of community-level biomonitoring data. U.S. Environmental Protection Agency, Corvallis, Oregon.
- Ahmat, A. L. (1995) Geology of the Kanowna 1:100 000 Sheet: Western Australian Geological Survey, 1:100 000 Geological Series Explanatory Notes. Department of Minerals and Energy, Perth.
- Anand, R. R. and Paine, M. (2002) Regolith geology of the Yilgarn Craton, Western Australia: implications for exploration. *Australian Journal of Earth Sciences* 49: 3-162.
- Anderson, E. D., Lochhead, J. H., Lochhead, M. S. and Huebner, E. (1970) The origin and structure of the tertiary envelope in thick-shelled eggs of the brine shrimp, *Artemia*. *Journal of Ultrastructure Research* 32: 497-525.
- ANZECC. (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Volume 2, Aquatic Ecosystems - Rationale and Background Information (Chapter 8). Environment Australia, Paper 4., Australia.
- Arakel, A. V., Jacobsen, G. and Lyons, W. B. (1990) Sediment-water interaction as a control on geochemical evolution of playa lake systems in the Australian arid interior. *Hydrobiologia* 197: 1 - 12.
- Aranibar, J. N., Anderson, I. C., Ringrose, S. and Macko, S. A. (2003) Importance of nitrogen fixation in soil crusts of southern African arid ecosystems: actetylene reduction and stable isotope studies. *Journal of Arid Environments* 54: 345-358.

- Archibald, R. E. M. (1983) The diatoms of the Sundays and Great Fish Rivers in the Eastern Cape Province of South Africa. J. Cramer, Stuttgart.
- Atkins, K. J. (1996) Declared rare and priority flora list for Western Australia. Department of Conservation and Land Management, Western Australia.
- Audit, N. L. W. R. (2001) Australian dryland salinity assessment 2000: Extent, impacts, processes, monitoring and management options. National Land and Water Resources Audit, Canberra.
- Baker, P. D. and Fabbro, L. D. (1999) A Guide to the Identification of Common Blue-green Algae (Cyanoprokaryotes) in Australian Freshwaters. Identification and Ecology Guide No. 25. Cooperative Research Centre for Freshwater Ecology, Australia.
- Ball, J., Donnelley, L., Erlanger, P., Evans, R., Kollmorgen, A., Neal, B. and Shirley, M. (2001) Inland Waters. Australia State of the Environment Report. CSIRO Publishing on behalf of the Department of the Environment and Heritage, Canberra.
- Barley, M. E., Doyle, M. G., Kositcin, N., Krapez, B. and Cassidy, K. F. (2004) Late Archean arc and seamount volcanism in the Kurnalpi Terrane, Eastern Yilgarn Craton, Western Australia. In: CRC (ed.), Predictive mineral discovery, CRC Conference, Barossa Valley. CRC, 3-6.
- Barrett, G. (2006) Vegetation communities on the shores of a salt lake in semi-arid Western Australia. *Journal of Arid Environments* 67: 77-89.
- Basher, R., Bates, B., Finlayson, M., Gitay, H. and Woodward, A. (2001) Chapter 12: Australia and New Zealand. In: McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. and White, K. S. (ed.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge: 591-639.
- Batley, G. E., Humphrey, C. L., Apte, S. C. and Stauber, J. L. (2003) A guide to the application of the ANZECC/ARMCANZ water quality guidelines in the mineral industry. Australian Centre for Mining Environmental Research (ACMER), Kenmore.

- Bauld, J. (1981) Occurrence of benthic microbial mats in saline lakes. *Hydrobiologia* 81: 87-111.
- Bauld, J. (1986) Benthic microbial communities in Australian saline lakes. In: De Deckker, P., and Williams, W. D. (ed.), *Limnology in Australia*. Dr. W. Junk Publishers, The Netherlands: 95-112.
- Bayly, I. A. E. (1967) The general biological classification of aquatic environments with special reference to those of Australia. In: Weatherley, A. H. (ed.), *Australian inland waters and their fauna: 11 studies*. A. N. U. Press, Canberra.
- Bayly, I. A. E. (1993) The fauna of athalassic saline waters in Australia and the Altiplano of South America: Comparisons and historical perspectives. *Hydrobiologia* 267: 225-231.
- Bayly, I. A. E. and Williams, W. D. (1966) Chemical and biological studies on some saline lakes of south-east Australia. *Australian Journal of Marine and Freshwater Research* 17: 177-228.
- Beard, J. S. (1979) Phytogeographic Regions. In: Gentilli, J. (ed.), *Western Landscapes*. University of Western Australia Press, Perth: 107-121.
- Belk, D. (1998) Hotspots of inland water crustacean biodiversity. *Species* 30: 50.
- Bellchambers, K. and Carpenter, G. (1990) Birds recorded at Lake Torrens during its 1989 flooding. *South Australian Ornithologist* 31: 1 - 7.
- Belnap, J. and Gillette, D. A. (1997) Disturbance of biological soil crusts: impacts on potential wind erodibility of sandy desert soils in southeastern Utah. *Land Degradation and Development* 8: 355-362.
- Belnap, J. and Gillette, D. A. (1998) Vulnerability of desert biological soil crusts to wind erosion: The influences of crust development, soil texture, and disturbance. *Journal of Arid Environments* 39: 133-142.
- Belnap, J. and Lange, O. L. (Ed.) (2003). *Biological Soil Crusts: Structure, Function, and Management* (2nd edn). Ecological Studies 150 Springer-Verlag, Berlin Heidelberg.



- Belnap, J. (2003a) Biological soil crusts and wind erosion. . In: Belnap, J. and Lange, O. L. (eds), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag, Berlin: 339-347.
- Belnap, J. (2003b) Comparative structure of physical and biological soil crusts. In: Belnap, J. and Lange, O. L. (eds), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag, Berlin: 177-191.
- Belnap, J., Budel, B. and Lange, O. L. (2003a) Biological soil crusts: Characteristics and distribution. In: Belnap, J. and Lange, O. L. (ed.), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag., Berlin Heidelberg: 3-30.
- Belnap, J., Prasse, R. and Harper, K. T. (2003b) Influence of biological soil crusts on soil environments and vascular plants. In: Belnap, J. and Lange, O. L. (eds), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag, Berlin Heidelberg: 281-302.
- Blakers, M., Davies, S. J. J. F. and Reilly, P. N. (1984) *The Atlas of Australian Birds*. Royal Ornithologists Union. Melbourne University Press, Melbourne.
- Blinn, D. W. (1991) The diatom flora of Lake Eyre South: a large episodically filled salt lake in South Australia. *Hydrobiologia* 210: 101-104.
- Blinn, D. W. (1993) Diatom community structure along physiochemical gradients in saline lakes. *Ecology* 74(4): 1246-1263.
- Blinn, D. W. and Bailey, P. C. E. (2001) Land-use influence on stream water quality and diatom communities in Victoria, Australia: A response to secondary salinisation. *Hydrobiologia* 466: 231-244.
- Blinn, D. W., Halse, S. A., Pinder, A. M., Shiel, R. J. and McRae, J. M. (2004) Diatom and macro-invertebrate communities and environmental determinants in the western Australian wheatbelt: A response to secondary salinisation. *Hydrobiologia* 528: 231-244.
- Boggs, D. A., Eliot, I. and Knott, B. (2007) Salt lakes of the northern agricultural region, Western Australia. *Hydrobiologia* 576: 49-59.
- BOM (2003) Climate information for Kalgoorlie, 2001 - 2002. Commonwealth of Australia, Bureau of Meteorology. <http://www.bom.gov.au/>.

- BOM (2007) Wind roses for selected locations in Australia: Kalgoorlie-Boulder airport. Commonwealth of Australia, Bureau of Meteorology. [http://www.bom.gov.au/climate/averages/wind/selection\\_map.shtml](http://www.bom.gov.au/climate/averages/wind/selection_map.shtml).
- Borowitzka, L. J. (1981) The microflora: adaptations to life in extremely saline lakes. *Hydrobiologia* 81: 33-46.
- Borowitzka, M. A. and Hallegraeff, G. M. (2007) Economic importance of algae. In: McCarthy, P. M. and Orchard, A. E. (ed.), *Algae of Australia: Introduction*. CSIRO Publishing, Melbourne: 594-622.
- Boulton, A. J. and Brock, M. A. (1999) *Australian Freshwater Ecology: Processes and Management*. Gleneagles Publishing, Australia.
- Bourrelly, P. (1970) *Les algues d'eau douce. Tome III: Les Algues bleues et rouges, Les Eugleniens, Peridiniens et Cryptomonadines*. N. Boubée and Cie, Paris.
- Bowler, J. M. (1976) Aridity in Australia: Age, origins and expression in aeolian landforms and sediments. *Earth-Science Reviews* 12: 279-310.
- Bowler, J. M. (1981) Australian Salt Lakes: A palaeohydrologic approach. *Hydrobiologia* 81: 431-444.
- Brearley, D. (2002) Flora and vegetation at seven control sites around Lake Yindarlgooda. Report prepared for Bulong Nickel. Onshore Environmental Consultants Pty Ltd.
- Brendonck, L. and Belk, D. (1997) On potentials and relevance of the use of copulatory structures in anostracan taxonomy. *Hydrobiologia* 359: 83-92.
- Brendonck, L. and Coomans, A. (1994) Egg morphology in African Streptocephalidae (Crustacea: Branchiopoda: Anostraca) Part 2: North of Zambezi and Kunene rivers, and Madagascar. *Archiv Hydrobiologia Supplement* 99(3): 335-356.
- Brendonck, L. and De Meester, L. (2003) Eggs banks in freshwater zooplankton: evolutionary and ecological archives in the sediment. *Hydrobiologia* 491: 65-84.

- Brendonck, L. and Riddoch, B. (1997) Anostracans (Branchiopoda) of Botswana: Morphology, distribution, diversity, and endemism. *Journal of Crustacean Biology* 17: 111-134.
- Brendonck, L. and Riddoch, B. J. (1999) Wind-borne short-range egg dispersal in anostracans (Crustacea: Branchiopoda). *Biological Journal of the Linnean Society* 67: 87-95.
- Brendonck, L. and Williams, W. D. (2000) Biodiversity in wetlands of dry regions (drylands). In: Gopal, B., Junk, W. J. and Davis, J. A. (ed.), Biodiversity in wetlands: Assessment, function and conservation. Backhuys Pub., The Netherlands: 181-194.
- Brock, M. A. (1981) The ecology of halophytes in the south-east of South Australia. *Hydrobiologia* 81: 23-32.
- Brock, M. A. (1986) Adaptations to fluctuations rather than to extremes of environmental parameters. In: De Deckker, P., and Williams, W. D. (ed.), Limnology in Australia. Dr. W. Junk, The Netherlands: 131-140.
- Brock, M. A. (1997) Aquatic vegetation of inland wetlands. In: Groves, R. H. (ed.), Australian Vegetation. Cambridge University Press, Cambridge.
- Brock, M. A. (1998) Are temporary wetlands resilient? Evidence from seed banks of Australian and South African wetlands. In: McComb, A. J. and Davies, J. A. (ed.), Wetlands for the Future. Gleneagles Publishing., Australia: 193-206.
- Brock, M. A. and Shiel, R. J. (1983) The composition of aquatic communities in saline wetlands in Western Australia. *Hydrobiologia* 105: 77-84.
- Brock, M. A., Nielsen, D. L., Shiel, R. J., Green, J. D. and Langley, J. D. (2003) Drought and aquatic community resilience: The role of eggs and seeds in sediments of temporary wetlands. *Freshwater Biology* 48: 1207-1218.
- Browne, R. A., Sallee, D., Grosch, D. S., Segretti, W. O. and Purser, S. M. (1984) Partitioning genetic and environmental components of reproduction and lifespans in *Artemia*. *Ecology* 65: 279-960.
- Bunn, S. E., Davies, P. M. and Winning, M. (2003) Sources of organic carbon supporting the food web of an arid zone floodplain river. *Freshwater Biology* 48: 619-635.

- Bunting, J. A. and Williams, S. J. (1976) Explanatory Notes on the Sir Samuel Geological Sheet. Geological survey of Western Australia, Perth.
- Burbridge, A. A. and Fuller, P. J. (1982) Banded Stilt breeding at Lake Barlee, Western Australia. *Emu* 82: 212-216.
- Burke, C. M. and Knott, B. (1989) Limnology of four groundwater-fed saline lakes in south-western Australia. *Australian Journal of Marine and Freshwater Research* 40: 55-68.
- Caceres, C. E. (1997) Dormancy in invertebrates. *Invertebrate Biology* 116: 371-383.
- Caceres, C. E. and Hairston, N. G. (1998) Benthic-pelagic coupling in planktonic crustaceans: The role of the benthos. *Limnologica* 52: 163-174.
- Cale, D. J., Halse, S. A. and Walker, C. D. (2004) Wetland monitoring in the wheatbelt of south-west Western Australia: Site descriptions, waterbird, aquatic invertebrate and groundwater data. *Conservation Science Western Australia* 5(1): 20-135.
- Campagna, V. S. and Taukulis, F. E. (2006) Aquatic Biota of Lake Way. Baseline monitoring for Agincourt Resources. Outback Ecology Services.
- Campagna, V. S. and John, J. (*in press*) A comparison of the cyst shell morphology of two *Parartemia* species (Crustacea: Anostraca) from Western Australia. *Hydrobiologia*.
- Capon, S. J. and Brock, M. A. (2006) Flooding, soil seed bank dynamics and vegetation resilience of a hydrologically variable desert floodplain. *Freshwater Biology* 51: 206-223.
- Casanova, M. T. and Brock, M. A. (1996) Can oospore germination patterns explain charophyte distribution in permanent and temporary wetlands? *Aquatic Botany* 54: 297-312.
- Cassidy, K. F., Champion, D. C., Krapez, B., Barley, M. E., Brown, S. J. A., Blewett, R. S., Groenewald, P. B. and Tyler, I. M. (2006) A revised geological framework for the Yilgarn Craton, Western Australia: Western Australia Geological Survey, Record 2006/8.

- Chaplin, S. (1998) The brine shrimp *Parartemia nova* a. (Lefroy-Cowan): in the Johnston Lakes: effects of pH, salinity and temperature on life history. Unpub. BSc. Hons. Curtin University of Technology.
- Chaplin, S., John, J., Brearley, D. and Dunlop, J. (1999) A limnological investigation of Lake Carey, a large ephemeral salt lake in Western Australia. Mine Rehabilitation Group, School of Environmental Biology, Curtin University of Technology., Perth.
- Chapman, A. and Lane, J. A. K. (1997) Waterfowl usage of wetlands in the south-east arid interior of Western Australia. *Emu* 97: 51-59.
- Chivas, A. R., De Deckker, P., Nind, M., Thiriet, D. and Watson, G. (1986) The Pleistocene palaeoenvironmental record of Lake Buchanan: an atypical Australian playa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 54: 131-152.
- Clarke, J. D. A. (2005) Complex depositional landscapes of the Western Australian wheat belt. In: Roach, I. C. (ed.), *Regolith 2005 - Ten years of CRC LEME*. CRC LEME, 49-54.
- Clarke, K. R. and Ainsworth, M. (1993) A method for linking multivariate community structure to environmental variables. *Marine Ecology Progressive Series* 92: 205-219.
- Clarke, K. R. and Gorlet, K. R. (2006) *PRIMER v6: User manual/tutorial*. PRIMER-E, Plymouth.
- Clarke, K. R. and Warwick, R. M. (2001) *Change in marine communities: An approach to statistical analysis and interpretation*, 2nd edition. PRIMER-E, Plymouth.
- Clavero, E., Garcia-Pichel, F., Grimalt, O. and Hernandez-Marine, M. (2001) Behaviour of diatoms apparently adapted to salinity. The case of *Climaconeis scopuloroides* and *Amphora* aff. *hyalina*. In: Elster, J., Seckbach, J., Vincent, W. F. and Lhotsky, O. (ed.), *Algae and extreme environments: Ecology and physiology; proceedings of the international conference*. J.Cramer, Berlin: 453-463.

- Clavero, E., Hernandez-Marine, M., Grimalt, O. and Garcia-Pichel, F. (2000) Salinity tolerance of diatoms from thalassic hypersaline environments. *Journal of Phycology* 36: 1021-1034.
- Clegg, J. S. (1997) Embryos of *Artemia franciscana* survive four years of continuous anoxia: The case for complete metabolic rate depression. *Journal of Experimental Biology* 200: 467-475.
- Clegg, J. S. and Campagna, V. S. (2006) Comparisons of stress proteins and soluble carbohydrate in encysted embryos of *Artemia franciscana* and two species of *Parartemia*. *Comparative Biochemistry and Physiology, Part B* 145: 119-125.
- Clegg, J. S. and Conte, F. P. (1980) A review of the cellular and developmental biology of *Artemia*. In: Persoone, G., Sorgeloos, P., Roels, O., and Jaspers, E. (eds), *The Brine Shrimp Artemia*, Vol 2. Universa Press, Wetteren, Belgium.: 11-54.
- Clegg, J. S. and Trotman, C. N. A. (2002) Physiological and biochemical aspects of *Artemia* ecology. In: Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S., and Sorgeloos, P. (ed.), *Artemia: basic and applied biology*. Kluwer Academic Pub., The Netherlands: 129-170.
- Clegg, J. S., Jackson, S. A. and Popov, V. I. (2000) Long-term anoxia in encysted embryos of the crustacean, *Artemia franciscana*: Viability, ultrastructure, and stress proteins. *Cell Tissue Research* 301: 433-446.
- Clegg, J. S., Jackson, S. A., Van Hoa, N. and Sorgeloos, P. (2000b) Thermal resistance, development rate and heat shock proteins in *Artemia franciscana*, from San Francisco Bay and southern Vietnam. *Journal of Experimental Marine Biology and Ecology* 252: 85-96.
- Clegg, J. S., Willsie, J. K. and Jackson, S. A. (1999) Adaptive significance of a small heat shock/alpha-crystallin protein in encysted embryos of the brine shrimp, *Artemia franciscana*. *American Zoologist* 39: 836-847.
- Cole, G. A. (1975) *Textbook of Limnology*. C. V. Mosby Co., Saint Louis.

- Coleman, M., Geddes, M. C. and Trotman, C. N. A. (1998) Divergence of *Parartemia* and *Artemia* haemoglobin genes. *International Journal of Salt Lake Research* 7: 171-180.
- Compere, P. (1994) Diatoms from hypersaline inland waters of Egypt. In: Kociolek, J. P. (ed.), *Memoirs of the California Academy of Sciences*, No. 17. *Proceedings of the 11th International Diatom Symposium*. California Academy of Sciences, San Francisco: 175-188.
- Congdon, J. D. and McComb, A. J. (1981) The vegetation of the Blackwood River Estuary, southwest Australia. *Journal of Ecology* 69: 1-16.
- Conley, D. J., Zimba, P. V. and Theriot, E. (1994) Silica content of freshwater and marine benthic diatoms. In: Kociolek, J. P. (ed.), *Memoirs of the California Academy of Sciences*, No. 17. *Proceedings of the 11th International Diatom Symposium*. Californian Academy of Sciences, San Francisco: 95-101.
- Conte, F. P. and Geddes, M. C. (1988) Acid brine shrimp: Metabolic strategies in osmotic and ionic adaptation. *Hydrobiologia* 159: 190-200.
- Cook, F. S. and Coleman, P. S. J. (2007) Benthic diatoms in the salinas of the Dry Creek saltfields, South Australia. *Hydrobiologia* 576: 61-68.
- Criel, G. R. J. and MacRae, T. H. (2002a) *Artemia* morphology and structure. In: Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S. and Sorgeloos, P. (eds), *Artemia: basic and applied biology*. Kluwer Academic Pub., 1-37.
- Criel, G. R. J. and MacRae, T. H. (2002a) *Artemia* morphology and structure. In: Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S. and Sorgeloos, P. (ed.), *Artemia: basic and applied biology*. Kluwer Academic Pub., The Netherlands: 1-37.
- Criel, G. R. J. and MacRae, T. H. (2002b) Reproductive biology of *Artemia*. In: Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S. and Sorgeloos, P. (ed.), *Artemia: basic and applied biology*. Kluwer Academic Pub., The Netherlands: 39-128.
- Datson, B. (2002) *Samphires in Western Australia: A field guide to Chenopodiaceae tribe Salicornieae*. Department of Conservation and Land Management Perth.

- Davey, B. (2001) The ecology and distribution of samphires in the Goldfields. In: Proceedings of the Salt Lake Workshop, 6th September 2001. Perth, Western Australia. Centre for Land Rehabilitation, UWA.
- Davis, J. A. and Christidis, F. (1999) A guide to the wetland invertebrates of southwestern Australia. Western Australian Museum, Perth.
- Davis, J. A., Harrington, S. A. and Friend, J. A. (1993) Invertebrate communities of relict streams in the arid zone: The George Gill Range, central Australia. *Australian Journal of Marine and Freshwater Research* 44: 486-505.
- Davis, J. S. (1972) Survival records in the algae and the survival role of certain algae pigments, fat and mucilaginous substances. *Biologist* 54: 52-93.
- De Deckker, P. (1981a) Taxonomic notes on some Australian ostracods with description of new species. *Zoologica Scripta* 10: 37-55.
- De Deckker, P. (1981b) Taxonomy and ecological notes of some ostracods from Australian inland waters. *Transactions of the Royal Society of South Australia* 105(3): 91-138.
- De Deckker, P. (1983) Australian salt lakes: Their history, chemistry, and biota - a review. *Hydrobiologia* 105: 231-444.
- De Deckker, P. (1988) Biological and sedimentary facies of Australian salt lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 62: 237-270.
- De Deckker, P. and Geddes, M. C. (1980) Seasonal fauna of ephemeral saline lakes near the Coorong Lagoon, South Australia. *Australian Journal of Marine and Freshwater Research* 31: 677-699.
- De Deckker, P. and Williams, W. D. (1982) Chemical and biological features of Tasmanian salt lakes. *Australian Journal of Marine and Freshwater Research* 33: 1127-32.
- De Deckker, P., Colin, J.-P. and Peypouquet, J.-P. (1988) Ostracoda in the Earth Sciences. Elsevier Science Publishing Co. Inc, New York.
- De Stasio, B. T. (1989) The seed bank of a freshwater crustacean: Copepodology for the plant ecologist. *Ecology* 70(5): 1377-1389.



- Decamps, H. and Tabacchi, E. (1994) Species richness in vegetation along river margins. In: Giller, P. S., Hildrew, A. G. and Raffaelli, D. G. (eds), *Aquatic Ecology: Scale, pattern and process*. The 34th Symposium of the British Ecological Society with the American Society of Limnology and Oceanography, University College, Cork, 1992. University Press, Cambridge: 1-20.
- Desikachary, T. V. (1972) *Taxonomy and biology of blue-green algae*. Madras.
- Dhont, J. and Sorgeloos, P. (2002) Applications of *Artemia*. In: Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S. and Sorgeloos, P. (ed.), *Artemia: basic and applied biology*. Kluwer Academic Publishers, Dordrecht: 251-271.
- Dor, I. and Danin, A. (2001) Life strategies of *Microcoleus vaginatus*: a crust-forming cyanophyte on desert soils. In: Elster, J., Seckbach, J., Vincent, W. F., and Lhotsky, O. (ed.), *Algae and extreme environments: ecology and physiology*. J. Cramer, Berlin: 317-340.
- Drinkwater, L. E. and Clegg, J. S. (1991) Experimental biology of cyst diapause. In: Browne, R. A., Sorgeloos, P., and Trotman, C. N. A. (eds), *Artemia Biology*. CRC Press, Inc., Boca Raton, Florida: 94-114.
- Dumont, H., Nandini, S. and Sarma, S. S. S. (2002) Cyst ornamentation in aquatic invertebrates: A defence against egg-predation. *Hydrobiologia* 486: 161-167.
- Dunlop, J. N. (1990) *Mining and the Goldfields desert lakes*. Australian Mining Industry Council, Canberra, Australia.
- Dussart, B. H. and Defaye, D. (1995) *Copepoda: Introduction to the Copepoda*. SPB Academic Publishing,
- Ehrlich, A. (1995) *Atlas of the inland-water diatom flora of Israel, Flora Palestina*. Publications of the Israel Academy of Science and Humanities, Israel.
- Eldridge, D. J. and Myers, C. A. (2001) The impact of warrens of the European rabbit (*Oryctolagus cuniculus* L.) on soil and ecological processes in a semi-arid Australian woodland. *Journal of Arid Environments* 47: 325-337.
- Eldridge, D. J. and Tozer, M. E. (1996) Distribution and floristics of Bryophytes in soil crusts in semi-arid and arid eastern Australia. *Australian Journal of Botany* 44: 223-247.

- Eldridge, D. J. (1996) Distribution and floristics of lichens in soil crusts in arid and semi-arid New South Wales, Australia. *Australian Journal of Botany* 44: 581-599.
- Eldridge, D. J. (1998) Trampling of microphytic crusts on calcareous soils, and its impacts on erosion under rain-impacted flow. *Catena* 33: 221-239.
- Eldridge, D. J. (2003) Biological soil crusts of Australia. In: Belnap, J. and Lange, O. L. (eds), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag, Berlin Heidelberg: 119-132.
- Eldridge, D. J. and Greene, R. S. B. (1994) Microbiotic soil crusts: A review of their roles in soil and ecological processes in the rangelands of Australia. *Australian Journal of Soil Research* 32: 389-415.
- Eldridge, D. J., Zaady, E. and Shachak, M. (2000) Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. *Catena* 40: 323-336.
- English, J. (2001) The ecophysiology of *Halosarcia*. In: Salt Lake Workshop, 6th September 2001. Perth, Western Australia. Centre for Land Rehabilitation, UWA.
- English, J. P. (2004) Ecophysiology of salt- and waterlogging tolerance in selected species of *Halosarcia* PhD. University of Western Australia.
- Felix, E. A. and Rushforth, S. R. (1979) The algal flora of the Great Salt Lake, Utah, U. S. A. *Nova Hedwigia* 31: 163-194.
- Finlay, J. C. (2001) Stable-carbon-isotope ratios of river biota: implications for energy flow in lotic food webs. *Ecology* 82: 1052-1064.
- Finston, T. (2000) Morphology and molecules conflict to confound species boundaries in salt lake ostracodes of the genus *Mytilocypris* (Crustacea: Ostracoda). *Australian Journal of Zoology* 48: 393-409.
- Finston, T. (2004) Effect of temporally heterogeneous environment on size and shape of the giant ostracods *Mytilocypris* (Ostracoda: Cyprididae) from Australian salt lakes. *Marine and Freshwater Research* 55: 499-507.

- Finucane, S. (2001) Monitoring the environmental impacts of mine water discharge to Lake Miranda. In: Proceedings of the Salt Lake Workshop. Bentley Technology Park, Perth, Western Australia(eds). Centre for Land Rehabilitation, University of Western Australia, City.
- Foged, N. (1978) Diatoms in Eastern Australia. J Cramer, Vaduz, Germany.
- Fritz, S. C., Cumming, B. F., Gasse, F. and Laird, K. R. (1999) Diatoms as indicators of hydrological and climatic change in saline lakes. In: Stoermer, E. F. and Smol, J. P. (eds), *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge University Press, Cambridge: 41-72.
- Gannon, J. E. (1971) Two counting cells for the enumeration of zooplankton microcrustacea. *Transactions of the American Microscopical Society* 90: 486.
- Garcia, A. (1999) Charophyte Flora of South-eastern South Australia and South-western Victoria, Australia: Systematics, Distribution and Ecology. *Australian Journal of Botany* 47: 407-426.
- Garcia, A. (2002) Charophytes (Stoneworts): taxonomy and ecology. In: 4th Australian Algal Workshop, Sept 28 - 29. Curtin University, Perth, WA.
- Garnett, S. (1992) Threatened and extinct birds of Australia. Report No. 82.
- Gasse, F. (1986) East African diatoms, taxonomy, ecological distribution. *Bibliotheca Diatomologica* 11: 1-201.
- Geddes, M. C. (1975a) Studies on the Australian brine shrimp *Parartemia zietziana* Sayce (Crustacea: Anostraca). I. Salinity tolerance. *Comparative Biochemistry and Physiology* 51A: 553-559.
- Geddes, M. C. (1975b) Studies on the Australian brine shrimp *Parartemia zietziana* Sayce (Crustacea: Anostraca). III. The mechanisms of osmotic and ionic regulation. *Comparative Biochemistry and Physiology* 51A: 573-578.
- Geddes, M. C. (1975c) Studies on the Australian brine shrimp *Parartemia zietziana* Sayce (Crustacea: Anostraca). II. Osmotic and ionic regulation. *Comparative Biochemistry and Physiology* 51A: 561-571.
- Geddes, M. C. (1976) Seasonal fauna of some ephemeral saline waters in western Victoria with particular reference to *Parartemia zietziana* Sayce (Crustacea:

- Anostraca). *Australian Journal of Marine and Freshwater Research* 27: 1-22.
- Geddes, M. C. (1981) The brine shrimps *Artemia* and *Parartemia*: Comparative physiology and distribution in Australia. *Hydrobiologia* 81: 169-179.
- Geddes, M. C. and Williams, W. D. (1987) Comments on *Artemia* introductions and the need for conservation. In: Sorgeloos, P., Bengtson, D. A., Decleir, W. and Jaspers, E. (ed.), *Artemia* Research and its Applications. Vol. 3. Ecology, Culturing, Use in aquaculture. Universa Press, Wetteren, Belgium: 19-26.
- Geddes, M. C., De Deckker, P., Williams, W. D., Morton, D. W. and Topping, M. (1981) On the chemistry and biota of some saline lakes in Western Australia. *Hydrobiologia* 81: 201-222.
- Geitler, L. (1985) Cyanophyceae. Koeltz Scientific Books, Koenigstein, Germany.
- Gell, P. A. (1997) The development of a diatom database for inferring lake salinity, Western Victoria, Australia: Towards a quantitative approach for reconstructing past climates. *Australian Journal of Botany* 45: 389-423.
- Gell, P. A. and Gasse, F. (1994) Relationships between salinity and diatom flora from some Australian saline lakes. In: Kociolek, J. P. (ed.), *Memoirs of the California Academy of Sciences*, No. 17. Proceedings of the 11th International Diatom Symposium. California Academy of Sciences, San Francisco: 631-647.
- Gentili, J. (1979a) Regions and landscapes. Nature and size, function and change. In: Gentili, J. (ed.), *Western Landscapes*. University of Western Australia, Academic Press, Perth: 3-48.
- Gentili, J. (1979b) *Western Landscapes*. University of Western Australia Press, Perth, Western Australia.
- Gibson, N., Keighery, G. J. and Lyons, M. N. (2000) The flora and vegetation of the seasonal and perennial wetlands of the southern Carnarvon Basin, Western Australia. *Records of the Western Australian Museum Supplement No. 61*: 175-199.

- Glassford, D. K. and Semeniuk, V. (1995) Desert-aeolian origin of late Cenozoic regolith in arid and semi-arid Southwestern Australia. *Palaeography, Palaeoclimatology, Palaeoecology* 114: 131-166.
- Graetz, R. D. and Tongway, D. J. (1986) Influence on grazing management on vegetation, soil structure and nutrient distribution and the infiltration of applied rainfall in a semi-arid chenopod shrubland. *Australian Journal of Ecology* 11: 347-360.
- Green, A. J. and Figuerola, J. (2005) Recent advances in the study of long-distance dispersal of aquatic invertebrates via birds. *Diversity and Distributions* 11: 149-156.
- Green, J. W. (1985) Census of the vascular plants of Western Australia. Western Australian Herbarium, Department of Agriculture, Western Australia.
- Green, J. W. (1987) Census of the vascular plants of Western Australia. Supplement No. 7. Western Australian Herbarium, Department of Agriculture, Western Australia.
- Greene, R. S. B. and Tongway, D. J. (1989) The importance of (surface) physical and chemical properties in determining soil surface condition of red earths in rangelands. *Australian Journal of Soil Research* 27: 213-225.
- Gregory, S. V., Swanson, F. J., McKee, W. A. and Cummins, K. W. (1991) An ecosystem perspective of riparian zones: Focus on links between land and water. *BioScience* 41(8): 540-551.
- Hacker, R. B. (1987) Species responses to grazing and environmental factors in an arid halophytic shrubland community. *Australian Journal of Botany* 35: 135-150.
- Hall, N. J. and McKenzie, N. L. (1994) Physical Environment. In: Hall, N. J., McKenzie, N. L. and Keighery, G. J. (ed.), *The Biological Survey of the Eastern Goldfields of Western Australia. Part 10: Sandstone-Sir Samuel and Laverton-Leonora Study Areas. Records of the Western Australian Museum Supplement No. 47.* Western Australian Museum, Perth: 9-23.

- Hall, N. J. and Milewski, A. V. (1994) Introduction. In: Hall, N. J., McKenzie, N. L. and Keighery, G. J. (ed.), The Biological Survey of the Eastern Goldfields of Western Australia. Part 10: Sandstone-Sir Samuel and Laverton-Leonora Study Areas. Records of the Western Australian. Records of the Western Australian Museum Supplement No. 47. Western Australian Museum, Perth: 1-8.
- Halse, S. A. (1990) Waterbirds at Lake Gregory: Available data and information required. In: Halse, S. A. (ed.), The Natural Features of Lake Gregory: A Preliminary Review. Proceedings of a workshop on Lake Gregory held at Woodvale April 1989. Occasional Paper 2/90 Dept of CALM, 20-29.
- Halse, S. A. (2002) Diversity of Ostracoda (Crustacea) in inland waters of Western Australia. *Verh. Internat. Verein. Limnol.* 28: 914-918.
- Halse, S. A. and McRae, J. M. (2001) *Calamoecia trilobata* n sp (Copepoda: Calanoida) from salt lakes in south-western Australia. *Journal of the Royal Society of Western Australia* 84: 5-11.
- Halse, S. A. and McRae, J. M. (2004) New genera and species of "giant" ostracods (Crustacea: Cyprididae) from Australia. *Hydrobiologia* 524: 1-52.
- Halse, S. A., Shiel, R. J. and Williams, W. D. (1998) Aquatic invertebrates of Lake Gregory, northwestern Australia, in relation to salinity and ionic composition. *Hydrobiologia* 381: 15-29.
- Hammer, U. T. (1981) Primary production in saline lakes: A review. *Hydrobiologia* 81: 47-58.
- Hammer, U. T. (1986) Saline Lake Ecosystems of the World. Dr. W. Junk Publishers, Dordrecht.
- Handley, M. (2003) The distribution pattern of algal flora in saline lakes in Kambalda and Esperance, Western Australia. Un published thesis, Master of Science. Curtin University of Technology.
- Harper, K. T. and Belnap, J. (2001) The influence of biological soil crusts on mineral uptake by associated vascular plants. *Journal of Arid Environments* 47: 347-357.

- Harper, R. J. and Gilkes, R. J. (2004) Aeolian influences on the soils and landforms of the southern Yilgarn Craton of semi-arid, southwestern Australia. *Geomorphology* 59: 215-235.
- Hart, B. T. and McKelvie, I. D. (1986) Chemical limnology in Australia. In: De Deckker, P. and Williams, W. D. (ed.), *Limnology in Australia*. Australian Society for Limnology, CSIRO., 3-32.
- Hawkes, C. V. and Flechtner, V. R. (2002) Biological soil crusts in a xeric Florida shrubland: composition, abundance, and spatial heterogeneity of crusts with different disturbance history. *Microbial Ecology* 43: 1-12.
- Hessler, R. R. (1982) Evolution within the Crustacea. Part 1. General: Remipedia, Branchiopoda, and Malacostraca. In: Abele, L. G. (eds), *The Biology of Crustacea. Vol. 1. Systematics, the Fossil Record, and Biogeography*. Academic Press, New York: 150-185.
- Hill, R. E. and Shepard, W. D. (1997) Observations on the identification of California anostracan cysts. *Hydrobiologia* 359: 113-123.
- Hingston, F. J. and Gailitis, V. (1976) The geographic variation of salt precipitation over Western Australia. *Australian Journal of Soil Research* 14: 319-335.
- Hopper, K. R. (1999) Risk-spreading and bet-hedging in insect population biology. *Annual Review of Entomology* 44: 535-560.
- Hulsman, A., Bracke, S., Moreau, K., Riddoch, B. J., De Meester, L. and Brendonck, L. (2006) Dormant egg bank characteristics and hatching pattern of the *Phallocryptus spinosa* (Anostraca) population in the Makgadikgadi Pans (Botswana). *Hydrobiologia* 571: 123-132.
- Humphries, P. and Baldwin, D. S. (2003) Drought and aquatic ecosystems: an introduction. *Freshwater Biology* 48: 1141-1146.
- Hutchinson, G. E. (1957) *A treatise on limnology. I. Geography, physics and chemistry*. John Wiley and Sons, New York.
- ICME. (1996) *Heavy metals in the environment: A geoscience perspective*. The International Council on Metals and the Environment, Ottawa, Ontario.

- Issa, O. M., Le Bissonnais, Y., Défarge, C. and Trichet, J. (2001a) Role of a cyanobacterial cover on structural stability of sandy soils in the Sahelian part of western Niger. *Geoderma* 101: 15-30.
- Issa, O. M., Stal, L. J., Defarge, C., Coute, A. and Trichet, J. (2001b) Nitrogen fixation by microbial crusts from desiccated Sahelian soils (Niger). *Soil Biology and Biochemistry* 33: 1425-1428.
- Issa, O. M., Trichet, J., Defarge, C., Coute, A. and Valentin, C. (1999) Morphology and microstructure of microbiotic soil crusts on a tiger bush sequence (Niger, Sahel). *Catena* 37: 175-196.
- Jackson, S. A. and Clegg, J. S. (1996) The ontogeny of low molecular weight stress proteins p26 during early development of the brine shrimp, *Artemia franciscana*. *Development, Growth and Differentiation* 38: 153-160.
- Jacobs, S. W. L. (1999) Terrestrial wetlands and waterplants. In: Orchard, A. E. (eds), *Flora of Australia*. CSIRO, Melbourne: 403-415.
- Jasper, D. (1999) Salt Lake Ecology Seminar - A synthesis of issues raised in group discussions. In: *Salt Lake Ecology Seminar*. Perth, July 7th 1999. Centre for Land Rehabilitation, UWA.
- Jenkins, K. M., Boulton, A. J. and Ryder, D. S. (2005) A common parched future? Research and management of Australian arid-zone floodplain wetlands. *Hydrobiologia* 552: 57-73.
- Johansen, J. R. (1993) Cryptogamic crusts of semiarid and arid lands of North America. *Journal of Phycology* 29: 140-147.
- Johansen, J. R., Britton, C., Rosati, T. C., Xuesong, L., St Clair, L. L., Webb, B. K., Kennedy, A. J. and Yanko, K. S. (2001) Microbiotic crusts of the Mojave Desert: factors influencing distribution and abundance. In: Elster, J., Seckbach, J., Vincent, W. F. and Lhotsky, O. (ed.), *Algae and extreme environments: Ecology and physiology; proceedings of the international conference, 11-16 Sept. 2000, Trebon, Czech Republic*. J.Cramer, Berlin: 341-371.
- John, J. (1983) *The Diatom Flora of the Swan River Estuary, Western Australia*. J. Cramer, Germany.



- John, J. (1988) Morphology and ecology of *Navicula elegans* W. Smith populations from Western Australia. In: Round, F. E. (ed.), Proceedings of the 9th International Diatom symposium. Biopress Ltd and Sven Koeltz, Bristol and Koenigstein: 417-425.
- John, J. (1994) *Mastogloia* species associated with active stromatolites in Shark Bay, west coast of Australia. In: Kociolek, P. (ed.), Memoirs of the California Academy of Sciences, No. 17. Proceedings of the 11th International Diatom Symposium. California Academy of Sciences, San Francisco: 189-209.
- John, J. (1999) Aquatic flora. In: Osborne, J. and Dunlop, J. N. (ed.), Baseline ecological study of Lake Lefroy. School of Environmental Biology, Curtin University of Technology, Perth, Western Australia.
- John, J. (2000) A guide to diatoms as indicators of urban stream health. National River Health Program, Urban Sub Program, Report No. 7. LWRDCC Occasional Paper 14/99. Land and Water Resources and Development Corporation, Canberra.
- John, J. (2003) A temporary inland salt lake: A case history - Lake Miranda. In: Workshop on Water Quality Issues in Final Voids, Salt Lakes and Ephemeral Streams. Perth, Western Australia. ACMER.
- John, J. (2003) Chemical and biological characteristics of salt lakes in Western Australia. In: Workshop on Water Quality Issues in Final Voids, Salt Lakes and Ephemeral Streams. Perth, Western Australia, 12-13 May. (ACMER)(ed.). ACMER.
- John, J. (2007) Heterokontophyta: Bacillariophyceae. In: McCarthy, P. M. and Orchard, A. E. (ed.), Algae of Australia: Introduction. CSIRO Publishing, Melbourne: 288-310.
- John, J., Dunlop, N., Goldberg, J., Lowe, E. and Osborne, J. (2000) Baseline Aquatic Biology Survey of Lake Miranda. URS (for Sir Samuel Mines NL), Perth.
- John, J., Lowe, E., Butson, F. and Osborne, J. (2002) Impact of dewatering on Lake Miranda, January - October 2002. Dept. of Environmental Biology, Curtin University of Technology, Perth.

- Johnson, E. R. L. and Baird, A. M. (1970) Notes on the flora and vegetation of the Nullarbor Plain at Forrest, Western Australia. *Journal of the Royal Society of Western Australia* 5: 56-61.
- Johnstone, R. E. and Storr, G. M. (1998) Handbook of Western Australian Birds. Western Australian Museum, Perth.
- Johnstone, R. E., Burbidge, A. H. and Stone, P. (2000) Birds of the southern Carnarvon Basin, Western Australia: distribution, status and historical changes. *Records of the Western Australian Museum Supplement No. 61*: 371-448.
- Karnieli, A., Kidron, G. J., Glaesser, C. and Ben-Dor, E. (1999) Spectral characteristics of cyanobacterial soil crusts in semiarid environments. *Remote Sensing Environment* 69: 67-75.
- Kefford, B. J., Papas, P. J., Metzeling, L. and Nugegoda, D. (2004) Do laboratory salinity tolerances of freshwater animals correspond with their field salinities? *Environmental Pollution* 129: 355-362.
- Keighery, G. J., Hall, N. J. and Milewski, A. V. (1994) Vegetation and flora. In: Hall, N. J., McKenzie, N. L. and Keighery, G. J. (eds), The Biological Survey of the Eastern Goldfields of Western Australia. Part 10: Sandstone-Sir Samuel and Laverton-Leonora Study Areas. *Records of the Western Australian Museum Supplement No. 47*. Western Australian Museum, Perth: 24-50.
- Kingsford, R. T. (1989) The effect of drought on duckling survival of Maned Ducks. *Australian Wildlife Research* 16: 405-412.
- Kingsford, R. T. (1995) Occurrence of high concentrations of waterbirds in arid Australia. *Journal of Arid Environments* 29: 421-425.
- Kingsford, R. T. (1998) Management of wetlands for waterbirds. In: Williams, W. D. (ed.), Wetlands in a Dry Land: Understanding for Management. Environment Australia, Biodiversity Group., Canberra: 111-121.
- Kingsford, R. T. and Halse, S. A. (1998) Waterbirds as the 'flagship' for the conservation of arid zone wetlands of Australia? In: McComb, A. J. and Davies, J. A. (ed.), Wetlands for the Future. Gleneagles, Adelaide: 139-160.

- Kingsford, R. T. and Porter, J. L. (1994) Waterbirds on an adjacent freshwater lake and salt lake in arid Australia. *Biological Conservation* 69: 219-228.
- Kingsford, R. T., Curtin, A. L. and Porter, J. (1999) Water flows on Cooper Creek in arid Australia determine 'boom' and 'bust' periods for waterbirds. *Biological Conservation* 88: 231-248.
- Kinhill. (1996) Resolute Resources Limited, Bulong Nickel Laterite Project. Consultative Environmental Review, Vol. 1. Kinhill Engineers Pty Ltd, Milton, QLD, Australia.
- Kociolek, J. P. and Herbst, D. B. (1992) Taxonomy and distribution of benthic diatoms from Mono Lake, California, USA. *Transactions of the American Microscopical Society* 111: 338-355.
- Krammer, K. and Lange-Bertalot, H. (1986) Susswasserflora von Mitteleuropa. Bacillariophyceae, Teil i: Naviculaceae. Gustav Fischer Verlag, Stuttgart.
- Krammer, K. and Lange-Bertalot, H. (1988) Susswasserflora von Mitteleuropa. Bacillariophyceae, Teil ii: Bacillariophyceae, Epithemiaceae, Surirellaceae. Gustav Fischer Verlag, Stuttgart.
- Lane, B. A. (1987) Shorebirds in Australia. Nelson Publishers, Victoria, Australia.
- Lange, C. B. and Tiffany, M. A. (2002) The diatom flora of the Salton Sea, California. *Hydrobiologia* 473: 179-201.
- Laubhan, M. K. and Gammonley, J. H. (2000) Density and foraging habitat selection of waterbirds breeding in the San Luis valley of Colorado. *Journal of Wildlife Management* 64(3): 808-819.
- Lavens, P. and Sorgeloos, P. (1987) The cryptobiotic state of *Artemia* cysts, its diapause deactivation and hatching: A review. In: Sorgeloos, P., Bengtson, D. A., Decler, W. and Jaspers, E. (ed.), *Artemia* Research and its Applications. Vol. 3: Ecology, Culturing, Use in aquaculture. Universa Press, Wetteren, Belgium.: 27-63.
- Linder, F. (1941) Contributions to the morphology and the taxonomy of the Branchiopoda Anostraca. *Zoologiska Bidrag fran Uppsala* 20: 101-302.

- Lyons, W. B., Chivas, A. R., Lent, R. M., Welch, S., Kiss, E., Mayewski, P. A., Long, D. T. and Carey, A. E. (1990) Metal concentrations in surficial sediments from hypersaline lakes, Australia. *Hydrobiologia* 197: 13-22.
- MacRae, T. H. and Pandey, A. S. (1991) Effects of metals on early life stages of the brine shrimp, *Artemia*. *Archives of Environmental Contamination and Toxicology*. 20: 247-252.
- Maffei, C., Muller, M. and Zarattini, P. (2002) Assessing anostracan (Crustacea: Branchiopoda) cyst bank size: An attempt at a standardized method. *Hydrobiologia* 486: 255-261.
- Maffei, C., Vagaggini, D., Zarattini, P. and Mura, G. (2005) The dormancy problem for Crustacea Anostraca: A rigorous model connecting hatching strategies and environmental conditions. *Ecological Modelling* 185: 469-481.
- Mann, A. W. (1982) Hydrogeochemistry and weathering on the Yilgarn Block, Western Australia - ferrolysis and heavy metals in continental brines. *Geochemica et Cosmochimica Acta* 47: 181-190.
- Marchant, R. and Williams, W. D. (1977) Population dynamics and production of a brine shrimp, *Parartemia zietziana* Sayce (Crustacea: Anostraca) in two salt lakes in western Victoria, Australia. *Australian Journal of Marine and Freshwater Research* 28: 471-438.
- Mattiske. (2000) Flora and vegetation survey of the proposed Bulong Evaporation Pond at Lake Yindarlgooda, Kalgoorlie. Mattiske Consulting Pty Ltd, Perth.
- McComb, A. J. and Qui, S. (1998) The effects of drying and reflooding on nutrient release from wetland sediments. In: Williams, W. D. (ed.), *Wetlands in a Dry Land: Understanding for Management*. Environment Australia Biodiversity Group, Canberra: 147-159.
- McMahon, T. A., Finlayson, B. L., Haines, A. T. and Srikanthan, R. (1982) *Global Runoff: Continental Comparisons of Annual Flows and Peak Discharges*. Catena, Cremlingen-Destedt, Germany.
- McMasters, K., Savage, A., Finston, T., Johnson, M. S. and Knott, B. (2007) The recent spread of *Artemia parthenogenetica* in Western Australia. *Hydrobiologia* 576: 39-48.

- McQuoid, M. R. and Hobson, L. A. (1996) Diatom resting stages. *Journal of Phycology* 32: 889-902.
- Meagher, D. and Fuhrer, B. (2003) Field guide to the mosses and allied plants of Southern Australia. Flora of Australia Supplementary Series No. 20. Australian Biological Resources Study (ABRS), Blackburn, Victoria.
- Mitchell, A. A. and Wilcox, D. G. (1994) Arid shrubland plants of Western Australia. University of Western Australia Press, Perth.
- Mitchell, A. and Baldwin, D. S. (1998) The effects of desiccation/oxidation on the potential for bacterially mediated P release from sediments. *Limnol. Oceanograph.* 43: 481-487.
- Mitchell, B. D. and Geddes, M. C. (1977) Distribution of the brine shrimps *Parartemia zietziana* Sayce and *Artemia salina* (L.) along a salinity and oxygen gradient in a South Australian saltfield. *Freshwater Biology* 7: 461-467.
- Morgan, K. H. (1993) Development, sedimentation and economic potential of palaeoriver systems of the Yilgarn Craton of Western Australia. *Sedimentary Geology* 85: 637-656.
- Morris, J. E. and Afzelius, B. A. (1967) The structure of the shell and other membranes in encysted *Artemia salina* embryos during cryptobiosis and development. *Journal of Ultrastructure Research* 20: 244-259.
- Mosisch, T. (2001) Effects of desiccation on stream epilithic algae. *New Zealand Journal of Marine and Freshwater Research* 35: 173-179.
- Muir, B. G. (1977) Biological Survey of the Western Australian Wheatbelt. Records of the Western Australian Museum. Supplement No. 3.
- Munksgaard, N. C. and Parry, D. L. (2002) Metals, arsenic and lead isotopes in near-pristine estuarine and marine coastal sediments from northern Australia. *Marine and Freshwater Research* 53: 719-729.
- Mura, G. (1991) SEM morphology of resting eggs in the species of the genus *Branchinecta* from North America. *Journal of Crustacean Biology* 11: 432-436.

- Mura, G. (2001) Morphological diversity of the resting eggs in the anostracan genus *Chirocephalus* (Crustacea, Branchiopoda). *Hydrobiologia* 450: 173-185.
- Mura, G. (2005) Cyst distribution and hatching pattern of *Chirocephalus ruffoi* (Crustacea, Anostraca) in an experimental undisturbed pool. *International Review of Hydrobiology* 90(3): 277-291.
- Newall, P. and Walsh, C. J. (2005) Response of epilithic diatom assemblages to urbanization influences. *Hydrobiologia* 532: 53-67.
- Newbey, B. J. (1996) Report on the Hooded-Plover Project. Supplement Western Australian Bird Notes 76.
- Newson, T. A. and Fahey, M. (2003) Measurement of evaporation from saline tailings storages. *Engineering Geology* 70: 217-233.
- Nichols, J. (2005) The ecology of *Ruppia* spp. in South Australia, with reference to the Coorong. A literature review. South Australian Research and Development Institute (Aquatic Sciences). SARDI Publication No. RD 04/0427-2., Adelaide.
- NLWRA. (2001) Australian dryland salinity assessment 2000: Extent, impacts, processes, monitoring and management options. National Land and Water Resources Audit. Land and Water Australia, Braddon, ACT, Canberra.
- Oren, A. (2001) The bioenergetic basis for the decrease in metabolic diversity at increasing salt concentrations: Implications for the functioning of salt lake ecosystems. In: Melack, J. M., Jellison, R. and Herbst, D. B. (ed.), *Developments in Hydrobiology, Salt Lakes*. Kluwer Publishers, The Netherlands.
- Oren, A. (2002) *Halophilic Microorganisms and their Environment*. Kluwer Academic Publishers, Dordrecht.
- Owino, A. O., Oyugi, J. O., Nasirwa, O. O. and Bennun, L. A. (2001) Patterns of variation in waterbird numbers on four Rift Valley lakes in Kenya, 1991 - 1999. *Hydrobiologia* 458: 45-53.
- Perrins, C. M. (1990) *The Illustrated Encyclopaedia of Birds*. Marchall Editions Developments Ltd, London.

- Peterson, L. R., Trivett, V., Baker, A. J. M., Aguiar, C. and Pollard, A. J. (2003) Spread of metals through an invertebrate food chain as influenced by a plant that hyperaccumulates nickel. *Chemoecology* 13: 103-108.
- Philippi, T. and Seger, J. (1989) Hedging one's evolutionary bets, revisited. *Trends in Ecology and Evolution* 4(2): 41-44.
- Pilgrim, A. T. (1979) Landforms. In: Gentilli, J. (ed.), *Western Landscapes*. University of Western Australia Press, Perth 49-87.
- Pinder, A. M., Halse, S. A., McRae, J. M. and Shiel, R. J. (2005) Occurrence of aquatic invertebrates of the wheatbelt region of Western Australia in relation to salinity. *Hydrobiologia* 543: 1-24.
- Porter, J. L. (2007) Contrasting emergence patterns of *Lamprothamnium macropogon* (Characeae, Charophyceae) and *Ruppia tuberosa* (Potamogetonaceae) from arid-zone saline wetlands in Australia. *Charophytes* 1(1): 19-27.
- Post, F. J. (1981) Microbiology of the Great Salt Lake North Arm. *Hydrobiologia* 81: 59-70.
- Qui, S. and McComb, A. J. (1996) Drying induced stimulation of ammonium release and nitrification in reflooded lake sediment. *Marine and Freshwater Research* 47(3): 531-536.
- Radke, L. C., Howard, K. W. F. and Gell, P. A. (2002) Chemical diversity in south-eastern Australian saline lakes I: Geochemical causes. *Marine and Freshwater Research* 53: 941-959.
- Radke, L. C., Juggins, S., Halse, S. A., De Deckker, P. and Finston, T. (2003) Chemical diversity in south-eastern Australian saline lakes II: Biotic implications. *Marine and Freshwater Research* 54: 895-912.
- RAOU. (2001) Western Australia Bird Notes. *Quarterly Newsletter of Birds Australia Western Australian Inc (a division of the Royal Australasian Ornithologists Union)* No. 98 (June 2001).
- Redfield, E., Barns, S. M., Belnap, J., Daane, L. L. and Kuske, C. R. (2002) Comparative diversity and composition of cyanobacteria in three

- predominant soil crusts of the Colorado Plateau. *FEMS Microbiology Ecology* 40: 55-63.
- Remigio, E. A. and Hebert, P. D. N. (2000) Affinities among anostracan (Crustacea: Branchiopoda) Families inferred from phylogenetic analyses of multiple gene sequences. *Molecular Phylogenetics and Evolution* 17(1): 117-128.
- Remigio, E. A., Hebert, P. D. N. and Savage, A. (2001) Phylogenetic relationships and remarkable radiation in *Parartemia* (Crustacea: Anostraca), the endemic brine shrimp of Australia: Evidence from mitochondrial DNA sequences. *Biological Journal of the Linnean Society* 74: 59-71.
- Reuter, J. E., Rhodes, C. L., Lebo, M. E., Kotzman, M. and Goldman, C. (1993) The importance of nitrogen in Pyramid Lake (Nevada, USA), a saline, desert lake. In: Hulbert, S. H. (ed.), *Saline Lakes*, V. Kluwer Publishers, The Netherlands.
- Rogers, C. (2002) The amplexial morphology of selected Anostraca. *Hydrobiologia* 486: 1-18.
- Rogers, R. W. (1982) Lichens of arid Australia. *Journal of Hattori Bot Lab* 53: 351-355.
- Rogers, R. W., Lange, R. T. and Nicholas, D. J. D. (1966) Nitrogen fixation by lichens of arid zone crusts. *Nature* 209: 96-97.
- Rogers, S. L. and Burns, R. G. (1994) Changes in aggregate stability, nutrient status, indigenous microbial populations, and seedling emergence, following inoculation of soil with *Nostoc muscorum*. *Biology and Fertility of Soils* 18: 209-215.
- Roshier, D. A., Robertson, A. and Kingsford, R. T. (1999) The availability of wetland habitat for waterbirds in arid Australia. Final report to the National Wetlands Research and Development Program. Environment Australia, Canberra.
- Roshier, D. A., Robertson, A. I. and Kingsford, R. T. (2002) Responses of waterbirds to flooding in an arid region of Australia and implications for conservation. *Biological Conservation* 106: 399-411.



- Roshier, D. A., Whetton, P. H., Allan, R. J. and Robertson, A. I. (2001) Distribution and persistence of temporary wetland habitats in arid Australia in relation to climate. *Austral Ecology* 26: 371-384.
- Round, F. E., Crawford, R. M. and Mann, D. G. (1990) The diatoms. Biology and morphology of the genera. Cambridge University Press, Cambridge.
- Sabbe, K., Verleyen, E., Hodgson, D. A., Vanhoutte, K. and Vyverman, W. (2003) Benthic diatom flora of freshwater and saline lakes in the Larsemann Hills and Rauer Islands, East Antarctica. *Antarctic Science* 15(2): 227-248.
- Salama, R. B. (1997) Geomorphology, geology and palaeo hydrology of the Salt River System, Western Australia. *Australian Journal of Earth Sciences* 44: 751-765.
- Salama, R., Otto, C. J. and Fitzpatrick, R. W. (1999) Contributions of groundwater conditions to soil and water salinization. *Hydrogeology Journal* 7: 46-64.
- Saros, J. E. and Fritz, S. C. (2000a) Nutrients as a link between ionic concentration/composition and diatom distributions in saline lakes. *Journal of Paleolimnology* 23: 449-453.
- Saros, J. E. and Fritz, S. C. (2000b) A review of evidence for nutrients as a mechanistic link between ionic concentration/composition and diatom distributions in saline lakes. *Journal of Paleolimnology* 23: 449-453.
- Saros, J. E. and Fritz, S. C. (2002) Resource competition among saline-lake diatoms under varying N/P ratio, salinity and anion composition. *Freshwater Biology* 47: 87-95.
- Savage, A. and Knott, B. (2004) Biogeography of the Australian brine shrimp family Parartemiidae. In: Proceedings of the 5th International Large Branchiopod Symposium. Toodyay, Western Australia. (Timms, B. V. and Knott, B.) (eds).
- Savage, A. (2004) Taxonomic revision of the Australian brine shrimp Family Parartemiidae. In: Proceedings of the 5th International Large Branchiopod Symposium. Toodyay, Western Australia. Timms, B. V. and Knott, B.(eds.)
- Schindler, D. E. and Scheuerell, M. D. (2002) Habitat coupling in lake ecosystems. *OIKOS* 98: 177-189.

- Segal, R. D., Waite, A. M. and Hamilton, D. P. (2006) Transition from planktonic to benthic algal dominance along a salinity gradient. *Hydrobiologia* 556: 119-135.
- Sergeev, V. and Williams, W. D. (1983) *Daphniopsis pusilla* Serventy (Cladocera: Daphniidae), an important element in the fauna of Australian salt lakes. *Hydrobiologia* 100: 293-300.
- Serventy, D. L. and Whittell, H. M. (1976) Birds of Western Australia. University of Western Australia Press, Perth.
- Shepard, W. D. and Hill, R. E. (2001) Anostracan cysts found in California salt lakes. *Hydrobiologia* 466: 149-158.
- Shepard, W. D. (1999) First record of fairy shrimp from Belize, and a comparison of cyst-shell morphology in the New World members of the *Streptocephalus sealii* species group (Anostraca: Streptocephalidae). *Journal of Crustacean Biology* 19(2): 355-360.
- Sherwood, J. E., Stagnitti, F., Kokkinn, M. J. and Williams, W. D. (1992) A standard table for predicting equilibrium dissolved oxygen concentrations in salt lakes dominated by sodium chloride. *International Journal of Salt Lake Research* 1: 1-6.
- Shiel, R. J. and Koste, W. (1986) Australian Rotifera: Ecology and biogeography. In: De Deckker, P. and Williams, W. D. (ed.), *Limnology in Australia*. CSIRO/Dr. W. Junk Publishers, The Netherlands: 141-150.
- Sim, L. L., Davies, J. A. and Chambers, J. M. (2006) Ecological regime shifts in salinised wetland systems. II. Factors affecting the dominance of benthic microbial communities. *Hydrobiologia* 573: 109-131.
- Simovich, M. A. and Hathaway, S. A. (1997) Diversified bet-hedging as a reproductive strategy of some ephemeral pool anostracans (Branchiopoda). *Journal of Crustacean Biology* 17(1): 38-44.
- Singer, M. (1999) Hooded Plover Report No. 2. Supplement to Western Australian Bird Notes 90.
- Slatkin, M. (1974) Hedging one's evolutionary bets. *Nature* 250: 704-705.

- Slater, P., Slater, P. and Slater, R. (2000) *The Slater Guide to Australian Birds*. National Direct Marketing Group, Australia.
- Smith, R. (2003) Existing approaches for sampling temporary waters for water quality. In: Workshop on water quality issues in final voids, salt lakes and ephemeral streams. Perth, Western Australia. (ACMER)(ed.). ACMER.
- Smith, R., Jeffree, R., John, J. and Clayton, P. (2004) Review of methods for water quality assessment of temporary streams and lake systems. Australian Centre for Mining Environmental Research, Kenmore, QLD.
- Smol, J. P. and Cumming, B. F. (2000) Tracking long-term changes in climate using algal indicators in lake sediments. *Journal of Phycology* 36: 986-1011.
- Stafford Smith, D. M. and Morton, S. R. (1990) A framework for the ecology of arid Australia. *Journal of Arid Environments* 18: 255-278.
- Stoermer, E. F. and Smol, J. P. (ed.) (1999). The diatoms: applications for the environmental and earth sciences. Cambridge University Press, Cambridge.
- Sugumar, V. and Munuswamy, N. (2006) Ultrastructure of cyst shell and underlying membranes of three strains of the brine shrimp *Artemia* (Branchiopoda: Anostraca) from south India. *Microscopy research and technique* 69: 000-000.
- Taukulis, F. E. and John, J. (2006) Diatoms as ecological indicators in lakes and streams of varying salinity from the wheatbelt region of Western Australia. *Journal of the Royal Society of Western Australia* 89: 17-25.
- Thiery, A. (1997) Horizontal distribution and abundance of cysts of several large branchiopods in temporary pool and ditch sediments. *Hydrobiologia* 359: 177-189.
- Timms, B. V. (1992) *Lake Geomorphology*. Gleneagles Publishing, Adelaide.
- Timms, B. V. (1997) A comparison between saline and freshwater wetlands on Bloodwood Station, the Paroo, Australia, with special reference to their use by waterbirds. *International Journal of Salt Lake Research* 5: 287-313.
- Timms, B. V. (1998) Further studies on the saline lakes of the eastern Paroo, inland New South Wales, Australia. *Hydrobiologia* 381: 31-42.

- Timms, B. V. (2001) A study of the Werewilka Inlet of the saline Lake Wyara, Australia - a harbour of biodiversity for a sea of simplicity. *Hydrobiologia* 466: 245-254.
- Timms, B. V. (2001) Large freshwater lakes in arid Australia: A review of their limnology and threats to their future. *Lakes and Reservoirs: Research and Management* 6: 183-196.
- Timms, B. V. (2002) The fairy shrimp genus *Branchinella* Sayce (Crustacea: Anostraca: Thamnocephalidae) in Western Australia, including a description of four new species. *Hydrobiologia* 486: 71-89.
- Timms, B. V. (2004a) The continued degradation of Lake Corangamite, Australia. In: Nihoul, J. C. J., Zavialov, P. O. and Micklin, P. P. (ed.), *Dying and Dead Seas - climatic versus anthropogenic causes*. Kluwer Academic Publishers, Netherlands: 307-319.
- Timms, B. V. (2004b) An Identification Guide to the Fairy Shrimps (Crustacea: Anostraca) of Australia. Cooperative Research Centre for Freshwater Ecology, Thurgoona.
- Timms, B. V. (2005) Salt lakes in Australia: Present problems and prognosis for the future. *Hydrobiologia* 552: 1-15.
- Timms, B. V. (2006) The geomorphology and hydrology of saline lakes of the middle Paroo, arid-zone Australia. *Proceedings of the Linnean Society of New South Wales* 127: 157-174.
- Timms, B. V. (2007) The biology of the saline lakes of central and eastern inland of Australia: A review with special reference to their biogeographical affinities. *Hydrobiologia* 576: 27-37.
- Timms, B. V. and Sanders, P. R. (2002) Biogeography and ecology of Anostraca (Crustacea) in middle Paroo catchment of the Australian arid-zone. *Hydrobiologia* 486: 225-238.
- Timms, B. V., Datson, B. and Coleman, M. (2006) The wetlands of the Lake Carey catchment, northeast Goldfields of Western Australia, with special reference to large branchiopods. *Journal of the Royal Society of Western Australia* 89: 175-183.

- Timms, B. V., Shepard, W. D. and Hill, R. E. (2004) Cyst shell morphology of the Fairy Shrimps (Crustacea: Anostraca) of Australia. *Proceedings of the Linnean Society of New South Wales* 125: 73-95.
- Tongway, D. J. and Ludwig, J. A. (1990) Vegetation and soil patterning in semi-arid mulga lands of eastern Australia. *Australian Journal of Ecology* 15: 23-34.
- Tongway, D. J. and Smith, E. L. (1989) Soil surface features as indicators of rangeland site productivity. *Australian Rangeland Journal* 11(1): 15-20.
- Townsend, S. A. and Gell, P. A. (2005) The role of substrate type on benthic diatom assemblages in the Daly and Roper Rivers of the Australian wet/dry tropics. *Hydrobiologia* 548: 101-115.
- Trotman, C. N. A. (1991) Normality and abnormality in early development. In: Browne, R. A., Sorgeloos, P. and Trotman, C. N. A. (ed.), *Artemia Biology*. CRC Press, Boca, Raton, Florida: 75-92.
- Turner, J. (1999) Surface hydrology of salt lake systems. In: Salt Lake Ecology Seminar, 7th July 1999. Perth, Western Australia. Centre for Land Rehabilitation, UWA.
- Turner, J., Barr, A. D., Challen, R. P., Johnson, S. L., Townley, L. R., Wright, K. D., Woodbury, R. J., Watson, G. D., Bartle, G. A. and Gailitis, V. (1996) Groundwater supply to the mining industry in the WA Goldfields. Minerals and Energy Research Institute of Western Australia. Report 154, Perth.
- Ullman, I. and Budel, B. (2003) Ecological determinants of species composition of biological soil crusts on a landscape scale. In: Belnap, J. and Lange, O. L. (eds), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag, Berlin Heidelberg: 203-213.
- Ungar, I. A. (1974) Inland halophytes of the United States. In: Reimold, R. J., and Queen, W. H. (eds), *Ecology of Halophytes*. Academic Press, New York: 235-306.
- van den Berg, M. and Coops, H. (1999) Stoneworts. RIZA Institut for inland water management and waste water treatment, Lelystad, the Netherlands.

- van der Graaf, W. J. E., Crowe, R. W. A., Bunting, J. A. and Jackson, M. J. (1977) Relict early Cainozoic drainages in arid Western Australia. *Zeitschrift fur Geomorphologie* 21: 379-400.
- van Etten, E. J. B. and Vellekoop, S. E. (2006) Response of fringing vegetation to flooding and discharge of hypersaline water at Lake Austin, Western Australia. In: International Society for Salt Lake Research, 9th Conference. 26th - 30th September 2005. Perth, Western Australia. John, J. (ed).
- Van Stappen, G. (2002) Zoogeography. In: Abatzopoulos, T. J., Beardmore, J. A., Clegg, J. S. and Sorgeloos, P. (eds), *Artemia: Basic and applied biology*. Kluwer Academic Pub., The Netherlands: 171-224.
- Varo, I., Amat, F., Navarro, J. C., Barreda, M., Pitarch, E. and Serrano, R. (2006) Assessment of the efficacy of *Artemia* sp. (Crustacea) cyst chorion as a barrier to chlorpyrifos (organophosphorus pesticide) exposure. Effect on hatching and survival. *Science of the Total Environment* 366: 148-153.
- Walter, M. R. (1976) *Stromatolites*. Elsevier, Amsterdam.
- WAM. (1992) *The biological survey of the Eastern Goldfields of Western Australia*. Western Australian Museum, Perth, Western Australia.
- Warren, S. D. and Eldridge, D. J. (2003) Biological soil crusts and livestock in arid ecosystems: Are they compatible? In: Belnap, J. and Lange, O. L. (ed.), *Biological Soil Crusts: Structure, Function, and Management*. Springer-Verlag Berlin Heidelberg: 401-416.
- Weekers, P. H. H., Murugan, G., Vanfleteren, J., Belk, D. and Dumont, H. (2002) Phylogenetic analysis of anostracans (Branchiopoda: Anostraca) inferred from nuclear 18S ribosomal DNA (18S rDNA) sequences. *Molecular Phylogenetics and Evolution* 25: 535-544.
- Weeks, S. C., Sanderson, T. F., Reed, S. K., Zofkova, M., Knott, B., Balaraman, U., Pereira, G., Senyo, D. M. and Hoeh, W. R. (2006a) Ancient androdioecy in freshwater crustacean *Eulimnadia*. *Proceedings of the Royal Society B-Biological Sciences* 273: 725-734.

- Weeks, S. C., Zofkova, M. and Knott, B. (2006b) Limnadiid clam shrimp distribution in Australia (Crustacea: Branchiopoda: Spinicaudata). *Journal of the Royal Society of Western Australia* 89: 155-161.
- Weston, M. A. and Elgar, M. A. (2000) The effect of a major rainfall event on Hooded Plovers on a salt-lake in Western Australia. *Emu* 100: 64-69.
- Wetzel, R. G. (1983) *Limnology*. Saunders College Publishing, USA.
- Williams, W. D. and Geddes, M. C. (1991) Anostracans of Australian salt lakes, with particular reference to a comparison of *Parartemia* and *Artemia*. In: Browne, R. A., Sorgeloos, P. and Trotman, C. N. A. (eds), *Artemia Biology*. CRC Press, Florida: 351-368.
- Williams, W. D. (1966) Conductivity and the concentration of total dissolved solids in Australian lakes. *Australian Journal of Marine and Freshwater Research* 17: 169-176.
- Williams, W. D. (1967) The chemical characteristics of lentic surface waters in Australia. In: Weatherley, A. H. (ed.), *Australian inland waters and their fauna*. Australian National University Press, 18-77.
- Williams, W. D. (1980) *Australian Freshwater Life: The invertebrates of Australian inland waters*. Macmillan Educational Australia, Pty Ltd, Melbourne.
- Williams, W. D. (1985) Biotic adaptations in temporary lentic waters, with special reference to those in semi-arid and arid regions. *Hydrobiologia* 125: 85-110.
- Williams, W. D. (1986) *Limnology, the study of inland waters: A comment on perceptions of studies of salt lakes past and present*. In: De Deckker, P. and Williams, W. D. (eds), *Limnology in Australia*. Dr. W. Junk Publishers, Dordrecht: 471-484.
- Williams, W. D. (1993) The Importance of Salt Lakes in Australia. *Search* 24(7): 197-200.
- Williams, W. D. (1998a) *Guidelines of lake management, Vol. 6. Management of inland saline waters*. International Lake Environment Committee, United Nations Environment Programme.

- Williams, W. D. (1998b) Salinity as a determinant of the structure of biological communities in salt lakes. *Hydrobiologia* 381: 191-201.
- Williams, W. D. (1998c) Biodiversity in salt lakes. In: McComb, A. J. and Davies, J. A. (eds), *Wetlands for the Future*. Gleneagles Publishing, Adelaide: 161-166.
- Williams, W. D. (2001) Anthropogenic salinisation of inland waters. *Hydrobiologia* 466: 329-337.
- Williams, W. D. (2005) Lakes in arid environments. In: O'Sullivan, P. E. and Reynolds, C. S. (eds), *The Lake Handbook*. Vol. 2. Lake Restoration and Rehabilitation. Blackwell Science, Oxford: 200-240.
- Williams, W. D. and Buckney, R. T. (1976) Chemical composition of some inland surface waters in south, western and northern Australia. *Australian Journal of Marine and Freshwater Research* 27: 379-397.
- Williams, W. D. and Buckney, R. T. (1976) Stability of ionic proportions in five salt lakes in Victoria, Australia. *Australian Journal of Marine and Freshwater Research* 27: 367-377.
- Williams, W. D. and Geddes, M. C. (1991) Anostracans of Australian salt lakes, with particular reference to a comparison of *Parartemia* and *Artemia*. In: Browne, R. A., Sorgeloos, P. and Trotman, C. N. A. (ed.), *Artemia Biology*. CRC Press, Florida: 351-368.
- Williams, W. D. and Kokkinn, M. J. (1988) The biogeographical affinities of the fauna in episodically filled salt lakes: A study of Lake Eyre South, Australia. *Hydrobiologia* 158: 227-236.
- Witkowski, A., Lange-Bertalot, H. and Metzeltin, D. (2000) *Diatom Flora of Marine Coasts I. Volume 7*. Koeltz Scientific Books, Königstein, Germany.
- Zeng, H., Wyrwoll, K. H., Zhengxiang, L. and Mac Powell, C. (1998) Onset of aridity in southern Western Australia - a preliminary palaeomagnetic appraisal. *Global and Planetary Change* 18: 175-187.



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