Department of Environmental Biology

The Distribution Pattern of Algal Flora in Saline Lakes in Kambalda and Esperance, Western Australia

Michelle Anne Handley

This thesis is presented for the Degree of
Master of Science
of
Curtin University of Technology

August 2003

Declaration

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

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.

Signature: ..

Date: 28/8/03

ABSTRACT

The study has attempted to characterise the physicochemical limnology and distribution of algal flora of two salt lake systems in Western Australia, one from the coastal Esperance region and the other from the inland Kambalda region. Climatic conditions, water regimes and physicochemistry were found to differ markedly between the two lake systems and a total of 171 algal taxa, representing five divisions, were recorded. Of these, 82 were members of Bacillariophyta, 48 of Cyanophyta, 33 of Chlorophyta, two of Euglenophyta and six of Dinophyta.

The physical limnology of salt lakes in the Esperance region was seasonally variable, defined by climatic conditions. As such, the lakes investigated in the region exhibited a stable cycle of filling during winter and spring, and drying out in summer. Four of the lakes in the region could be classified as near-permanent, and one as seasonal on the basis of predictability and duration of filling. Seasonal fluctuations in water depth resulted in fluctuations in salinity levels. Salinity levels ranged from subsaline to hypersaline, and all the lakes in the region were alkaline. In addition, the lakes were well mixed in terms of oxygen and temperature, and were impacted by eutrophication from their catchments. They were either mesotrophic or eutrophic with respect to both nitrogen and phosphorus. In geological terms, lakes in the Esperance region were separated only recently from the ocean, and two lakes retain a connection with marine waters, one through a creek during years of high rainfall and one through hydrological interactions with groundwater of marine origin.

In general, the algal communities of lakes in the Esperance region were similar to those of other Australian coastal salt lakes. Diatoms and cyanobacteria were dominant in all lakes except the most eutrophic, Lake Warden, in which benthic green algae were most abundant. All algal species recorded were known for their wide geographic distribution and their distribution in Australian coastal waters. Characteristically coastal diatom species included *Achnanthes brevipes*, *Achnanthes coarctata*, *Achnanthes lanceolata* var. *dubia*, *Achnanthidium cruciculum*, *Campylodiscus clypeus*, *Cyclotella atomus*, *Cyclotella meneghiniana*, *Cyclotella striata*, *Mastogloia elliptica*, *Mastoglia pumila*, *Nitzschia punctata* and *Thalassiosira weissflogii*.

The inland salt lakes of the Kambalda region form part of an extensive palaeodrainage system, and were much less predictable in terms water regime than lakes in Esperance. Water depth was determined by seasonal variability in rainfall and evaporation, and by summer cyclonic rainfall events that were unreliable from year to year. In addition, rainfall varied spatially within the region. As such, most lakes were classified as intermittent. Two lakes in the region were not classified on the basis of water regime as they were too highly impacted by mining activities including water diversion and impoundment, water extraction and discharge of groundwater. Salinity varied in accordance with drying and filling cycles in the lakes except the most

hypersaline as the volume of water received during rainfall events was insufficient to dilute the extensive surface salt crusts they each supported when dry. Salinities recorded in the region ranged from subsaline to hypersaline, and ionic compositions exhibited the same spectrum as seawater. Calcium levels were significantly higher than in lakes from the Esperance region due to weathering of calcium rich sediments, and pH ranged from weakly acidic in the most hypersaline lakes to alkaline in the least saline lakes. All were well mixed in terms of oxygen and temperature.

Kambalda salt lakes support distinctive algal communities dominated by diatoms and cyanobacteria that are adapted to intermittent water regimes, extended periods of desiccation and variable salinity. Not surprisingly then, none of the algal taxa recorded from the region were regionally restricted, all noted previously in the literature to have wide geographic distributions, and to be tolerant of a range of physicochemical conditions.

Canonical correspondence analysis showed that, of the physicochemical parameters that were investigated in this study, both salinity and pH interacted in determining algal community structure. Both of these attributes were correlated with water depth, which varied according to climatic conditions in a seasonal drying and filling cycle.

The general relationship between species richness and pH and salinity, and species diversity and pH and salinity was simple and linear; with increasing pH and salinity, species diversity and species richness decreased. What was less simple, and non-linear, was the nature of the relationship between species richness and diversity and salinity within more narrowly defined ranges of salinity. As salinity increased from <1ppt to 30ppt there was a dramatic reduction in species richness and diversity, then, as salinity increased from 30ppt to 100ppt the rate of decrease slowed. Between 100ppt and 250ppt there was almost no relationship between salinity and species richness and species diversity, but after 250ppt both species diversity and species richness declined markedly.

ACKNOWLEDGEMENTS

I would like to take this opportunity to acknowledge those people who without their advice, expertise and encouragement this study would not have been undertaken and completed.

Firstly I acknowledge my supervisor Associate Professor Jacob John for his guidance and his willingness to share his time and expertise to train me. I also thank him for his unwavering belief that I would complete this study.

It is for this that I would also like to acknowledge the Department of Environmental Biology. This thesis is a testament to their ongoing commitment to their postgraduate students.

Thanks to Mr Jim Lane, of the Department of Conservation and Land Management, and Mr Colin Woolard for their financial contribution to the water analysis component of this work and for their interest in the results.

I'd also like to thank my ex office-mate and long time friend Stuart Helleren for his input and enthusiasm. Similarly, thanks to my husband, Greg and my mum, Jean whose willingness to help with anything I asked, be it carrying a boat into a salt lake at 4am in winter, dodging tiger snakes in samphire marsh or checking formatting page by page, contributed so much.

Finally I would like to acknowledge my father and grandfather. Both of these men live their lives with courage and commitment. This is what it took for me to complete this study and they provided a daily reminder of this. I dedicate this thesis to them.

TABLE OF CONTENTS

List of Figures

List of Tables

1.0 INTRODUCTION

Salt lakes present an array of physical, chemical and biological diversity in basins throughout every continent of the world. In terms of absolute volume and percent of total water of the biosphere, they are almost as significant as freshwater lakes (Williams, 1993a). But how does one define a salt lake and under what circumstances do they form and persist?

The lower concentration boundary of what constitutes a salt lake is not easy to define. Nonetheless, the suggestion of such a boundary, though arbitrary, is useful. Beadle (1974) discussed possible criteria for distinguishing fresh from saline waters and chose the boundary at about 5ppt dissolved solids, based principally on biological tolerance. Williams (1982; 1998) regarded salt lakes as those with concentrations of total dissolved solids greater than 3ppt. The latter value has received considerable acceptance (Mianping, 2001) and has been adopted for use in this thesis.

The concentration range reported by Hammer *et al.* (1983) for classification has been used herein to further define salt lakes on the basis of salinity. That is, hyposaline at 3 to 20ppt, mesosaline at 20 to 50ppt, and hypersaline at >50ppt. Concentrations below 3ppt are referred to as subsaline and may include fresh waters. Such a classification system is useful to distinguish between the vast array of composition and concentration ranges encountered in salt lake environments.

The prominence of salt lakes in Australia occurs primarily as a function of climatic aridity, almost 70% of the continent is arid or semi-arid, and topography. The majority are temporary in terms of water regime, impacted not just by Australia's low rainfall but also by the highly variable nature of precipitation and runoff. The variability of rainfall patterns in Australia increases as distance inland from the coast increases (John, 2002). As such, the spatial and temporal distribution of water in Australian salt lakes is uneven, particularly in inland regions.

At the individual lake scale, the exact reason for the existence and physicochemical characteristics of any given salt lake is often a combination of unique local features of the climate and landscape (Paijmans *et al.*, 1985). In Australia, most occur in hydrologically closed basins, since their formation is often dependent on a balance between water inputs and outputs (Evans, 1993). Water inputs include rain, inflowing rivers and groundwater while evaporation, outflowing groundwater and regulated or man-made outflows are the primary sources of water loss from salt lakes. Water inputs from inflowing rivers can range in duration from minutes to months as rain-fed flood events flow quickly down dry drainage lines to terminal lakes, or traverse many hundreds of kilometres in large drainage basins (Roshier *et al.*, 2001).

Salinity, solute composition and habitat stability collectively play a key role in shaping the distribution of biota inhabiting saline lakes (Herbst, 2001). Because salt lakes are enriched in dissolved solids, salt lakes exclude many biological groups. Many organisms can not osmoregulate in such waters (Oren, 2001). Biota is further excluded by the temporary nature of most salt lakes, in which case water is a limiting factor. Because of this habitat unreliability, salt lakes are thought to be poor evolutionary loci, a hypothesis supported by the presence of widely dispersed species and few endemics (John, 1999; Timms, 2001).

It should not be assumed, however, that salt lakes are unproductive. They can be highly productive and often support a distinctive flora and fauna. Given their biological significance, and the prevalence of salt lakes in Australia, it is surprising then that comprehensive information detailing the limnology of Australian salt lakes, particularly those in Western Australian, is not prevalent (Roshier et al., 2001; Williams, 2001).

It is for these reasons that two lake systems in Western Australia were selected for investigation in this study. Both lake systems were located at a similar latitude but one was located on the coast at Esperance and thus was exposed to higher, more reliable seasonal rainfall than the other, located further inland in the Kambalda region. As such, the latter experienced lower and less predictable rainfall events. Few of the lakes of these two systems had been the subject of limnological studies previously so this study has provided baseline information on both the physicochemical and algal flora characteristics of salt lakes in these two regions. It has also provided preliminary information on the influence of selected environmental parameters, particularly water depth, salinity and pH, on the distribution pattern of salt lake algal flora in Western Australia.

1.1 Salt Lake Values

The contribution of salt lakes to biodiversity of the biosphere has, for many years, been undervalued and they have been the subject of far fewer extensive studies on their hydrology, geochemistry, sedimentology and biology than their freshwater counterparts. Instead, salt lakes have commonly been viewed as environmental wastelands, devoid of life, and severely lacking in aesthetic appeal. Like other aquatic environments, they do, however, possess a variety of economic, cultural, recreational, educational, scientific, and ecological values based on the benefits of their functions, uses and attributes (see Table 1).

The scientific values of salt lakes are of most relevance to an ecological study such as this one. Ecologists have stressed that in order to understand fully the biosphere, whole ecosystems must be studied, not merely components of them (Walker, 1973). Typically, however, ecosystems are so complex that comprehensive studies are extremely difficult. An alternative is to investigate less complex systems. Salt lake ecosystems offer such loci in an aquatic setting (Williams, 1993a).

Table 1: Values commonly recognised in association with salt lakes (from Jensen, 1993; Agriculture WA *et al.*, 1996; Kingsford and Halse, 1998; Mianping, 2001).

Values		
Functions	Uses	Attributes
Groundwater recharge Groundwater discharge Nutrient retention Flood control (including reduction of soil erosion during storms) Sediment/toxicant retention Food chain support Wildlife habitat Active recreation	Floral and faunal resources Fisheries and aquaculture Forage resources Agricultural resources Water supply Mineral resources eg. salt, zeolites, lithium, borax, gypsum and uranium Resource for education and scientific study across a range of disciplines including geology, geochemistry, ecology, physiology, evolution, palaeolimnology and other biological studies	Biological diversity Uniqueness to culture Landscape integrity

Salt lakes exhibit greatly reduced species diversities compared with those of freshwater ecosystems and, because most are situated in a hydrologically closed basin, they are perhaps more discrete than any other ecosystem of similar size (Eugster and Hardie, 1978). Further, their substrata is often uniform across the lake and their waters are mostly shallow and well mixed by wind action when they are full (Timms, 2001). As such, they exhibit minimal vertical or horizontal stratification of physical, chemical or biological parameters (Blinn, 1995). On a seasonal or annual basis, however, they may exhibit hydrological and chemical heterogeneity. For example, during periods of high rainfall they may fill to maximum depth, and reach their lowest salinity, and progressively dry out as rainfall reduces. Salinity may increase as the lake dries. Changes in species composition may occur in response to these hydrological and chemical changes (Boulton and Brock, 1999).

The inverse correlation between salinity and species diversity has long been recognised (Bayly and Williams, 1966; Blinn, 1993; John, 2002; Williams, 1981). Williams *et al.* (1990) remind us, however, that while this relationship is so over the total range of salinity it becomes less significant over intermediate ranges of salinity. It should be kept in mind that once a salt lake species "solves" the problem of osmoregulatory stress, it is often able to occupy a wide salinity range within which it is subjected to biotic and abiotic parameters that are not direct functions of salinity. Ecological stresses other than salinity *per se* can determine which species will persist. While physical and chemical factors exert primary control on community composition in saline waters, biological factors such as interspecific competition and degree of predation also influence species distribution and abundance (Colburn, 1988; Masojidek, 2001).

For most living organisms salt lakes are hostile, physiologically stressing parts of the biosphere. High and variable salinity, high surface light intensity and temperature, temporary water regimes, and lowered oxygen tension all provide difficulty (Brock, 1986). Clearly, numerous plants and animals have solved such difficulties and it is the nature of these solutions that is of interest to both ecologists and physiologists.

Part of this increasing interest lies in the basic science of the mechanisms of adaptation to high salinity. Halophilic and salt-tolerant microorganisms do not adapt to high external solute concentrations by actively maintaining much lower internal concentrations. Rather, they maintain internal osmolar conditions equivalent to the external ones, but use solutes that permit intracellular processes to function (Oren, 2001). Investigation of such "compatible solutes" has culminated in the commercial exploitation of a number of species, including the alga *Dunaliella salina* (Post *et al.*, 1983).

Salt lakes are also of interest to biogeographers. The discrete, simple, and generally temporary nature of salt lake ecosystems in inland Australia, for example, means that salt lakes in these regions are essentially "immature" ecosystems. As such *"they contain a high proportion of opportunistic and fugitive species, and species with shallow survivorship curves on which, consequently, natural selection will act most strongly in the early phases of life. The result is that evolution proceeds much more rapidly for such species than it does for most vertebrates (upon which many evolutionary studies are based)"* (Williams, 1981).

Another feature of salt lakes that makes them of interest to science is that their biota responds quickly to changes in climate, effectively acting as sensitive recording devices of climatic change (Evans, 1993). A change in annual cloud cover over a lake, for example, will have a direct impact on the hydrological regime of the lake since it controls the evaporation - precipitation ratio. This affects its water chemistry, salinity and biota (Evans, 1993). Salt lakes can, therefore, be viewed as a window through which one can look to interpret the past, through the study of palaeolimnology.

Palaeolimnology arms us with a diagnostic tool with which we can extend beyond the limits of one observer's experience, allowing us to introduce the dimension of time in to our investigations of why things are as they are (De Deckker, 1988). In many regions of the world, lake sediments contain a "library" of information applicable to many environmental management questions, especially those that are anthropogenically induced. The validation of climatic models is one current application of palaeolimnological information (Blinn, 1995).

1.2 Geographical Occurrence

Salt lakes occur on all continents and, in terms of total inland biosphere water, constitute a volume of at least $104 \times 10^3 km^3$, which corresponds to approximately 0.008%. These figures are marginally smaller that those estimated for freshwater lakes, which have been estimated to be $125 \times 10^3 km^3$ or 0.009% (Vallentyne, 1972). They commonly occur in dry regions but salt lakes are not simply confined to the inaccessible fringes of the desert. About 40% of the total land area of the world is either arid or semi-arid, and over 500 million people live in regions where salt lakes are a common feature of the landscape (Williams, 1993a).

A brief sketch of salt lake occurrence on each continent is presented below. Individual salt lakes, or salt lake systems, that have been the subject of much limnological interest are highlighted to illustrate the range of salt lakes that occur, the range of conditions in which salt tolerant and halophilic algal flora persist and to provide a context for salt lakes in Australia.

1.2.1 South America

South America has many salt lakes, located in a variety of regions, on which little biological work has been completed (Servant-Vildary and Roux, 1990). Physical attributes such as stratigraphy, geochemistry, clay neoformation, hydrobiology and geocryology have been the subjects of more interest but salt lakes in South America remain an "unknown environment", particularly from a biological perspective.

1.2.2 North America

Saline lakes are common in North America. They are particularly prevalent in a number of States in the western half of the United States and the western Provinces of Canada. Studies on Canadian salt lakes are relatively few (Hammer *et al.*, 1983), although detailed studies have been carried out on lakes in Alberta and Saskatchewan (Hammer et al., 1990). Salt lakes in the United States have received more attention.

The Great Salt Lake (Utah) is one salt lake in Northern America that is of particular geographical importance. It is the fourth largest terminal lake in the world (Stephens, 1990) and is thought to be the remnant of a much larger precursor, Lake Bonneville, which was first studied by Gilbert in 1890 (Eugster and Hardie, 1978). The limnology of the Great Salt Lake has been altered considerably by the construction of a causeway in 1959 which effectively divided the lake into two ecologically distinct lakes. This division occurred as a result of changes to the lake's water regime and circulation pattern. Such physical and chemical changes have resulted in marked changes in the biological community of the lake (Oren, 2002). Obligate halophiles such as *Dunaliella salina* and *D. viridis* have, for example, been replaced by opportunistic algal forms such as *Nodularia spumigena*.

1.2.3 Asia

Asiatic salt lakes occupy a vast endorheic area which extends from a longitude above the Black Sea to eastern Mongolia. Smaller endorheic drainage basins within the vast semi-arid region to the south also feature many salt lakes (Williams, 1981). The world's largest salt lake, the Caspian Sea, occurs in Asia, covering an area of 422 000 km^2. The Aral Sea is also of significant proportion, covering 33 500 km^2 (Williams, 1993a). Salt lakes on the Sinai Peninsula or solar salt ponds in India have been the subject of much limnological interest, with Solar Lake (Sinai Peninsula) in particular receiving considerable focus (Williams, 1981).

Solar Lake is an extremely small (50m x 140m), shallow (4-6m), sea-marginal pond with an approximate salinity range of 60ppt to 180ppt (Cohen *et al.*, 1977a). The lake itself consists of a body of water subject to density stratification, intense solar heating, high evaporation rates, and complex and intense microbial interactions in the water column, on the benthos and in the sediments (Cohen *et al.*, 1977b,c). A total of 149 species have been recorded from Solar Lake (Hirsch, 1980). Of these, 81% were prokaryotes. The eukaryotes were represented by diatoms, flagellates, non-flagellated algae and ciliates. Four different types of microbial mat have also been reported from the lake. Wilbert and Kahan, 1981 (in Javor, 1989) described a shallow flat mat and a pinnacle mat, both of which occur down to the lower boundary of the epilimnion. Krumbein *et al.* (1977) and Jorgensen *et al.* (1983) detailed the morphology, species composition and location of a further two types of mat; deep flat mats and gelatinous or flocculose mats.

1.2.4 Europe

Europe's temperate climate and topographical features do not produce the large endorheic basins that are so characteristic of other continents such as Asia, Africa and Australia. Southern Russia, which drains into the northern end of the Caspian Sea, is one exception. Salt lakes are, however, not uncommon in Europe. They often feature in local endorheically drained areas, as waters overlying salt deposits, and as anthropogenetically induced saline ponds (Williams, 1981).

Literature on European salt lakes is scattered and dates back from the last century. There has, however, been an increase in interest in Spanish salt lakes; the extent of limnological data increasing markedly since 1981 (Comin and Alonso, 1988). Part of the impetus for this increase has been the importance of Spanish salt lakes as a modern day stepping stone for bird migration. Salt lakes on the Iberian Peninsula, for example, act as a 'land bridge' for migratory birds on the way down to Africa and back again to Europe in summer (Baltanas *et al.*, 1990).

1.2.5 Africa

Salt lakes are widely distributed in Africa (Seaman *et al.*, 1991). They feature prominently in the topography of the arid northern and southern belts, and in the dry savannah that separates them. Saline lakes also commonly occur in the humid equatorial tropics and in two Rift Valleys; including all of the Great Lakes of eastern Africa.

While salt lakes in northern Africa were among the first lakes to be investigated comprehensively in the African continent, it is the salt lakes of the East African Rift Valleys that have received most focus. This region contains about two dozen closed basin lakes, stretching from Ethiopia to Kenya and Tanzania. Some are fresh but most are saline (Melack, 1981). Those fed by underground seepages through soluble carbonatite volcanic rocks have become highly saline, and enriched with sodium carbonate-bicarbonate (Beadle, 1974). Despite containing surface waters of high osmotic pressure, high pH and an unusual ionic balance, these shallow soda lakes have been reported to be amongst the most productive ecosystems in the world (Tudorancea and Harrison, 1988; Wood and Talling, 1988).

1.2.6 Antarctica

The Antarctic climate is severe. It features elements such as extreme seasonal range in solar radiation levels, low temperature, low humidity, sand abrasion and freeze-thaw cycles (Quesada *et al.*, 2001). Salt lakes occur in several areas that remain ice-free all year, although some are covered in a thick, and sometimes permanent ice cover. Most occur in the Vestfold Hills, in dry valleys in South Victoria land, on Ross Island and around Lutzow-Holm Bay (Burton, 1981). Four classes of salt lake have been reported to persist in Antarctica; those produced by the evaporation of freshwater, ectogenic meromictic lakes, seawater isolated by relative sea level changes, and lakes produced by volcanic activity.

Antarctic salt lakes support algae and other organisms in, at times, large populations (Laybourn-Parry and Marchant, 1992). The range of species is however much smaller than in lakes of similar salinity in temperate regions. The blue-green algae Oscillatoriaceae, especially species of *Oscillatoria* and *Phormidium* are particularly dominant in Antarctic lakes of moderate salinity. They are not, however, present in hypersaline lakes, unlike the cyanobacteria of temperate regions. Green algae are poorly represented. *Dunaliella* has been reported only from hypersaline lakes, although the genus *Chlamydomonas* is widely represented. *Prasiola* and *Pleurococcus* have also been recorded. Pennate diatoms far outweigh the centric diatoms in abundance and number of genera represented, the families Naviculaceae and Achnanthaceae being dominant (Wright and Burton, 1981).

1.2.7 Australasia

While saline lakes are rare in New Zealand they are widespread in Australia (Williams, 1981). Despite the dubious distinction of being the most waterless continent, salt lakes are a prominent part of the Australian landscape, occurring in every State, particularly in semi-arid areas in Western and South Australia, and on the volcanic plains of western Victoria (Geddes et al., 1981). Salt lakes are so abundant in the inland Eastern Goldfields region in Western Australia, for example, that the region has been labelled *"Salinaland"* (Gentilli, 1979; John, 1999).

Of the salt lakes described in the literature from Australia, Lake Eyre is one of the best-known (Lothian and Williams, 1988). Lake Eyre is the largest inland salt lake in Australia (1.14 x 10^6 km^2 in area) and the largest temporary lake in the world. It is most often dry but periodic floods (only four this century) fill the lake with varying amounts of water (Paijmans *et al.*, 1985). Water is received from a vast network of temporary streams draining one sixth of Australia; including large parts of South Australia, Queensland, and the Northern Territory (Blinn, 1991).

The expansive lake system is divided into two sections, a large northern part, Lake Eyre North, and a smaller southern lake, Lake Eyre South. During the rare flood events that occur Lake Eyre North tends to have a thin sheet of water over its surface which is easily driven by wind from one part of the lake to another, while Lake Eyre South is a saline marsh. When present, water is always saline with values ranging from <25ppt to >250ppt (Blinn, 1991). Despite the predominance of sodium chloride in the lake's water, the dominant evaporite minerals in the lake are gypsum and halite. The salt composition is different from the ocean and from inflowing water, which is thought to be a reflection of the complex history of contributions from the underlying basin materials and windborn salts (Javor, 1989).

Most previous work on the Lake Eyre system has dealt with physicochemical and geological features. Only limited attention has been given to the algal flora (Blinn, 1991). A study conducted by Williams and Kokkinn (1988), after the 1984 filling of Lake Eyre, addressed the assumed lack of importance of episodically filled salt lakes as evolutionary loci for invertebrates. It was concluded that since most species in the lake were widely dispersed, rather than endemic, this assumption was found to be valid.

Salt lakes are also common features of coastal environments. In Australia, they are often geologically younger than inland salt lakes, forming as a result of recent sea level changes (CALM, 1997; Moore, 1991). Distinctive biological elements described from a number of coastal hypersaline lake environments in Western Australia include the presence of thick algal mats and microbialite structures constructed by cyanobacteria and diatoms. These benthic microbial communities do occur in some inland salt lakes in Western Australia, but extensive structures have been described from lakes along the coastline from Lake Clifton (Moore, 1993), to Rottnest Island (Playford, 1988), to Cervantes (Grey *et al.*, 1990), to Shark Bay (Bauld, 1986).

To form such organosedimentary features, a combination of microbial activity and sediment deposition must occur. The resultant structure is usually laminated, reflecting vertical stratification of both the physiological attributes of microbial components and the associated physicochemical regimes. They include variations in the frequency and extent of sediment input, and may also reflect growth or tactic responses of the constructing microorganisms (Bauld, 1986).

The microbialites of Lake Clifton occupy the largest area reported ($4km^2$) outside of Hamelin Pool at Shark Bay. The lake occurs in an interdunal depression between a series of linear coastal boundaries that formed as a result of repeated sea level changes between 3000 and 6000 years BP, and is located 100km south of Perth on the western edge of the Swan Coastal Plain (Moore, 1991). By far the most abundant cyanobacterium within the microbialites of Lake Clifton is *Scytonema* sp. Other cyanobacteria include *Oscillatoria* sp., *Dichothrix* sp., *Chroococcus* sp., *Gloeocapsa* sp., *Johanesbaptistia* sp., *Gomphosphaeria* sp. and *Spirulina* sp. Pennate diatoms are also particularly numerous (Moore, 1993).

1.3 Objectives

Recognising that the prominence of salt lakes in Australia, and their contribution to national biodiversity, has not been reflected in the level of limnological interest accorded them in the literature, particularly at the time this investigation was initiated in 1992 (Roshier et al., 2001; Williams, 2001), the primary objective of this study was to provide baseline limnological information on selected salt lakes on the coast in the Esperance region and inland in the Kambalda region of Western Australia. In doing so this study sought specifically to address the following aims:

1. To characterise five coastal temporary salt lakes in the Esperance region and eight inland temporary salt lakes in the Kambalda region in terms of physicochemical properties and algal flora.

2. To compare and classify the above coastal (Esperance) and inland (Kambalda) lake systems on the basis of the distribution pattern of algal flora.

3. To relate the distribution pattern of algal flora to selected environmental parameters in the above coastal (Esperance) and inland (Kambalda) lake systems.

2.0 AUSTRALIAN SALT LAKES – AN OVERVIEW

2.1 Physical Limnology

Limnology, as defined by Williams (1986a), is the study of athalassic (non-marine) waters, fresh or saline, and includes both biological and physicochemical components. The majority of physicochemical information collected from salt lakes in Australia is fragmentary, based upon observations made at one time of the year only. This is largely insignificant with respect to ionic proportions since they remain almost constant despite seasonal changes in solute concentration (Williams, 1985). There is however a suite of environmental parameters, the wide fluctuation and extremity of which, are intrinsic elements of Australian saline lakes. It is imperative that these more dynamic parameters be recorded on more than one occasion (Herbst, 2001).

2.1.1 Chemical Variation

The influence of salinity on the biota of salt lakes, over its total range, is immense and is compounded by the extreme variability most salt lakes exhibit, since most Australian salt lakes are not permanent. The salinity of these lakes can approach saturation when the water has nearly dried, and usually exhibits pronounced seasonal variation (Oren, 2001). It has long been recognised that salinity and species diversity, and species richness, are inversely correlated (John, 2002; Williams, 1998). This relationship is reported to be less significant over an intermediate salinity range (Williams *et al.*, 1990).

Most Australian athalassic saline waters are dominated by ions similar to those of sea water. The cationic order of dominance is usually Na > Mg > K > Ca, whilst the anionic order is commonly Cl > SO_4 > HCO_3 (Hart and McKelvie, 1986; Williams and Buckney, 1976a and b; Williams, 1986b). Sometimes the positions of K and Ca are transposed as are those of SO_4 and HCO_3 (Williams, 1981). The ionic dominance of salt lakes that lie within the volcanic plains of eastern Australia can be more variable due to weathering and leaching of solutes from surrounding volcanic rocks (Gell, 1997).

Relict marine deposits, or connate salts, are the major source of salts in Australian salt lakes (De Deckker, 1983). Atmospherically transported oceanic salts and groundwater of marine origin may also contribute (Javor, 1989). Water with ionic deviations from the 'norm' are likely to have arisen from either evaporative concentration and selective precipitation of certain salts or weathering of catchment rock strata (Williams, 2001). Climatic aridity has diminished the influence of the latter in the Australian landscape.

The pattern of ionic dominance is ecologically significant, since some sort of balance between monovalent and divalent ions is usually essential for the proper functioning of a wide variety of cellular tissues. The toxic effects of an excess of one ion or group of ions is offset, in ionically balanced surface waters, by an adequate amount of another (Oren, 2001).

Individual cations and anions can also influence salt lake ecology. Sodium, for example, has a major impact on the salinity of Australian salt lakes (Rayment and Higginson, 1992). It is usually present in excess of biological requirements, and imposes considerable osmotic stress on aquatic biota, though nitrogen metabolism in blue-green algae may benefit from additional quantities, as may phosphorus uptake in some phytoplankton and macroalgae species (Clavero *et al.*, 1990).

Whilst the aforementioned ions give the overall chemical stamp to Australian saline waters, many others occur, some of which are of greater biological importance. These include silicate, trace elements such as Mn, Cu, Zn, Co, and Mo, and organic complexes (Round, 1981). Dissolved silica (silicic acid: H_2SiO_4) in particular has the potential to significantly influence the productivity and succession of algal populations in salt lakes (Egge and Aksnes, 1992).

Diatoms, which are often dominant constituents of salt lake algal flora, utilise large quantities of dissolved silica in the construction of their cell walls or frustules. Consequently dissolved silica has the potential to regulate the success of diatoms although the converse can also occur with diatoms having the capacity to modify dissolved silica concentration (Royle and King, 1992). Other forms of silicate, such as colloidal silica and clays, play a physicochemical role, providing sorption sites for phosphate and ammonia thus influencing the cycling of these nutrients in aquatic ecosystems.

The pH of the vast majority of Australian athalassic saline waters lies within the range 4.0-10.0 but the biological and ecological importance of pH *per se* seems not to be very great (Gell, 1997). Blinn (1995) suggests that it has been overemphasised as an ecological factor, stressing that caution should be exercised in attributing observed distribution or abundance of biota to pH. This does not mean that pH should be excluded from a study such as this one. It frequently gives a clue to the existence of other factors that may be highly significant and exerts some control over the chemical state of many lake nutrients, including carbon dioxide, phosphate, ammonia, iron, and trace metals. The solubility of particulate amphorous silica for example is inversely related to pH at values between 3 and 7, increasing somewhat at alkaline values to a pH of 9.

2.1.2 Surface Water Temperature and Dissolved Oxygen

The direct influence of temperature on the primary productivity of many Australian saline waters is reduced somewhat, since many are too shallow to support thermal stratification, which is often of more significance than absolute temperature. Attention has been drawn, however, to the high temperatures that can be reached in some Australian salt lakes (from 31.5°C to in excess of 45°C). Such temperatures may approach the lethal limits for aquatic biota. Similarly, high sediment temperatures may be of consequence to the survival of encysted eggs or other resistant bodies of temporary salt lake biota when lakes are dry (Oren and Seckbach, 2001).

Temperature is also the single most important factor regulating the concentration of dissolved oxygen (DO), which in a terrestrial environment is not usually limiting but is frequently a limiting factor of major importance in an aquatic environment (Nishri and Ben-Yaakov, 1990). The solubility of oxygen increases with decreasing temperature and salinity, and also depends on pressure (Stephens, 1990). The influence of salinity on oxygen solubility is of profound ecological significance largely since salts dissolved in water reduce the intermolecular space available for oxygen. Bayly and Williams (1974) suggest that the upper limit of tolerance of some aquatic organisms may actually be determined more by decreasing availability of oxygen than by increasing osmotic stress imposed by salinity.

Dissolved oxygen levels are also influenced by photosynthesis, respiration, aeration, the presence of other gases and any chemical oxidation that may occur (Round, 1981). When photosynthesis is occurring at a high rate, oxygen production may exceed the diffusion of oxygen out of the system and bubbles from supersaturation (ie. levels for percentage saturation in excess of 100) may result. The very presence of this high production has the opposite effect at night when respiration by the same organisms may lower oxygen levels appreciably. Hence enormous diurnal fluctuations in oxygen saturation can occur as a result of photosynthesis and respiration (Beutel, 2001). Because of heterotrophic respiration, the oxygen in sediments of temporary salt lakes during the dry phase may often fall to zero. This may be of significance to any resting bodies of the biota (Williams, 1985).

2.1.3 Light Penetration

There are many factors that influence the amount of radiation arriving at the surface of any given water body and how much of it penetrates the water column. These factors include water clarity; which is affected by organic and inorganic turbidity, light intensity and wavelength, and the direction from which the light comes. Since most Australian salt lakes are shallow the diminishing effects on primary productivity of reduced light penetration is minimised, although this can result in photoinhibition of photosynthesis due to high irradiance (Albertano and Hernandez-Marine, 2001). Lakes in which high turbidity frequently occurs are one significant exception. A number of the aforementioned factors significantly influence the degree to which light is scattered which can also influence the intensity of light received by aquatic biota.

It is not simply primary producers that are influenced by the intensity and penetration depth of solar radiation. Zooplankton visibility and thus vulnerability to predation by higher order consumers is, for example, also affected (Seip et al., 1992). Radiation in sufficient quantities may also be a significant cause of damage to aquatic flora and fauna in a number of shallow Australian salt lakes (Oren and Seckbach, 2001).

2.1.4 Transient Water Regime

Apart from salinity, which is intimately linked to changes in water depth, transient water regimes are the most likely factor controlling the biota of salt lakes in a country such as Australia, where precipitation is low and variable over at least 70% of the continent. The majority of Australian salt lakes are not permanent, particularly those in arid and semi-arid inland regions, and exhibit strongly seasonal and highly variable water regimes (John, 2002; Roshier et al., 2001). The length of time during which they remain dry varies from less than a few days to many years.

The duration over which surface water persists is determined by climatic factors including rates of evaporation, rainfall and rainfall variability. Rainfall variability in Australia is comparatively low near the coast but increases further inland (Paijmans *et al.*, 1985). For most predictably filled waters, of which there are more in coastal regions, the length of dry period is usually less than a year, but occasional drought years may prolong this.

Regardless of the duration in which lakes are dry, many have been reported to develop a characteristic, diverse biological community following the occurrence of water in them (Williams, 1998). Lake Eyre in South Australia, for example, has been reported to contain water on only few occasions in the last 100 years (ie. 1890, 1949-1950, 1974, 1984, 1989 and 1991). Despite these long periods of desiccation the lake is known to support a characteristic biological community whenever water is present (Blinn, 1991; Kotwicki and Isdale, 1991). The drying cycles that follow filling events in temporary saline lakes also play a key role in determining the distribution pattern of biota inhabiting salt lakes. As lakes dry, physicochemical conditions change which has a direct influence on species diversity, richness and composition (Herbst, 2001).

Apart from variation in water level due to rainfall, many shallow salt lakes also undergo short-term variation due to wind action. Directional changes in the wind cause the movement of bodies of water across or along the lake floor. If the lake is shallow, large areas of the lake bottom may become exposed to desiccation (Clarke, 1991).

2.2 Biological Limnology

The biota of Australian salt lakes is, in general, less diverse and more widely distributed than those recorded from fresh waters. Possibly as a result of this low diversity some species occur only in bloom proportions, which can have a marked effect on the abiotic environment of salt lakes (De Deckker, 1988). Although species diversity is inversely correlated with salinity, the total diversity of taxa recorded from salt lakes is commonly underestimated (Williams, 1998).

2.2.1 Adaptations to Life in Saline Waters

As outlined above, for biota to survive in Australian salt lake environments they must survive both wide fluctuations and extreme levels in a range of physical attributes. High salt concentrations should not be considered to be the only environmental stress encountered. The influence of water transience is immense. Australia's long history of aridity has required salt lake biota to develop physiological or lifecycle strategies to withstand extended periods of desiccation. Similarly, high light intensities and high day temperatures, often coupled with low night temperatures, add to the extreme nature of saline lakes (Oren, 2002).

Individually these environmental parameters are important determinants of the biota in salt lakes, but biota must also be able to tolerate or avoid the changing levels of combinations of environmental parameters. Adaptations to survive and reproduce when exposed to one of these stress factors alone is unlikely to ensure survival. The biota of saline lakes must have adaptations to cope with a variety of parameter combinations. The physiological tolerance to do so may be considered a means of establishing habitat refugia, escaping the adverse influences of predation and competition found more in the diverse communities of other, less extreme, environments (Herbst, 2001).

Means by which salt lake biota cope with physical stressors include mechanisms of both tolerance and avoidance. Morphology, physiology and life cycle patterns are often all involved in the total pattern of a species adaptation. Osmoregulatory mechanisms provide a physiological answer to how many species cope with changes in salinity (Oren, 2001). Dormancy mechanisms enable survival of desiccation due to water transience. Morphological adaptations include resistance to desiccation, the production of asexual propagules, and phenotypic plasticity. Life cycle patterns, namely the length of lifecycle, the proportion of energy devoted to reproduction, and the number of reproductive units produced, provide a total system whereby a species can withstand the extreme and variable nature of salt lake environments and allow for synchronization of lifecycles with the occurrence of water (Henley, 2001).

Salt tolerance is clearly an adaptive feature of biota in salt lakes and it is possible to distinguish 3 categories or levels of tolerance; a group of salt tolerant freshwater organisms, halophiles tolerant of salinities between 10-60ppt, and halobionts tolerant of salinities >50ppt. There are two basic mechanisms open to these groups of biota by which they can operate in saline water namely osmoconformity or osmoregulation.

The majority of animals found living in Australian salt lakes are osmoregulators, effectively drinking the external medium and then excreting unwanted ions (Williams, 1985). The unicellular green algae *Dunaliella* has been much studied and can grow in both high and low salt concentrations. To do so over a range of salt concentration *Dunaliella* employs a physiological strategy of accumulating a high intracellular concentration of compatible solute to balance the concentration of salts in the external medium. The solute it accumulates is not however NaCl nor KCl but glycerol (Oren, 2001). Similarly, the aquatic macrophyte *Ruppia* has been reported to accumulate amino acids such as proline in the cytoplasm to counterbalance high vacuolar, and therefore external solute, concentrations (Brock, 1986).

Two halobiont genera of heterotrophic bacteria, *Halobacterium* and *Halococcus* have been reported to not just tolerate high NaCl but to require it. The enzymes of most organisms cannot function in the presence of high salt concentrations but the enzymes of these bacteria not only function optimally in high salt concentrations but require molar concentrations of KCl or NaCl to prevent denaturation. As a result, these bacteria cannot grow below 100ppt NaCl because in adapting to function in high intracellular salt concentration their enzymes and cell envelope proteins have lost the ability to function in low salt concentrations (Oren, 2002).

Salt concentration and fluctuations in it are clearly associated with water transience but this is not the only stress to biota associated with the temporary nature of surface waters in most Australian salt lakes. Biota must withstand extended periods of desiccation. This can be achieved in fauna by survival as adults, as juveniles, or as eggs. Algal flora and aquatic macrophytes do so as spores, seeds, or as dormant vegetative parts (Brock and Lane, 1983; Henley, 2001).

The most obvious survival technique is that shown by birds and insects; adults escape the rigours of the dry season simply by flying to refuges elsewhere (Kingsford and Halse, 1998). For animals unable to fly, survival as adults mostly involves protective resistant devices and/or behavioural adaptations. Clear examples of this can be found amongst aquatic invertebrates. The gastropod *Coxiella striata* is able to survive as an adult because it has an impermeable shell which can be closed by a tight fitting operculum. Within closed shells *Coxiella* can withstand many months of desiccation (Williams, 1985).

A more common strategy of invertebrates is to survive as larvae or as eggs which have undergone an arrested development or diapause. Survival of embryos in an arrested state of development is known for some cyclopoid and harpacticoid copepods (Williams, 1985). During dormancy the embryos dehydrate and can then withstand almost complete desiccation, very high and low temperatures, and extreme salinities. Many crustaceans also survive desiccation by means of resistant dehydrated eggs (Kennedy *et al.*, 1998). Several Australian calanoid copepods utilise this strategy as well as many anostracans, ostracods, cladocerans, notostracans and conchostracans. A few animals such as *Elphidium* sp., an Australian foramniferan characteristic of coastal salt lakes, survive as resistant bodies not associated directly with the reproductive cycle. In the case of *Elphidium* sp. it is as a dehydrated speck of protoplasm (Kennedy *et al.*, 1998).

As already noted, survival of desiccation by algal flora and aquatic macrophytes relies on the production of resistant spores, seeds, or dormant vegetative bodies. Many cyanobacteria and green algae produce resistant bodies either asexually or sexually. *Anabaena*, a cyanobacteria, produces akinetes which are thick-walled cells filled with food reserves (Oren, 2001). The green alga *Dunaliella* is known to produce thick-walled non-motile aplanospores asexually and large, heavy, thick-walled zygospores sexually while the charophyte *Lamprothamnium papulosum* utilises the production of fertilised, resistant oogonia (Henley, 2001).

For aquatic macrophytes the production of seeds is the characteristic way by which they survive desiccation, but common salt lake angiosperms such as *Ruppia tuberosa, Ruppia megacarpa, Ruppia polycarpa* and *Lepilaena preissi* are also known to produce perenniating organs or turions to ensure survival. Two structural types of turion occur, one as a swelling at the leaf base, the other as a swelling at the tip of the rhizome (Brock and Casanova, 1991).

Like most halophiles, halophytic species of *Dunaliella* have relatively high growth temperature optima. *D. viridis* and *D. salina* are also very resistant to cold. Glycerol may serve a dual role in *Dunaliella* cells as a major osmoregulatory compatible solute and also as a solute which reduces the effects of heat and cold stress on enzymes (Oren, 2001). Many animals employ behavioural adaptations to the stress of high temperatures by moving to cooler refugia beneath vegetation and near the sediment surface (Williams, 1986a).

High salt concentration, high light intensity and high temperature also cause *D. salina* to accumulate carotenoids which have been proposed to have a photoprotective role. *Halobacterium* and *Halococcus* also accumulate carotenoids, heavily pigmented with pink, orange or red, which it has again been suggested play a photoprotective role (Borowitzka, 1981).

Because many saline lakes are located in endoreic drainage basins, the possession of efficient dispersal mechanisms, at least to achieve dispersal within local areas, represents another adaptation needed. Biota commonly disperse either as winged adults (eg. insects, birds), terrestrial non-winged adults (eg. frogs), or as small resistant stages (eg spores, cysts, eggs) that are dispersed by the wind, in floods and by birds (Baltanas *et al.*, 1990).

2.2.2 Fauna

Despite the prominence of salt lakes in Western Australia, the biota of saline lakes have been studied more extensively in Victoria and South Australian. Of the investigations conducted, the vast majority have focussed on physicochemical parameters and faunal composition rather than aquatic flora (Blinn, 1995). Since this project has focussed on the algal flora of salt lakes in Western Australian the fauna of Australian salt lake environments is discussed only briefly.

The major faunal elements collected from Australian salt lakes include ciliates, foraminiferans, spirochaetes, rotifers, gastropods (the genus *Coxiella* is particularly significant in Australia waters), oligochaetes, crustaceans, insects (chironomids, ephydrids, ceratopogonids, and culicids), fish and birds (Williams, 1985; Kingsford and Halse, 1998; Timms, 2001). Fauna from these groups do not, however, occur collectively in any one locality or region and their distribution across the continent displays marked regional differences (Williams, 1998).

While there are similarities in the fauna recorded from salt lakes in Western Australia and eastern Australia, such as the cladoceran *Daphniopsis pusilla* and the halobiont copepods *Calamoecia clitellata* and *C. salina*, the diversity of salt lake fauna has been reported to be greater in Western Australia than in eastern Australia. This is particularly evident when compared with the fauna of western Victorian salt lakes, which have been the focus of considerable limnological interest (Brock and Shiel, 1983).

Geddes *et al.* (1981) reported that it is possible that southern Western Australia may have been the centre of evolution for many endemic genera found in Australian salt lakes. In the cyclopoid copepod genus *Microcyclops* and the anostracan genus *Parartemia* there has been more speciation in western salt lakes than eastern ones. This may also be true for the gastropod *Coxiella*. Increased speciation may be related to the more stable geology and climate of Western Australia as opposed to that of the east. A large part of Western Australia has been geologically stable and climatically arid since the early Tertiary and so it is likely the State has had temporary saline lakes as a major limnic environment over this long period. As a result, this long history of large numbers of salt lakes extending over various climatic regions may have provided the conditions for speciation to proceed.

Crustaceans represent the most conspicuous faunal group in Australian saline waters. Halobiont crustacean taxa recorded are mostly endemic, and some are able to withstand high salinities and the harsh conditions common in inland Australian salt lakes. Ostracods form the most diversified group recorded. More species have been collected in Australia than compared with the ostracod fauna of other continents. Other significant crustacean components of salt lake fauna include copepods, isopods, cladocerans, amphipods and anostracans (De Deckker, 1983).

2.2.3 Algal Flora and Aquatic Macrophytes

Many primary producers occur in Australian saline lakes where the salt concentration is below 100ppt. Biota range from algal flora such as diatoms, through filamentous green algae (eg *Rhizoclonium*, *Cladophora, Enteromorpha*) and dinoflagellates (eg. *Gymnodinium aeruginosum*) to aquatic macrophytes such as *Ruppia* and *Lepilaena*. Photosynthetic and heterotrophic bacteria and cyanobacteria also abound. Though diversity is reduced, algal taxa have been reported to grow and contribute significantly to primary production at salinities in excess of 200ppt (Brock and Shiel, 1983; John, 2002; Oren, 2002).

Benthic microbial communities (BMCs), which are comprised of the bacterial, fungal and microalgal inhabitants of lake sediments and often contribute significantly to primary production (Bauld, 1986). Halophilic bacterial mats commonly occur in salt lakes above 100ppt (Brock and Shiel, 1983) and BMC's are common in many salt lakes across Australia, particularly the southern coastal portion of the continent (Moore, 1993). BMCs may interact with sediments in three main ways: as films or veils in which the BMC is dispersed through loosely consolidated sediment; as mats in which the BMC is closely associated with trapped and bound sediment; and as indurated masses (including stromatolites) produced by sediment trapping, binding and/or precipitation (often of limestone) in association with the BMC (Burne and Moore, 1987).

BMC's commonly inhabit shallow sublittoral waters, and the littoral or supralittoral margins of saline lakes. John (1999) reported that the filamentous, mat forming cyanobacteria, *Schizothrix* sp. was a dominant feature of the algal flora at the periphery of the Lake Lefroy, a hypersaline lake in Western Australia. These mats have two important functions in this environment. Firstly, the mucilaginous sheaths of the trichomes bind sand particles together, reducing erosion of the lake margins. Secondly, the mats provide a primary source of carbon and therefore form the basis of the food chain within the lake.

Diatoms also dominate microbial mats in some instances (Bauld, 1986) and have been reported to play a significant role in stromatolite formation, particularly in salt lakes in Western Australian (Grey *et al.*, 1990; John, 1990; Moore *et al.*, 1983).

A variety of bacteria have been isolated from saline lakes and a wide range of heterotrophic activities have been attributed to bacteria from extremely saline lakes. Bacterial photosynthesis is known to be a particularly important source of primary productivity in these environments (Hammer, 1981). Two genera of heterotrophic bacteria, known to occur in highly saline Australian waters, have been the subject of particular interest; they are *Halobacterium* and *Halococcus*. Halophilic photosynthetic sulphur bacteria such as *Ectothiorhodospira* are also known to occur in salt lakes, under anaerobic conditions (Borowitzka, 1981).

Many genera of cyanobacteria occur in Australian saline lakes. They tend to be characteristic components of the phytoplankton of highly productive saline lakes with a specific conductance less than 50 mS cm^{-1}. When lakes are less productive, a variety of other species may occur, and the plankton is not dominated by a single species (Hammer, 1981). The filamentous cyanobacteria *Nodularia spumigena* is known to be particularly significant in moderately (ie 10-50ppt) saline Australian lakes (Walker, 1973; Williams, 1978). Predominant filamentous cyanobacteria in lakes with a salinity of 50-100ppt include *Phromidium* sp., *Oscillatoria* sp., *Microcoleus* sp., and *Spirulina* sp. (Borowitzka, 1981). The number of cyanobacteria species diminishes at salinities above 100ppt although *Phormidium tenue* and species of *Oscillatoria* and *Microcoleus* have been reported from some extremely saline lakes (John, 1999). The unicellular cyanobacterium, *Aphanothece halophytica* has also been reported at salinities in excess of 100ppt (Playford, 1988).

The only green alga reported to grow in extremely saline waters is *Dunaliella*. *Dunaliella salina*, *D. viridis*, *D. minuta*, *D. parva* and *D. euchlora* have all been reported from highly saline waters in Australia. Of these, *D. salina* and *D. viridis* are the most salt tolerant. The former has been reported from waters ranging in salinity from 20ppt to saturation while the latter's range is 9ppt to 304ppt (Oren and Seckback, 2001).

While diatoms commonly occur in salt lakes, particularly if they are also alkaline, salinity is one of the most important predictors of diatom community structure (Blinn, 1995; John, 1998). Many diatom species are widely distributed, inhabiting waters of a similar nature through both Australia and the rest of the world. Few species recorded from Australian waters are endemic, although there have not been many extensive studies of non-marine diatoms in Australia (Gell, 1997). Of those published, most have concentrated on river or estuarine systems.

Members of the Naviculaceae, Nitzschiaceae, Fragilariaceae, and Cymbellaceae are often the dominant diatom taxonomic groups in saline lakes (Blinn, 1993). In their study on the relationships between salinity and diatom flora from 32 saline lakes in western Victoria, Gell and Gasse (1990) reported that saline lakes of lower salinity (1-5000 μScm^{-1}) supported the greatest variety of common species, the most widespread being *Amphora* *veneta*. Assemblages that included *Eunotia lunaris*, *Achnanthidium minutissimum*, *Stauroneis pachycephala*, *Navicula angusta*, *Anorthoneis excentrica*, *Navicula salinarum*, *N. symmetrica*, and *Gomphonema* sp. were recorded only or most commonly within this lower salinity range. *Tabularia* sp. aff. *parva* and *Navicella pusilla* were also most commonly recorded in water within the 1-5000 μScm^{-1} salinity range or the 5-15000 μScm^{-1} range.

Anomoeoneis sphaerophora was found to be most abundant in lakes of 15-30000 μScm^{-1}. *Navicula elegans* and a large unidentified *Nitzschia* were characteristic of waters 30-40000 μScm^{-1} and waters 40-70000 μScm^{-1}, although *Rhopalodia* sp. aff. *musculus* was dominant in one lake with surface waters of 30-40000 μScm^{-1}. *Achnanthes brevipes*, *Berkeleya rutilans*, *Amphora coffaeformis*, and *Nitzschia* sp. aff. *latens* seemed to be characteristic of hypersaline lakes (>70000 μScm^{-1}), in which *Entomoneis paludosa*, *Navicula* sp. aff. *incerata*, and *Hantzschia* sp. aff. *amphioxys* var. *gracilis* were also common.

Gell (1997) reported that the most widespread diatom species collected from salt lakes in the same region were *Cocconeis placentula* and *Nitzschia liebetruthii*, *Amphora coffeaeformis*, *Navicella pusilla*, *Nitzschia palea* and *Nitzschia pusilla*. *Nitzschia pusilla* has also been recorded as the dominant diatom species from Lake Eyre South (Blinn, 1991). The second most dominant species reported by Blinn (1991) was *Tabularia fasciculata*. *T. fasciculata* is one of the most common diatoms in the Swan River Estuary, Western Australia and has long been considered an indicator of coastal saline environments (John, 1983).

The most common macrophyte species recorded from salt lakes in Australia belong to three salt tolerant genera *Ruppia*, *Lepilaena* and *Lamprothamnium* (Brock, 1981; Brock and Casanova, 1991). These genera are widely distributed and occur over a wide salinity range. They are the only halotolerant macrophytes to have been recorded above 10ppt TDS (Brock and Lane, 1983). It is not uncommon to find species of each genera co-existing in saline lakes (Brock and Shiel, 1983) but it must be noted that macrophytes are rare, or their numbers may be low, in hypersaline lakes (Hammer, 1981). In these salinities, most species are only present as dormant structures (Brock 1986).

2.3 Threats to Salt Lakes in Australia

Salt lakes possess a number of valuable functions, uses and attributes that have, to a large extent, gone unrecognised (Table 1). This lack of recognition has led to their degradation or loss (Williams, 1993c). Tampering with the processes that support these functions, uses and attributes, especially hydrological regimes, can quickly degrade these values and the impacts are far-reaching and increasing in Australia. Once degradation has occurred it can be extremely expensive to restore (Hollis and Finlayson, 1996).

The major threats to the conservation of Australia's salt lakes are presented below (Blinn and Bailey, 2001; Bunn *et al.*, 1997; John, 2000). They have been categorised into two groups; those that threaten the ecological integrity of salt lakes directly and those that threaten their integrity indirectly.

2.3.1 Direct Threats

2.3.1.1 Physical Disturbance to Habitat

Physical disturbance has had an immense influence on Australia's salt lakes (Williams, 1993c). The most common sources of physical disturbance are direct habitat modification, insect control, overgrazing, wildfires, inappropriate recreation and mining (Asquith and Messer, 1996; Godfrey *et al.*, 1992; National Parks Service, 1996).

Direct habitat modification encompasses activities such as drainage, infilling, and reclamation or modification. As Australia's urban population continues to expand, particularly in coastal regions, so too does the need for land suitable for housing, recreation and refuse disposal. This encroachment of urbanisation has resulted in a number of salt lakes in coastal regions, such as Lake Coogee on the Swan Coastal Plain in Western Australia, being drained or filled and peripheral vegetation being cleared (Helleren, 1993). Similarly, agriculture and developments like roads, in both inland and coastal regions, have resulted in habitat reclamation and modification (Donohue and Phillips, 1991).

In terms of mining, which is most common in the inland regions of Australia, impacts include "on site" modification due to the extraction of materials such as salt, gypsum, zeolites, lithium, borax and uranium directly from lakes, changes to hydrological regimes due to dewatering and causeway construction, lowering of water tables and pollution with heavy metals, other toxicants and suspended solids (Williams, 1993b). Pollution sources associated with the mining industry include leaching from tailings dumps and retention ponds and the discharge of hypersaline, sometimes acidic and heavy metal-loaded, groundwater into salt lakes as part of dewatering activities.

Lake Miranda, a temporary salt lake around 500km north-east of Perth in the arid goldfields region of Western Australia, is one example of the impacts of the mining industry, specifically the discharge of hypersaline groundwater (150ppt), on the salinity and diversity of biota (John *et al.*, 2001). Phytoplankton and macrophytes characteristic of the lake prior to the initiation of dewatering activities were no longer present, and salinity had increased and an accumulated salt crust had started to form, within a year of commencement.

2.3.1.2 Changes in Water Regime

Water regime, which describes where, when and to what extent water is present, is a major key to salt lake ecology. It involves both above and below ground hydrology and has been modified markedly in many Australian salt lakes (Blinn and Bailey, 2001).

Changes in water regime components including timing, frequency, duration, depth and extent, and predictability of wetland inundation have resulted from a wide range of water and land use practices. These include irrigated agriculture, river management, surface water and groundwater drainage, damming, water abstraction for water supply, and rises in groundwater to name a few (Jensen, 1996a, b, c, d, e; Jensen and McPhail, 1996; Jensen *et al.* 1996a, b; Munks, 1996).

Modification of water regime has seen the significant modification of salt lakes at local, regional or landscape levels, having a particularly marked effect on the physicochemistry and ecology of temporary salt lakes (Roshier, et al., 2001). Lake Corangamite in Victoria, for example, has experienced a significant reduction in water levels, as a result of human activities, between 1960 and the early 1990s. This has resulted in an increase in salinity from 35 to more than 50g/L (Williams, 2001).

Symptoms of modification of hydrological processes include water quality degradation and alteration of ecosystem function. Changes to ecosystem function can occur in a number of ways including altering growth, viability and reproduction of species, population structure, community structure, species richness, maintenance of aesthetic, agricultural, cultural and heritage values, water quality and by creating opportunities for exploitation by invasive species. In extreme cases, the end result of water diversions from salt lakes is the complete desiccation of lakes involved (Kingsford and Halse, 1998).

2.3.1.3 Invasive Species

Introduced species can have a profound effect on salt lake ecology (Williams, 1993a, d). The issue of invasive species can be subdivided into broad categories including weeds, introduced animals, pathogenic organisms, and translocation of native species (Munks, 1996). While the latter is currently considered to be a minor problem, the movement of native biota by man to new habitats outside their natural distribution can result in ecological shifts in species composition and the relative sizes of the populations of different species (McComb and Lake, 1990). Saline habitats that are subject to interference with their hydrological regime or nutrient status are also susceptible to such shifts; caused by the excessive proliferation of one or several existing components of the system.

2.3.2 Indirect Threats

2.3.2.1 Pollution

Salt lakes may be adversely affected by five main classes of pollutants; plant nutrients, inorganic compounds other than nutrients (especially NaCl), toxic compounds including heavy metals and pesticides, natural organic compounds and suspended solids (Williams, 2001). Each class of pollutant requires a specific management approach which targets both the source of pollution and mitigation of the pollutant's impacts on ecosystem health. It must be remembered, when addressing such management issues, that pollutants may enter from either diffuse or point sources and, once introduced, often become associated with particulate matter and incorporated into the bottom sediments of a salt lake.

Modern agricultural practices and urbanisation are the major causes of salt lake pollution throughout much of Australia and result in impacts such as eutrophication and changes, often increases, in salinity. The magnitude of impacts associated with agriculture and urbanisation is primarily due to the clearing of catchments and management techniques (Blinn and Bailey, 2001). In addition to excessive nutrient inputs into salt lake environments and increased salinity arising from changes in water tables and hydrological regimes, pollution by pesticides (be they herbicides or insecticides) is common. Other effects of catchment clearing include erosion, resulting in increased water turbidity, flooding and inundation (Williams, 1993a, b).

3.0 MATERIALS AND METHODS

3.1 Study Sites - Location and Environment

3.1.1 Lakes in the Esperance Region

The Esperance Region is located on the south coast of Western Australia between latitudes 33° 47'S and 33°52'S, longitudes 121°47'E and 122°E and is commonly known as the Esperance Sandplain (DCE, 1986).

The region has a Mediterranean climate with warm, dry summers and cool, wet winters. The average annual rainfall is 663mm, most of which falls between May and September. Average maximum temperatures range from 26.4°C in February to 17.1°C in July. The average annual pan evaporation is 1700mm, exceeding average rainfall by more than 1000mm per year. Evaporation is, however, often exceeded by rainfall in May through to August.

The Esperance region overlies a basement of Proterozoic rocks of the Albany-Fraser Orogen. This Precambian basement is comprised primarily of granite and gneiss and is in close contact with the Archean Yilgarn Craton. Tertiary sediments of the Plantagenet Group form a veneer infilling palaeovalleys incised into the bedrock during periods of sea level change. The Eocene sea reached 275m above the present sea level when widespread sedimentation took place. These sediments consist of Pallinup Siltston; a marine deposit laid down during this period of high sea-level. Quarternary sandplain deposits overlie the basement and Plantagenet group occupying a dissected sandplain. Recent coastal sands form long parallel dunes along the coastal plain behind the present coastline.

Changes in sea level appear to have had the greatest effect upon the development of landforms in the Esperance region. Dissection to produce an elevated plain occurred in stages during the Pleistocene with a lowering of the sea level. Pleistocene and recent deposits include the sand dunes on the coast, the coastal plain and sand plain, and dissected alluvium in the eastern portion of the region on partly dissected, high-level floodplains and river terraces (Morgan and Peers, 1973).

Inland drainage lines on the Esperance Sandplain plateau flood out onto the plain that features a chain of small interconnected salt lakes on the northern boundary of the Esperance townsite (Figure 1). Sandy, yellow duplex soils occur on the level plain and saline, grey-blue duplex soils occur on the poorly drained winter wet flats (CALM, 1997). Five of these salt lakes were selected for investigation in this study; Mullet Lake, Woody Lake Reserve Marsh, Lake Wheatfield (Figure 2), Lake Warden (Figure 3 and 4) and Pink Lake (Figure 3).

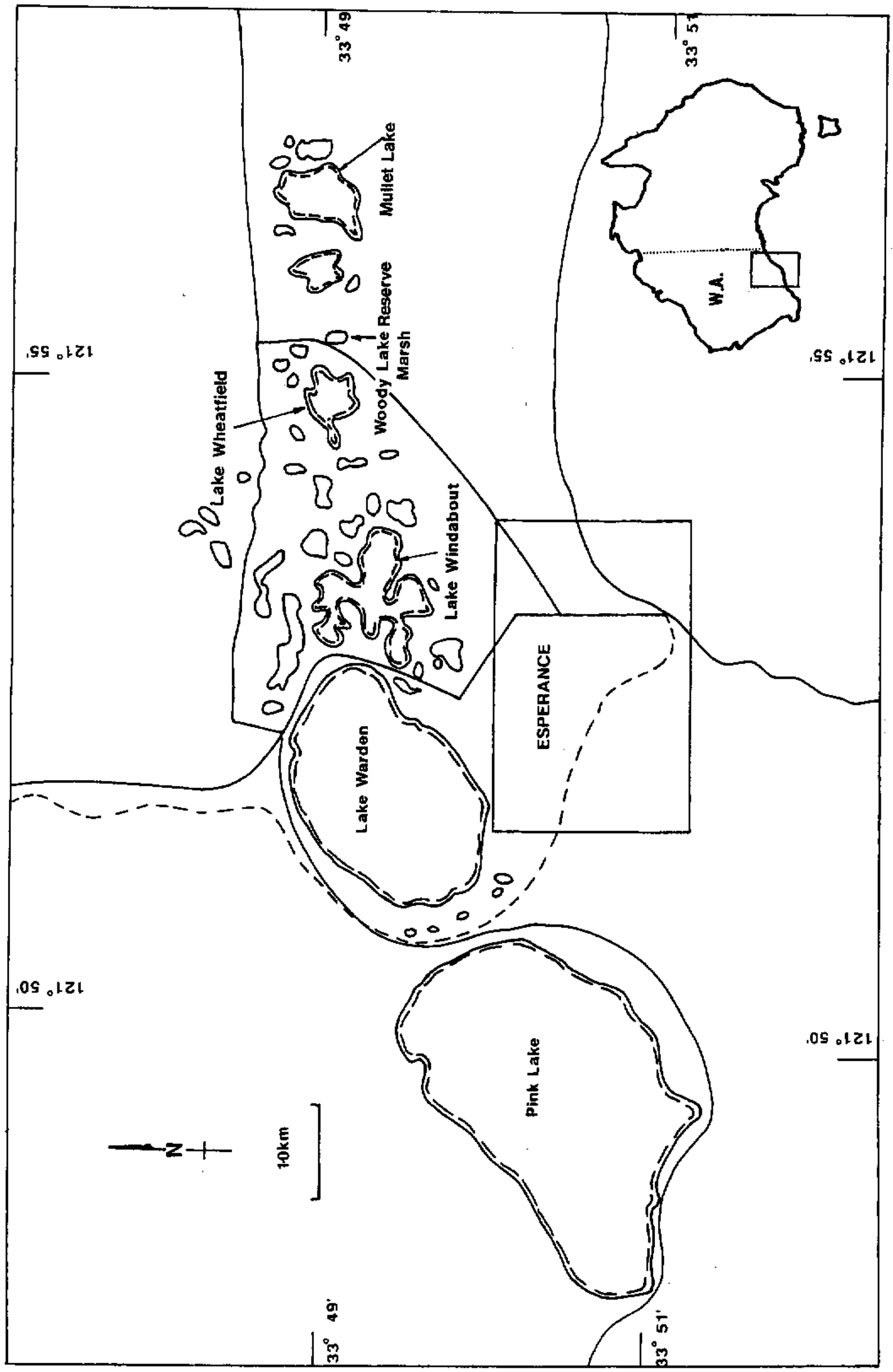


Figure 1: Salt lakes in the Esperance region, locality map showing approximate sampling sites of five lakes investigated in this study.

Vegetation of the Esperance region was first described by Beard (1973) as the Fanny's Cove system. The seaward side of the region's parallel dunes support low scrub in which *Scaevola crassifolia* is dominant. Behind this there is a scattered mallee of *Eucalyptus angulosa* with an understorey of *Melaleuca pentagona*. Further inland the dunes carry thickets of tall *Acacia* and *Melaleuca* or *Banksia speciosa*. *Eucalyptus platypus* forms thickets in depressions between the dunes.

Melaleuca cuticularis trees grow down to the water in the majority of wetlands although in some places there are narrow zones of rushes, principally *Baumea juncea*. Other rushes and sedges, including *Juncus kraussii*, *Isolepis nodosa* and *Gahnia trifida* also grow around the shoreline in the tree zone.

Lake Wheatfield (Figure 2) and the lakes westwards frequently support *Acacia cyclops* behind *Melaleuca cuticularis* as the land rises, before it is replaced by low woodland of *Banksia speciosa* or by mallee and scrub. At the eastern end some lakes in the chain such as Mullet Lake are fringed by a tree zone of *Melaleuca preissiana* as well as *M. cuticularis*. Fringing vegetation gives way to samphire species, especially *Halosarcia pterygosperma*, *H. pergranulata* and *Sarcocornia blackiana*, as the ground drops away from the embankment around the lakes.

Figure 2: Lake Wheatfield, fringed by *Melaleuca cuticularis* before it is replaced by *Banksia speciosa* woodland. Clearing for agricultural and urban development has occurred within close proximity to the lake.

In higher parts of the samphire marsh the grass *Stipa juncifolia* grows profusely, and in areas fed by springs *Suaeda australis* occurs (CALM, 1990).

Collectively the lakes investigated in this study support at least 59 species of waterbird, including two declared rare species; the Recherche Cape Barren Goose (*Cereopsis novaehollandiae grisea*) and the Freckled Duck (*Stictonetta naevosa*). In terms of numbers of birds occurring, the lakes are some of the most important in the south of Western Australia for Banded Stilts (*Cladorhynchus leucocephalus*), Australian Shelducks (*Tadoma tadornoides*), Black Swans (*Cygnus atratus*), Chestnut Teals (*Anas castanea*), Musks Ducks and Australasian Shovelers. They are also extremely important for the Hooded Plover (*Thinornis rubicollis*), an uncommon species restricted to southern Australia. One anostracan species, *Parartemia longicaudata* has been recorded from both Pink Lake and Lake Warden (Geddes *et al.*, 1981).

The average maximum depths of these lakes, which vary from being dry in summer to about two metres depth in winter, are related to seasonal and annual rainfall (DCE, 1986). Pink Lake and Mullet Lake have been reported to be generally less than one metre depth following winter rains while Lakes Warden and Wheatfield are generally deeper than one metre (CALM, 1997). Lake salinity is influenced by seasonal and annual rainfall, although the hydrology of these lakes is also likely to be affected by marine groundwater. Surface waters of the lakes of the region are dominated by sodium chloride, in keeping with the pattern of ionic dominance reported for Western Australia by Williams and Buckney (1976b).

Two main stream channels discharge into the lakes; the Coramup Creek and the Bandy Creek. Coramup Creek originates 25km to the north and flows in to Lake Wheatfield, in wetter years flowing through the system to Lake Warden. Lake Warden also receives inflow from creeks originating up to 9km north-west. Bandy Creek originates 32km north of the lakes and, in wetter years, flows in to Mullet Lake and eventually to the Southern Ocean. Few clearly defined stream channels discharge into Pink Lake. During flood years, lakes to the east and north of Pink Lake fill and interconnect to Lake Warden. However, surface flows through this system are separated from Pink Lake due to the construction of railway embankments. It is very likely, however, that groundwater may flow from the Lake Warden area to Pink Lake. (DCE, 1986).

The primary land use in the immediate surrounds of the lakes and in the catchments of these drainage channels is broadacre agriculture, comprised predominantly of annual pastures and cropping. As a consequence, increased salinity due to rising watertables and increased runoff from the agricultural land have had a direct impact on the water regime and water quality of all of the lakes (Platt, 1996). These impacts are primarily the result of clearing of deep rooted vegetation for agriculture. The impact of clearing for agriculture on the salinity of soils, streams and lakes in Western Australia was noted as early as 1924 (Williams and Buckney, 1976b). Eutrophication from fertiliser runoff, and siltation, from agricultural land within the lakes' catchments, also threatens the integrity of the lakes' ecosystems. Encroaching urbanisation exacerbates these problems. Areas of subdivided land for urban development have, in some instances, been pushed to the lakes' edge (Figure 3).

Figure 3: Rural subdivision developments encroach on Lake Warden (left) and Pink Lake (right).

Lakes Warden (Figure 4), and Wheatfield, Woody Lake Reserve Marsh and Mullet Lake are included in one of nine wetland areas in Western Australia recognised as wetlands of international importance under the Ramsar Convention.

The Ramsar Convention is an intergovernmental treaty which provides the framework for the conservation and management of wetland habitats. The first obligation under the Convention is to designate wetlands of international significance to the Ramsar List of Wetlands of International Importance and to maintain their ecological character. Wetlands are selected on the basis of ecological, botanical, zoological, limnological or hydrological criteria (Davis, 1994).

Pink Lake is not currently part of the Ramsar wetland system. All of the lakes from the Esperance region investigated in this study are, however, listed in the "Directory of Important Wetlands in Australia" in recognition of their contribution to Australia's wetland heritage. They also protect at least 17 species of waterbird cited in the Japan-Australia Migratory Birds

Agreement (JAMBA) and the China-Australia Migratory Birds Agreement (CAMBA).

Figure 4: Waterbirds at the margins of Lake Warden.

3.1.2 Lakes in the Kambalda Region

The Kambalda region is located in the Eastern Goldfields of Western Australia, between latitudes 31°05'S and 121°55'E (Figure 5). The region is typical of large areas of the Yilgarn Craton, consisting of gently undulating terrain, with scattered breakaways, dry creeks and low hills. Partly-connected salt lakes and associated dune systems occupy topographic lows or valleys (Clarke, 1991; 1994). Lake Lefroy, with an axial length of 59km, and a maximum width of 16km, is one of the largest of these salt lakes in the region. The surface area of Lake Lefroy itself is approximately 554km^2, the total catchment is 4528km^2.

The regional climate borders on arid to semi arid, with an average annual rainfall of 255mm at Kambalda and 267mm for Widgiemooltha (De Deckker, 1983). Kambalda experiences two rainfall maxima, one in January-March, the other in June-July. Widgiemooltha experiences a single rainfall maximum in June (Clarke, 1994). Winter rainfall in the region is generally related to cold frontal systems penetrating inland. Summer rainfall is due mainly to localised thunderstorms and remnant cyclonic systems. There is considerable variation in rainfall throughout the region, particularly in summer, due to the highly variable and localised nature of rainfall. Mean monthly maximum temperatures range from 33.6°C in January to 16.5°C in July. Frosts may occur during the winter months. Evaporation in the region has been reported to exceed precipitation by a factor of 10 (Clarke, 1991).

Lakes in the Kambalda region occupy a Mesozoic-Early Tertiary river valley which forms part of an extensive palaeodrainage system that originally drained south west to north east (Clarke, 1991). Since the Eocene, the valley has been infilled by Early to Late Eocene fluvio-lacustrine lignitic sediments, Late Eocene marine spongolites, Oligocene-Miocene red beds and minor lake carbonates and Pliocene-Holocene lacustrine evaporites (Clarke, 1990). The lowest part of the valley is approximately 100m below the surface of the lakes. The lakes form only a small portion of the hydrological basin, comprising the "above ground" component where most of the active sedimentary processes and biota occur and interact (De Deckker, 1988).

Eight salt lakes from the region were selected for inclusion in this study. These were Lake Lefroy (Figure 6), Mooreebar Dam, Victory Lake, Binneridgie Road Marsh, Lake Eaton North (Figure 7), Golf Lake (Figure 8), Lake Zot, and Lake Why.

Like many of the salt lakes in the region Lakes Lefroy, Zot and Eaton North are large playa lakes that exhibit a physiographic asymmetry with erosional western and northern shorelines and depositional eastern and southern shorelines. This directional asymmetry is due to the influence of the easterly prevailing wind direction (Clarke, 1991). Victory and Golf Lakes and Lake Why have a circular or elliptical outline, the result of wind driven eddies.

Binneridgie Road Marsh is a small claypan typical of a number of small lagoons and claypans that occur marginal to Lake Lefroy. It has been bissected by a road resulting in a buildup of surface water on the southern side of the road during rain events. Mooreebar Dam is an artificial dam, constructed by Western Mining Corporation (WMC) to provide water for mineral processing activities. It was constructed by damming Mooreebar Creek which previously provided surface flows into the north-western portion of Lake Lefroy.

Lake water levels vary seasonally with flooding of the lakes most common in winter. Rainfall events of greater than 30mm in total, and with an intensity of more than 5mm per day, are most likely to produce partial to complete inundation. When present, surface water in the lakes comes from two main sources, direct precipitation and surface runoff and stream discharge. There are some minor inputs to the lakes from groundwater inflow (Dames and Moore, 1999). Water depths rarely exceed 50cm. Rare flood events have been reported to cause much greater depths, with the 2000 year flood predicted to result in 6m of water in Lake Lefroy (Clarke,1990). Evaporation over the months following a major rainfall event causes surface water to disaggregate into small pools. The location of these pools varies according to the wind direction.

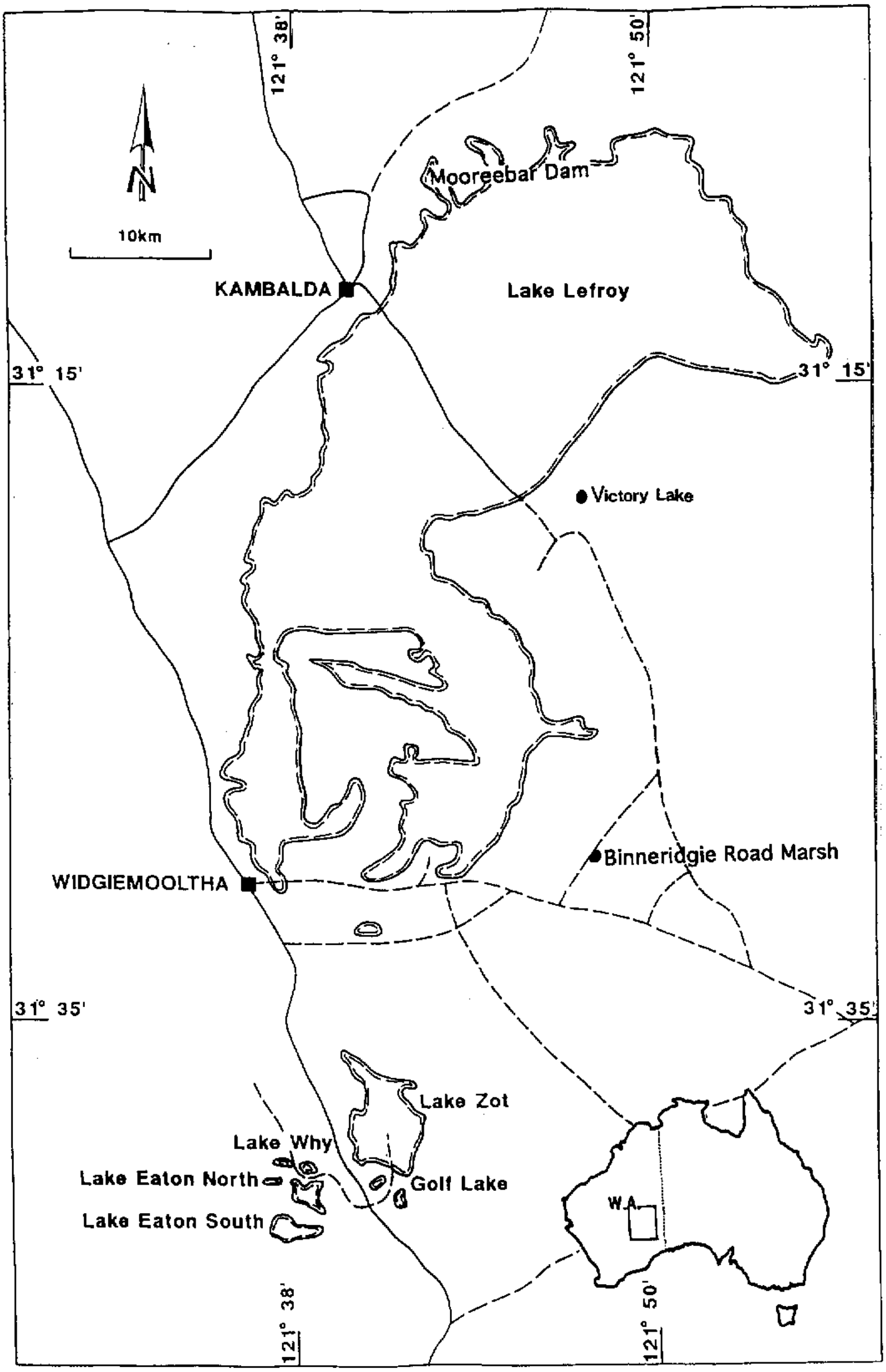


Figure 5: Salt lakes in the Kambalda region, locality map showing approximate sampling sites of eight lakes investigated in this study.

Victory Lake and Lake Lefroy support a crust over part of their surfaces. Lake water on the surface of Lake Lefroy dissolves the salt crust, re-precipitating it as detrital halite. The halite crust is typically 1-2cm thick and covers approximately 64% of the floor of Lake Lefroy (Clarke, 1991). Lakes Zot, Golf and Eaton North support thin ephemeral salt crusts (Figure 7), Lake Why and Binneridgie Road Marsh do not. The presence or absence of a salt crust is controlled by whether or not the lake floor is kept moist by capillary water from the underlying saline groundwater. All of the lakes proceed through a range of increasing water salinities during their drying cycles.

The pattern of ionic dominance of surface waters in the region is in broad agreement with the published data of Williams and Buckney (1976a,b). Subsurface waters differ markedly however, especially in the low total carbonate and K:Mg ratios (Clarke, 1990). None of the lakes contain strongly acidic or alkaline surface waters, most are weakly alkaline, with the exception of Lake Lefroy which contains weakly acidic surface water.

Figure 6: Lake Lefroy in summer, one of the largest salt lakes in the Eastern Goldfields region. A 1-2cm thick salt crust covers approximately 64% of the floor of the lake.

The Kambalda region lies within the "Coolgardie Botanical District" or the "South West Interzone" as defined by Beard (1990). Newbey (1984) described the vegetation of the region noting that nowhere else in the world does such a variety of trees occur in an area of such low rainfall. The dominant plant families in the region are the Myrtaceae, Asteraceae, Chenopodiaceae and Poaceae.

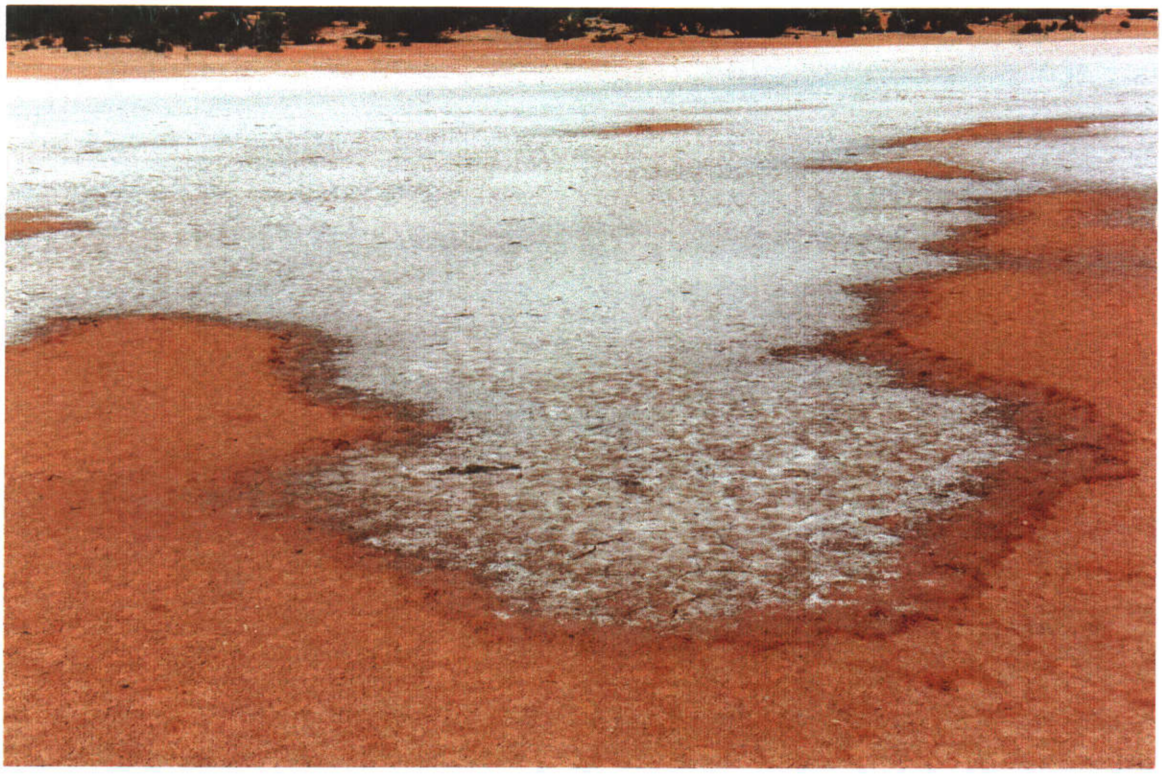


Figure 7: A thin ephemeral salt crust, driven by capillary water from underlying saline groundwater, encroaches on the floor of Lake Eaton North.

The vegetation associated with the salt lakes investigated in this study consists predominantly of *Halosarcia* Low Shrubland at the lake margins, encroaching to the lake floor in places, and on saline flats. The lake beds are otherwise devoid of vegetation. Dunes on the periphery of the lakes support Low Woodlands of either *Eucalyptus platycorys* or *Callitris columellaris* over tall shrubs of *Melaleuca uncinata* or a Dune Complex of variable structure that includes mallees of *Eucalyptus gracilis* and tall shrubs of *Melaleuca uncinata* over hummock grasses of *Triodia scariosa*. Where peripheral dunes are absent from the western margins Low Woodlands of *Eucalyptus lesouefii* over *Sclerostegia disarticulata* persist.

Melaleuca Tall Shrubland with only tall shrubs of *Melaleuca uncinata* are found growing on the non-saline to slightly saline claypan flats in the region; particularly on those adjacent to Lake Lefroy. Some areas, with soils of higher clay content and more prone to waterlogging, support *Cratystylis subspinescens* Low Shrubland. Where well-drained flats extend to the lake margin, *Atriplex vesicaria* Low Shrubland with associated low shrubs of *Halosarcia pruinosa*, *Disphyma clavellatun* and *Frankenia cinerea* occur. One Declared Rare Flora (DRF) species, *Pityrodia scabra*, is known to occur at the southern end of Lake Lefroy.

Figure 8: A view of salt marsh at the margin of Golf Lake when flooded. The lake supports a thin salt crust when dry.

A baseline survey of the aquatic flora of Lakes Lefroy and Zot by John (1999), reported that while the salt encrusted floor of Lake Lefroy is generally lacking in aquatic flora, temporary pools and samphire marsh at the margins of the lake support a number of bacteria, cyanobacteria, diatom and ciliate species. Cyanobacteria were most common. The filamentous, mat forming cyanobacteria *Schizothrix* sp. was dominant. Other cyanobacteria recorded include *Oscillatoria earlie*, *Chroococcus* sp., *Spirulina* sp., *Phormidium* sp., *Anabaena* sp., *Gomphosphaerium* sp. and *Caelosphaerium* sp. Diatom assemblages were dominated *by Amphora coffeaeformis*, *Navicula durrenbergiana*, *Amphora ventricosa*, *Nitzschia palea* and *Hantzschia virgata*. Algal mats dominated by *Schizothrix* sp. were also recorded from Lake Zot. In addition, the cyanobacterium *Synecoccus* sp. was common, as were the diatoms *Amphora coffeaeformis* and *Amphora ventricosa*.

Aquatic invertebrate species recorded from Lake Lefroy by Chaplin (1999) include two species of brine shrimp, an undescribed species resembling *Parartemia informis* and *Parartemia serventyi*. *Parartemia serventyi* was also recorded from Lake Zot along with one species of ostracod, *Diacypris fodiens*.

Two surveys have been conducted on the terrestrial invertebrates of salt lakes in the Kambalda region. The first, conducted by Hudson (1995) included investigation of Lakes Lefroy, Zot, Why, Eaton North and Golf Lake. Twenty seven species were collected from these lakes. At least 15 species could be considered as "typical" terrestrial fauna of salt lakes. The most abundant species were spiders and beetles.

Eleven species of spider from 6 families were recorded. The family with the highest species richness was Lycosidae (wolf spiders). All 5 species recorded were from the genus *Lycosa*. Other families recorded were Mygalomorphae (1 species), Amaurobiidae (2 species), Oxopidae (1 species), Salticidae (1 species), and Theridiidae (1 species). Ten species of beetle from 4 families were recorded. Six species from the Carabidae family were collected, 3 of which were from the tiger beetle genus *Cicindela*. 1 species from the Harpalinae and Staphylinidae families and 2 *Adeliem* species from the Tenebrionodae family were also noted.

The second survey, which included Lake Lefroy, was conducted by Brennan in 1999. A number of new species were recorded from the lake namely the spiders Amaurobiidae sp.C and Theridiidae sp.A, the staphylinid beetle Staphylinidae sp.A, the tiger beetles *Megacephala pulchra* and *Megacephala castelnaui*, and the pseudoscorpion *Austrohorus* sp.A. While most of the terrestrial invertebrates recorded by Hudson (1995) and Brennan (1999) have been recorded at other salt lakes in the Goldfields region some species, such as the salt lake wolf spider *Lycosa* sp.nov. and the tiger beetle *Cicindela* sp.nov. are currently considered to be endemic to Lake Lefroy.

Land use in the Kambalda region is vastly different from that of the Esperance region. Lakes Lefroy, Victory, Golf and Zot are subjected to engineering activities associated with the exploration, mining and processing of industrial minerals, lignite, precious metals, and base metals. Such activities include the construction of causeways and mining operations, alteration of drainage lines, surface water extraction and dewatering of mine groundwater. Often water pumped out of the mines during dewatering is of a lower pH than receiving bodies and contains heavy metals. Halite has been harvested in the past from evaporitic ponds on the southern half of Lake Lefroy (Clarke, 1991). In terms of agricultural activities, Lake Why is located on pastoral lease land and is used as a stock watering point when surface water salinity allows. Grazing has resulted in some impact on the *Melaleucas* fringing the Lake and has increased soil erosion in the lake's catchment.

3.2 Field Techniques

3.2.1 Collection Sites

A total of 13 salt lakes from two geographical regions were sampled during this investigation. Five salt lakes from the Esperance region were sampled, namely Pink Lake, Lake Warden, Lake Wheatfield, Woody Lake Reserve Marsh and Mullet Lake. Eight salt lakes from Kambalda were sampled; Lake Eaton North, Lake Why, Golf Lake, Lake Zot, Binneridgie Road Marsh, Victory Lake, Lake Lefroy and Mooreebar Dam. Individual sample collection sites were selected so as to maximise ecological data obtained (Figures 1 and 5).

The collection of field data and samples for analysis was restricted by the temporary nature of the lakes investigated. Lakes in the Esperance region were sampled in July 1992, September 1992, December 1992, February 1993, April 1993, July 1993 and October 1993. Lakes in the Kambalda region were sampled during October 1992, January 1993, February 1993, April 1993, July 1993 and October 1993.

3.2.2 Rainfall, Evaporation and Lake Depths

Data was obtained on local rainfall and evaporation as well as lakewater levels in both Esperance and Kambalda.

Monthly rainfall and mean pan evaporation data for the Esperance region was supplied by the Bureau of Meteorology, whose closest recording station was no more than 10km from any of the lakes included in this study. Comparable data for the Kambalda region was supplied by Western Mining Corporation whose weather station was located in the Kambalda township. Some of the lakes in the Kambalda region were up to 50 km south of this recording station.

Lake level measurements were recorded from the same point on each sampling occasion during 1992 and 1993. Depth was established using a pole marked with 10cm increments. The depth of Mooreebar Dam was recorded with a depth marker set in place by Western Mining Corporation. Depth data for Victory Lake was supplied by Western Mining Corporation.

3.2.3 Physicochemical Data Collection and Water Sampling Regime

The depth to which light penetrates, salinity, dissolved oxygen and water temperature were recorded *in situ* at each site. When present, surface water samples were collected. Light penetration was ascertained using a 20cm quartered black and white Secchi disk. Salinity was measured to the nearest $g100g^{-1}$ using an Atago^{TM} S-28 (salt: 0-28%) hand refractometer. Results were expressed in parts per thousand (ppt). Samples of surface waters too saline to be measured *in situ* (ie salinity in excess of refractometer limits) were collected for dilution and measurement in the laboratory.

Water temperature and dissolved oxygen profiles were recorded using either a YSI (Yellow Springs Instruments) Model 51A Oxygen meter or a YSI Model 50 Oxygen meter during sampling trips from April 1993 onwards. Measurements were taken at 0.5m depth intervals when lake depth permitted. Profile data was also collected during a 14 hour period (pre-dawn to post-dusk) from Lake Warden during Autumn 1993, Winter 1993 and Spring 1993. Much of the lake floor supported dense charophyte growth at these times.

Water samples for laboratory analysis were collected in 4oz. Nasco™ Whirl-Paks within wading distance from the shoreline. Samples were kept cool in eskies containing ice blocks and transported to Western Mining's environmental facilities in Kambalda or to a field base in Esperance.

Samples collected for pH analysis were kept cool until measurements could be recorded. Water collected for ionic and nutrient analyses was filtered through 0.45 Satorius™ filter papers during collection and frozen until just prior to analysis.

3.2.4 Biological Sampling Regime

Where possible phytoplankton, benthos (including benthic microbial mats), periphyton, and macroalgal samples were collected from each lake. The temporary nature the lakes included in this study meant that, at times, only benthic samples were able to be collected, particularly in summer.

3.2.4.1 Phytoplankton

Planktonic samples were collected using a 10μm plankton net at the lake margin and along transects across the lake. By using this pore size during sample collection some species smaller than 10μm may not have been collected. Samples were stored in plastic vials and preserved in Transeau's Algal Preservative (6 parts water:3 parts alcohol:1 part commercial formalin) and Lugol's solution.

3.2.4.2 Benthos and Benthic Microbial Mats

Benthic samples were collected from lakes with a standing water column by scraping the surface of the lake floor with a plastic vial as outlined by Hutchinson (1975). When the lakes were dry, samples were collected by pushing a plastic vial into the crust and upper layers of the lake floor to 8cm depth. Samples were preserved in Transeau's Algal Preservative and Lugol's solution.

When present, samples of benthic microbial mats were peeled from the lake floor or margin and stored in plastic vials. Microbial mats were preserved in Transeau's Algal Preservative after initial microscopic examination at Western Mining's environmental facilities or a field base in Esperance.

3.2.4.3 Periphyton

Periphytic samples were collected as per South and Whittick (1987). Samples were scraped from submerged, emergent or dead vascular plants, submerged rocks and macroalgal surfaces with a knife. Samples were stored in plastic vials containing Transeau's Algal Preservative and Lugol's solution.

3.2.4.4 Charales

When present, charale samples were collected for identification in the laboratory. Several specimens were collected in the event that species collected were dioecious. Specimens of each species collected were both dried and mounted on to paper and preserved in glass jars in 70% ethanol. Sediment samples were collected from the same locality and examined in the laboratory for the presence of oospores.

3.3 Laboratory Techniques

3.3.1 Water Analysis

A Metrohm E488 pH meter with a combination glass-pH electrode was used on the same day as sample collection to determine pH. Water colour was determined, at room temperature, by measuring sample absorbance, in a 4cm cuvette, with a Shimadzu Spectrophotometer UV-120-02 at 465nm wavelength. Recorded absorbance was then multiplied by 1000 and expressed as hazen units (hu) (K. Partridge, pers. comm.).

A number of techniques were used to quantify constituent cations. Calcium, magnesium and iron determinations required dilution then addition of an ionisation suppressant prior to direct aspiration into an air-acetylene flame. A similar method was applied for the determination silicon, although a nitrous oxide-acetylene flame was used. Both sodium and potassium were analysed using the flame photometric method (A) described in APHA, AWWA & WPCF (1989).

Anion determination was completed by the use of standard methods. Chloride was quantified using the Argentometric Method (APHA, AWWA & WPCF, 1989), while both carbonate and bicarbonate analysis was completed using the APHA, AWWA & WPCF (1989) alkalinity (2320 B.) titration method. The sulphate turbidimetric method (APHA, AWWA & WPCF, 1989 # 4500-SO_4 E.) was used to measure sulphate ion levels.

A number of specific analytical techniques were used to determine organic nutrient levels. Total nitrogen was quantified following the oxidisation of all nitrogen to nitrate, which preceded reduction to nitrite, after which the NO_2 Colorimetric Method (APHA, AWWA and WPCF, 1989 #4500-NO_2-B) was applied. Nitrite nitrogen was also quantified in this way. Nitrate nitrogen analysis was completed using the Cadmium Reduction Method (APHA, AWWA and WPCF, 1989 #4500-NO_3-E). Total phosphorous and soluble reactive phosphorus were measured using a modified Murphy and Riley technique (Rayment and Higginson, 1992). Samples were filtered, not digested with persulphate prior to this procedure.

3.3.2 Light Microscopy

All biological samples collected were examined by taking subsamples to make fresh mounts for microscopic examination using an Olympus™ compound microscope. In most cases 300 algal cells were counted from each sample collected according to Lund *et al.* (1958). Three replicate subsamples from a range of habitats were taken from each lake. Taxa were identified using specialised literature and photographed using an Olympus™ VANOX AH-2 photomicroscope and Kodak Technical Pan film (ASA 100). Voucher specimens for all species collected were lodged either in the International Diatom Herbarium, Curtin University or the Environmental Biology Algal Collection, Curtin University.

3.3.2.1 Benthic Microbial Mats

The general morphology and composition of all benthic microbial mats collected was described. Where feasible, microscopic dissection was used to determine species composition and vertical zonation within the mats. Each of the samples collected were sliced into three 1mm layers - top, middle and lower. Small subsamples were taken from each layer and examined for species composition and their relative abundance. Mats that were not in a form suitable for layer by layer analysis were analysed for component biota as one layer.

3.3.2.2 Cyanobacteria

The range of different systems of classification used to identify cyanobacteria restricted the level of taxonomic resolution possible in this study. Often only generic level was achievable. Cyanobacteria were identified using Baker and Fabbro (2002), Bourrelly (1970), Caljon (1983), Desikachary (1959), Dillard (1989), Ehrlich and Dor (1985), Felix and Rushforth (1979), Geitler (1932), Johansen *et al.* (1981), Johansen *et al.* (1983) and Ling and Tyler (1986).

3.3.2.3 Bacillariophyta - Permanent Slides

Diatoms were identified from permanently mounted subsamples that had been "cleaned" to remove organic material. Diatoms found producing mucilagenous secretions were photographed from fresh mounts. Alcian blue was used to stain the mucilage during examination.

Permanent diatom slides were prepared according to John (1983). Subsamples of all collections were chemically treated to separate and clear diatom frustules from surrounding organic material. Subsamples were pipetted into 100ml Pyrex beakers and boiled in 50 to 100mls of 90% Nitric Acid and 15mls of 32% Hydrochloric Acid until the final volume was reduced to approximately 10mls. Once cool, the samples were transferred to plastic centrifuge vials and 10mls of deionised water was added. Samples were then centrifuged at 3500 rpm for 7 minutes, after which the supernatant was poured off, water was added and the vial was shaken vigorously. This process was repeated 7 times to ensure that all traces of acid were removed.

Preliminary microscope slides were prepared, to determine the volume of resuspended cleaned diatom sample necessary to provide an adequate concentration of frustules on the permanent slides. This volume ranged from 300ul aliquots of cleaned planktonic material to 50ul aliquots of cleaned sediment material. Aliquots of the required volume were pipetted onto 22mm x 22mm glass coverslips. Deionised water was added to the coverslip to facilitate an even spread of cleaned sample over the coverslip surface. Coverslips were then left to evaporate. A hotplate was used, at a very low temperature setting, to accelerate the drying process.

Permanent diatom slides were prepared by inverting the dried coverslips onto a drop of Hyrax mounting medium (refractive index = 1.7), on microscope slides and heating until all the solvent had evaporated. Three replicate slides were made for each sample and labelled for counting.

Diatoms were identified using an Olympus^{TM} binocular compound microscope under oil immersion at 1000X magnification. At least 300 diatom frustules were identified and counted from two of the three slides prepared. Data from the slide replicates were averaged and tabulated to indicate relative abundance of each species recorded. Microhabitats sampled from each salt lake were prepared and examined separately.

Photographs were taken of all diatom species under oil immersion mostly at 1000X magnification using a Vanox photomicroscope. Diatom species were identified using specialised literature: Ehrlich (1978), Ehrlich and Dor (1985), Ehrlich and Ortal (1979), Felix and Rushforth (1979), Foged (1978), Gell and Gasse (1990), Johansen *et al.* (1981), Johansen et al. (1983) and John (1983, 1986, 1990, 1998 and 2000). Voucher slides for each species have been deposited in the International Diatom Herbarium at Curtin University of Technology, Western Australia.

3.3.2.4 Chlorophyta and Dinophyta

Identification of specimens was based on Caljon (1983), Dillard (1989 and 1999), Entwisle *et al.* (1997), Ling and Tyler (1986), Pentecost (1984), Prescott (1978) and Seamer (1998). Lugol's Solution was added to fresh mount subsamples to facilitate identification by staining cell chloroplasts.

3.3.2.5 Charales

The morphological characteristics of each specimen collected were examined using both a stereo microscope and a compound microscope. Wood and Imahori (1965) was used to identify species collected in this study. Dr Michelle Casanova, University of New England provided verification of identification.

3.3.3 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) was used to elucidate the structure of characteristic frustules of diatoms difficult to identify using light microscopy. Subsamples known to include target species were cleaned with acid using the same techniques described for the preparation of permanent diatom slides. Aliquots of the cleaned samples were pipetted onto glass coverslips and left to evaporate. Coverslips were then mounted on stubs and sputter coated with gold-palladium and examined using a JOEL 35C Scanning Electron Microscope at the Electron Microscopy Centre, School of Physical Science, Curtin University of Technology.

3.4 Statistical Analysis

Data collected in this project was summarised in a variety of ways using both single summary variables such as species richness (S); the Shannon Wiener Diversity Index (H'); and species evenness (J), Sorensen's Index of Similarity, one-way and two-way analysis of variance (ANOVA), correlation and regression analysis, canonical correspondence analysis, and divisive hierarchical cluster or classification analysis.

Data obtained from examination of both fresh mounts and permanent diatom slides prepared from subsamples of samples were averaged. Relative abundance of recorded species was calculated and used for species diversity index, species evenness and species richness using the following formulae from Zar (1984).

Species Richness:

R = number of species recorded in an area

Shannon Wiener Diversity Index:

$$H = \frac{n \log n - \sum(fi \log fi)}{n}$$

where, n = total of all individual sampled
fi = number of observations in each category

Species Evenness:

$$J = \frac{H}{H \max}$$

where, H max = log k
k = number of taxonomic categories

Differences in algal community structure, summarised in terms of species diversity, richness and evenness between lakes in the Esperance and Kambalda regions were investigated by one-way and two-way ANOVA's (Minitab Version 10.2) and summarised by a Scheffe' comparison test when ANOVA analysis indicated significant differences were present.

Similarities in the algal community composition of lakes in Esperance and Kambalda were investigated using Sorensen's Index of Similarity.

Sorensen's Index:

$$S = \frac{2c}{(a+b)} \times \frac{100}{1}$$

where, a = number of species in sample A
b = number of species in sample B
c = number of species common to samples A and B

Ter Braak's (1987) FORTRAN computer program, CANOCO, was used to carry out canonical correspondence analysis (CCA) to investigate the residual variation in species abundance and factors such as geographic location, salinity, pH and water depth for each sampling period. This procedure reduced the complexity of the data set to produce a graphical representation of algal taxa and correlated environmental factors. Points close together correspond to sites that display similar species composition, and points far apart correspond to sites that are dissimilar in species composition.

A divisive hierarchical cluster or classification analysis of algal taxa was undertaken using TWINSPAN (Two-way Indicator Species Analysis) to generate groupings based on the similarity of algal community species composition. The dendrogram order generated groups using the total algal species frequency data for each lake sampled, which was reduced to those species that were present in greater than 2% abundance. This process removed outliers and was used to confirm the results of the canonical correspondence analysis.

Correlation and regression analysis (Minitab Version 10.2) was used to investigate the nature of the relationship between species diversity and species richness and salinity, pH, and surface water depth. It was also used to investigate the relationship between data collected for physical limnological parameters.

4.0 RESULTS

4.1 Physical Limnology

4.1.1 Rainfall and Evaporation

4.1.1.1 Lakes in the Esperance Region

The annual precipitation in the Esperance region was 824.2mm in 1992, and 520.4mm in 1993 (Figure 9). Mean pan evaporation ranged from 1.7mm in June 1992 and 1993 to 7.7mm in December 1992 and 8.1mm in December 1993 (Figure 9). Seventy five percent of the region's annual precipitation fell between March and September in 1992, while in 1993 March to August represented the peak rainfall period (78%).

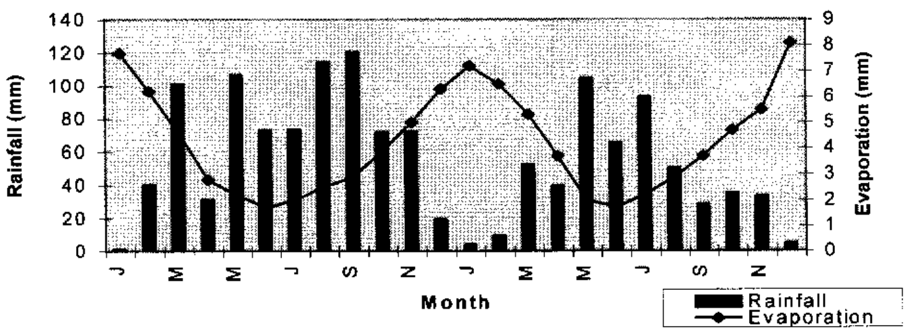


Figure 9: Monthly rainfall and monthly mean pan evaporation for the Esperance region during 1992 and 1993.

4.1.1.2 Lakes in the Kambalda Region

In the Kambalda region annual precipitation was 502.2mm in 1992 and 337mm in 1993 (Figure 10). Mean pan evaporation ranged from 13mm in December 1992 to 1.1mm in August of the same year (Figure 10). Similarly, in 1993 mean pan evaporation ranged from 11.6mm in January to 1.7mm in June 1993.

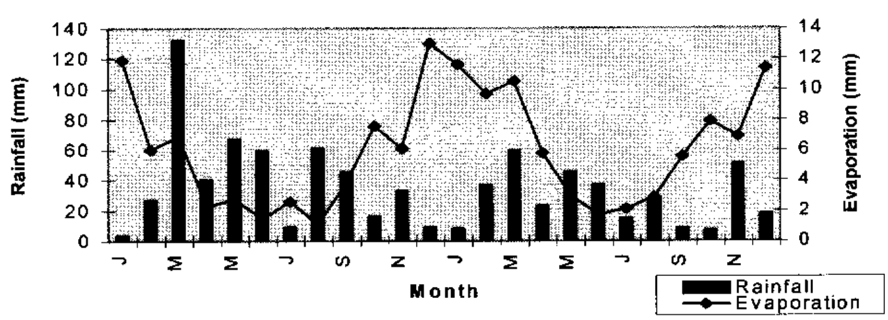


Figure 10: Monthly rainfall and monthly mean pan evaporation for the Kambalda region during 1992 and 1993.

Rainfall was more variable further from the coast, in Kambalda, than in Esperance. During 1992, 82% of the annual precipitation fell between March and September with a peak monthly rainfall event in March due to remnant cyclonic activity. In 1993, 33% of the annual precipitation was attributed to summer rainfall events in March and November, while 37% fell during May and August winter rainfall events.

4.1.2 Lake Depth and Salinity

4.1.2.1 Lakes in the Esperance Region

The depth of all lakes sampled in Esperance varied as climatic conditions varied from season to season (Figure 9, Table 2). Depths in Mullet Lake ranged from 0.70m to 1.80m; in Woody Lake Reserve Marsh from 0m to 1.50m; in Lake Wheatfield 1.10m to 2.30m; in Lake Warden from 0.72m to 2.25m; and in Pink Lake 0.15m to 1.10m. Water depth increased with decreasing evaporation and peak rainfall during both 1992 and 1993. Maximum depths occurred in July 1992 in Mullet Lake, September 1992 in Lake Wheatfield and Woody Lake Reserve Marsh and December 1992 in Pink Lake and Lake Warden. Woody Lake Reserve Marsh was the only lake in Esperance to dry out completely during this study.

Table 2: Lake depth (m) and surface water salinity (ppt) of lakes in Esperance, highlighted in Figure 6, during 1992 and 1993.

Lake	July 1992		Sep. 1992		Dec. 1992		Feb. 1993		April 1993		July 1993		Oct. 1993	
	ppt	m	ppt	m	ppt	m	ppt	m	ppt	m	ppt	m	ppt	m
Pink Lake	87.8	0.91	144	1.00	132	1.10	230	0.15	242	0.30	155	0.60	133	1.00
Lake Warden	67.3	0.72	32	2.00	28	2.25	42	2.00	47	1.65	48	1.92	39	2.00
Lake Wheatfield	8.6	1.54	5	2.30	1	1.53	12	1.50	6	1.10	8	1.50	6	1.10
Woody Lake Reserve Marsh	19.5	0.15	5	1.50	10	1.00	55	0.10	-	Dry	25	0.30	12	1.00
Mullet Lake	12.1	1.80	7	1.50	8	1.25	16	0.70	18	0.70	16	1.35	12	1.45

Where: (-) denotes no sampling regime conducted, and
(Dry) indicates no surface water present at time of sample collection

Surface water salinities were different in each lake, at each sampling time, during July 1992 to October 1993 (Table 2). Using the classification range reported by Hammer *et al.*, (1983), of the 5 lakes sampled in Esperance, Pink Lake remained hypersaline (ie >50ppt), Lake Warden was mostly mesosaline (ie 20-50ppt) but was hypersaline on one sampling occasion, Lake Wheatfield was predominantly hyposaline (ie 3-20ppt) with one subsaline (ie <3ppt) recording, Woody Lake Reserve Marsh fluctuated between hyposaline and hypersaline, and Mullet Lake was consistently hyposaline.

4.1.2.2 Lakes in the Kambalda Region

The depth of all lakes sampled in Kambalda, except for Mooreebar Dam, corresponded with evaporation and rainfall data (Figure 10, Table 3). Maximum lake depths were reached following highest rainfall figures and lowest evaporation rates. All lakes, except Lakes Why and Victory dried out during the study period. Golf Lake, Lake Zot and Lake Eaton North had completely dried out by October 1993. Binneridgie Road Marsh experienced an increase in depth (0.80m) between February 1993 and April 1993. Mooreebar Dam progressively dried from 3.4m depth in October 1992 to 0.03m in July 1993, and dried up in October 1993.

Lake depths ranged from 3.4m to 0m in Mooreebar Dam; 0.60m to 0.01m in residual pools in Lake Lefroy; 1.40m to 0.80m in Lake Victory; 1.0m to 0m in Binneridgie Road Marsh; 0.50m to 0m in Golf Lake; 0.30m to 0m in Lake Zot; 2.0m to 1.0m in Lake Why; and 1.2m to 0m in Lake Eaton North.

Table 3: Lake depth (m) and surface water salinity (ppt) of lakes in Kambalda, highlighted in Figure 1, during 1992 and 1993.

Lake	Oct. 1992		Jan. 1993		Feb. 1993		April 1993		July 1993		Oct. 1993	
	ppt	m	ppt	m	ppt	m	ppt	m	ppt	m	ppt	m
Mooreebar Dam	<1	3.40	1	2.40	4	2.00	6	1.30	12	0.03	-	Dry
Lake Lefroy	300	0.60	340	0.01	340	0.10	340	0.04	270	0.05	324	0.05
Victory Lake	324	1.40	-	1.10	300	1.10	340	0.90	324	0.80	308	0.80
Binneridgie Road Marsh	<1	1.00	-	Dry	-	Dry	<1	0.80	6	0.40	4	0.05
Golf Lake	255	0.50	350	0.30	340	0.30	274	0.05	260	0.15	-	Dry
Lake Zot	123	0.30	-	Dry	136	0.10	158	0.10	150	0.10	-	Dry
Lake Why	2	2.00	6	1.20	5	1.50	7	1.00	10	1.50	10	1.20
Lake Eaton North	21	1.20	69	0.60	136	0.30	178	0.03	111	0.02	-	Dry

Where: (-) denotes no sampling regime conducted, and
(Dry) indicates no surface water present at time of sample collection

Surface water salinities varied in each of the 8 lakes sampled in Kambalda during September 1992 to October 1993 (Table 3). Three of the lakes reached concentrations as high as 10 times that of sea water. The salinities recorded ranged from <1ppt in Mooreebar Dam and Binneridgie Road Marsh to 350ppt in Golf Lake. Lakes Lefroy, Golf, Zot and Victory Lake were consistently hypersaline, Lake Eaton North was mostly hypersaline with one recording within mesosaline limits, and Mooreebar Dam, Binneridgie Road Marsh and Lake Why ranged from subsaline to hyposaline.

4.1.2.3 The Relationship between Depth and Salinity

In all lakes, except Lake Wheatfield in Esperance and Lakes Lefroy, Victory and Golf in Kambalda, surface water salinity increased as lake depth decreased (Table 4).

Table 4: Pearson Correlation between lake depth (m) and surface water salinity (ppt) for each lake in Esperance and Kambalda sampled during 1992 and 1993.

Esperance Lakes	Correlation	Kambalda Lakes	Correlation
Pink Lake	- 0.874	Mooreebar Dam	- 0.940
Lake Warden	- 0.929	Lake Lefroy	- 0.322
Lake Wheatfield	- 0.109	Victory Lake	- 0.050
Woody Lake Reserve Marsh	- 0.773	Binneridgie Road Marsh	- 0.756
Mullet Lake	- 0.607	Golf Lake	0.085
		Lake Zot	- 0.809
		Lake Why	- 0.609
		Lake Eaton North	- 0.895

4.1.3 Ionic Composition

In all of the 13 lakes sampled sodium was the dominant cation and chloride the dominant anion (Table 5). The pattern of cationic dominance was Na>Mg>Ca>K in all lakes except Pink Lake and Golf Lake, in which the order was Na>Mg>K>Ca. Three of the hypersaline lakes from the Kambalda region, Lakes Lefroy, Zot and Eaton North had relatively higher levels of Ca than the coastal lakes in Esperance. The pattern of anionic dominance was Cl>SO_4 in all lakes, except Mooreebar Dam in Kambalda, where the order was Cl>HCO_3.

Table 5: Concentrations (meq L^{-1}) of major ions in surface waters from lakes in Esperance and Kambalda. Data included as <*x* indicates that ions were present in concentrations lower than the detection limits of analytical techniques employed. Iron is not presented as levels were less than detection limits (0.005 meq L^{-1}).

Water Source	Ionic Concentration (meq L^{-1})								
	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	CO_3^{2-}	NO_3^-	SO_4^{2-}
Esperance									
Pink Lake	3686.9	32.7	13.6	666.7	4575.9	10.1	<1	0.04	129.0
Lake Warden	503.5	5.0	8.73	73.2	515.6	1.1	3.1	0.006	19.5
Lake Wheatfield	59.1	0.6	2.24	10.78	64.9	2.54	0.07	0.005	6.41
Woody Lake Reserve Marsh	202.2	2.0	3.4	35.2	215.4	3.7	1.6	<0.2	17.6
Mullet Lake	109.1	1.0	3.0	17.2	122.4	1.5	1.0	0.003	10.4
Kambalda									
Mooreebar Dam	26.2	0.2	2.2	5.5	27.3	2.1	0.07	0.003	1.5
Lake Lefroy	5043.5	15.34	40.9	238.7	5134.6	-	0.73	-	208.1
Victory Lake	-	-	-	-	-	-	-	-	-
Binneridgie Road Marsh	-	-	-	-	-	-	-	-	-
Golf Lake	3434.8	58.6	13.9	1242	3986.6	2.7	<1	3.3	296.8
Lake Zot	3271.7	17.6	51.1	590.5	3560.6	-	6.5	-	201.9
Lake Why	33.9	0.2	1.7	5.3	35.2	0.3	0.9	0.005	1.5
Lake Eaton North	734.8	5.9	64.3	99.6	755.0	1.2	<1	0.005	53.3
Standard Sea Water	470.0	9.97	20.4	107.0	549.0	-	4.7	-	56.4

4.1.4 pH

The pH of lake waters varied slightly through the year in each of the lakes sampled (Table 6). Excluding one record of 6.5 taken in September 1992 at Woody Lake Reserve Marsh, all lakes in Esperance were alkaline. pH ranged from 7.5 to 9.6. Woody Lake Reserve Marsh experienced the largest range in pH, going from 6.5 to 9.6 respectively.

No strongly acidic or alkaline surface waters occurred in Kambalda (Table 6). Lake Lefroy was weakly acidic. The two other lakes in this region with salinities in excess of 255ppt, Victory Lake and Golf Lake, were also weakly acidic. Lake Zot and Lake Eaton North were neutral to weakly alkaline while the least saline lakes sampled, Mooreebar Dam, Binneridgie Road Marsh and Lake Why, were the most alkaline with pH between 8.4 and 10.6.

Table 6: pH values of surface waters from lakes sampled in Esperance and Kambalda during 1992 and 1993.

Lake Name	pH / Month Recorded 1992			1993				
	July	Sep.	Oct.	Jan.	Feb.	April	July	Oct.
Esperance								
Pink Lake	7.9	8.0	-	-	7.8	7.5	7.8	8.1
Lake Warden	8.2	7.5	-	-	9.4	9.5	8.7	8.7
Lake Wheatfield	8.2	7.6	-	-	8.4	8.8	8.2	8.6
Woody Lake Reserve Marsh	N.R.	6.5	-	-	8.7	Dry	8.5	9.6
Mullet Lake	8.3	7.6	-	-	8.5	8.7	8.1	8.9
Kambalda								
Mooreebar Dam	-	-	8.4	8.9	8.7	9.1	8.5	Dry
Lake Lefroy	-	-	6.4	6.5	6.8	7.0	6.9	6.9
Victory Lake	-	-	6.3	-	6.8	7.4	6.8	7.0
Binneridgie Road Marsh	-	-	9.0	Dry	Dry	9.3	10.1	9.3
Golf Lake	-	-	6.8	6.5	7.0	7.7	6.9	Dry
Lake Zot	-	-	7.1	Dry	7.2	8.0	7.4	Dry
Lake Why	-	-	9.0	10.6	10.3	10.2	9.3	10.3
Lake Eaton North	-	-	7.2	8.1	7.9	7.7	7.7	Dry

Where: (-) denotes no sampling regime conducted or pH not recorded, and
(Dry) indicates no surface water present at time of sample collection

4.1.5 Organic Nutrients and Light Penetration

The concentration of total phosphorus, soluble reactive phosphorus and total nitrogen showed considerable seasonal variability in all of the Esperance lakes, increasing from July 1993 to February 1994 (Table 7). Pink Lake had the highest total nitrogen concentration recorded, peaking at 28 mg/l. Lake Warden and Lake Wheatfield had the highest total phosphorus and soluble reactive phosphorus levels recorded. The TN:TP Atomic Ratios were highest in February 1994 for all lakes except Woody Lake Reserve Marsh which was dry. No nutrient data was recorded from the Lakes in Kambalda due to financial constraints.

Table 7: The total amount of phosphorus (P), soluble reactive phosphorus, total nitrogen (N) and total nitrogen (TN):total phosphorus (TP) atomic ratio from lakes in Esperance in July 1993, September 1993 and February 1994.

Lake Name	Total phosphorus (mg/l)			Soluble Reactive Phosphorus (mg/l)			Total Nitrogen (mg/l)			TN:TP Atomic Ratio		
	Jul	Sep	Feb	Jul	Sep	Feb	Jul	Sep	Feb	Jul	Sep	Feb
Pink Lake	0.05	0.03	0.02	<.01	<.01	<.01	4.6	5.9	28	203:1	435:1	3100:1
Lake Warden	0.16	0.04	0.06	0.02	0.01	0.01	4.6	3.3	6.8	63:1	182:1	251:1
Lake Wheatfield	0.08	0.07	0.07	<.01	0.02	0.01	1.9	2.4	3.0	52:1	76:1	95:1
Woody Lake Reserve Marsh	0.02	0.01	Dry	<.01	0.01	Dry	1.9	2.0	Dry	210:1	443:1	Dry
Mullet Lake	0.02	0.02	0.02	<.01	<.01	0.01	1.3	3.9	4.1	144:1	432:1	454:1

Secchi disc recordings have not been tabulated as the disc was visible to the lake bottom in all lakes in Kambalda and Esperance at each sampling occasion.

4.1.6 Water Temperature and Dissolved Oxygen

None of the lakes sampled in Esperance or Kambalda exhibited thermal stratification but temperatures in Lake Warden did vary markedly during a 24 hour period (Table 8, Figures 11, 12 and 13). Temperatures ranged from 11.8°C to 25.2°C in the Esperance lakes and 11.7°C to 27°C in the Kambalda lakes.

All of the lakes sampled were well oxygenated to the sediment. Supersatured dissolved oxygen levels were recorded at Woody Lake Reserve Marsh in October 1993, Binneridgie Road Marsh in July 1993, Lake Why in April, July and October 1993, Mooreebar Dam in April 1993, and Lake Warden in April, July and October 1993. Oxygen saturation levels in April, July and October 1993 were higher at the bottom of Lake Warden than at the surface during daylight hours and immediately after dusk, but were lower than the surface prior to dawn (Figures 11, 12 and 13).

Table 8: Water temperature (°C) and dissolved oxygen concentration (% saturation) of lakes, excluding Lake Warden, in both Esperance and Kambalda lake systems during April, July and October 1993.

Lake	April 1993				July 1993				October 1993	
	Temp.		Dis. O_2		Temp.		Dis. O_2		Temp.	Dis. O_2
Sampling Depth (m)	**0**	**0.5**	**0**	**0.5**	**0**	**0.5**	**0**	**1.0**	**0**	**0**
Esperance										
Pink Lake	25.2		77.5		14.5		85.6		17	98.6
Lake Wheatfield	18	17.6	105	102	12	11.9	117.7	61	16.5	111
Woody Lake Reserve Marsh	-		-		13.8		102.3		17.5	136
Mullet Lake	17	17	96.1	82.8	11.8		119		17	126
Kambalda										
Mooreebar Dam	23.4		132.5		-		-		Dry	Dry
Lake Lefroy	-		-		-		-		-	-
Victory Lake	26.7		78.8		14.3		76.2		27	62
Binneridgie Road Marsh	23.1		80.2		12.1		148.7		-	-
Golf Lake	-		-		-		-		Dry	Dry
Lake Zot	-		-		-		-		Dry	Dry
Lake Why	23.1		180.6		11.7	11.5	120.3	109	23	166
Lake Eaton North	-		-		-		-		Dry	Dry

Where: (-) denotes surface water too shallow for data collection, and
(Dry) indicates no surface water present at time of sample collection

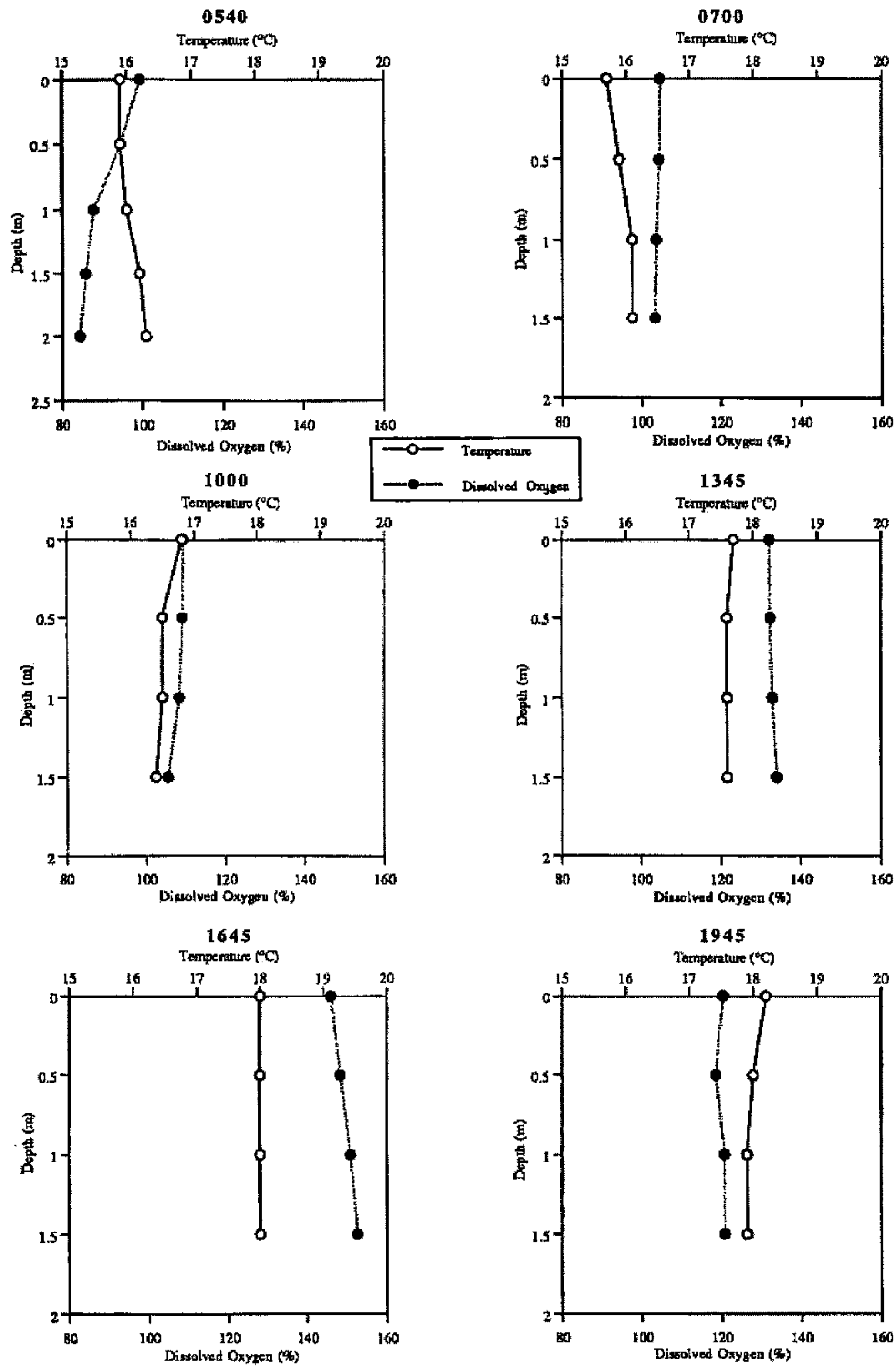


Figure 11: Water temperature (°C) and dissolved oxygen concentration (% saturation) data collected from Lake Warden, at specific depths in the water column, at specific times of the day, in April 1993. Dawn was at 0600 and dusk at 1800.

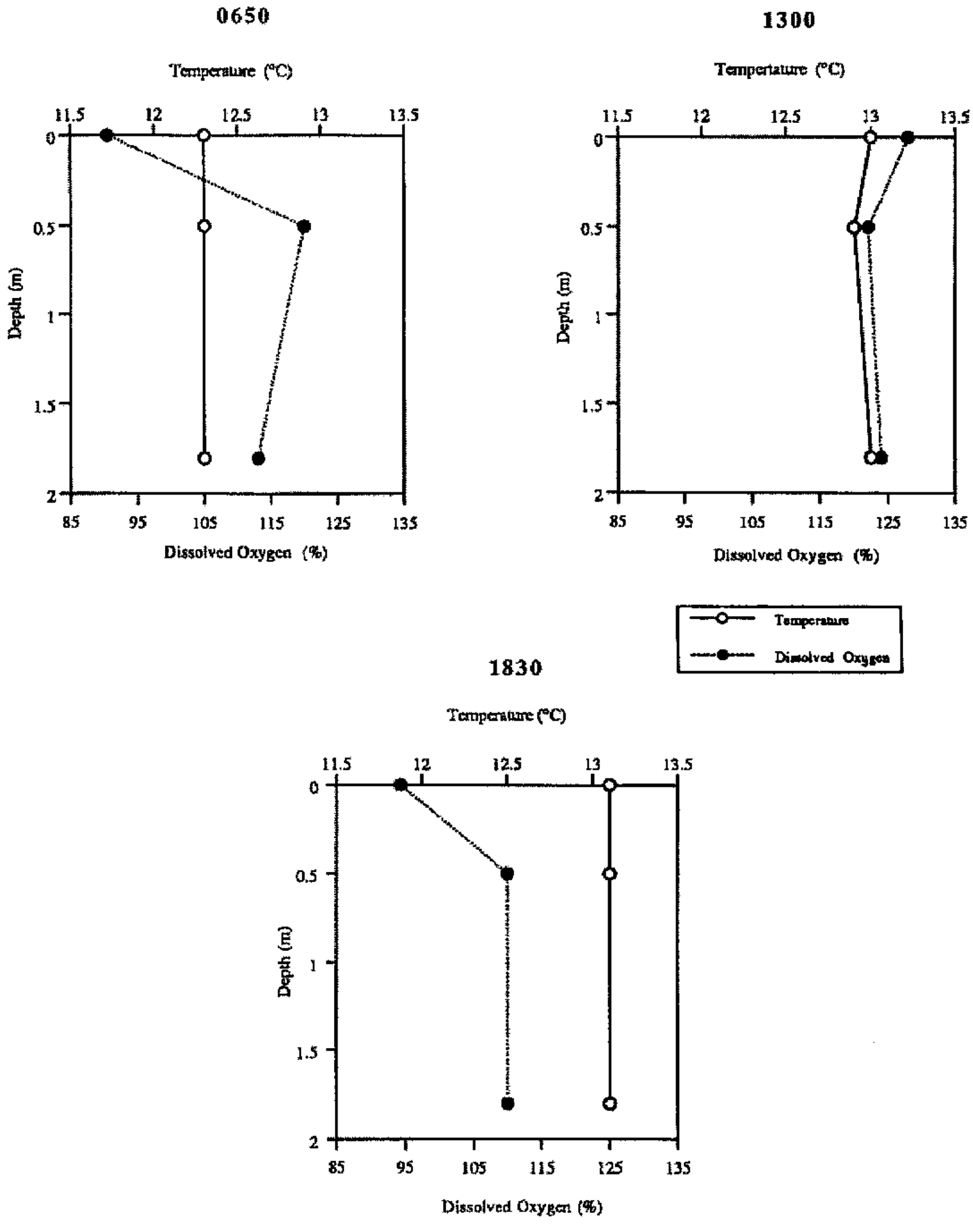


Figure 12: Water temperature (°C) and dissolved oxygen concentration (% saturation) data recorded in July 1993 from Lake Warden, at specific depths in the water column, at 0650, 1300 and 1830. Dawn was at 0700 and dusk at 1730.

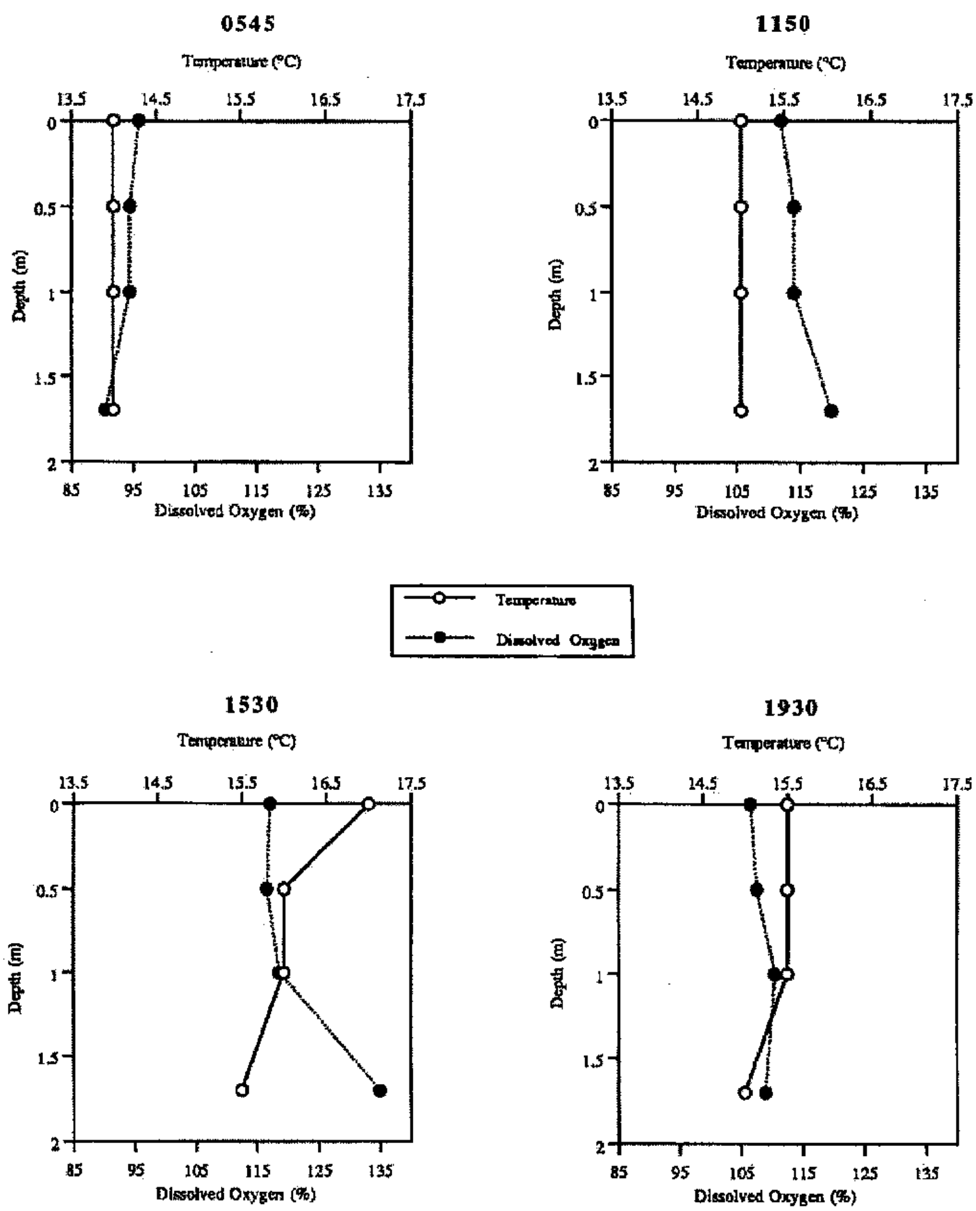


Figure 13: Water temperature (°C) and dissolved oxygen concentration (% saturation) data recorded in October 1993 from Lake Warden, at specific depths in the water column, at 0545, 1150, 1530 and 1930. Dawn was at 0520 and dusk at 1800.

4.2 Biological Limnology

4.2.1 Algal Flora Taxa Recorded

A total of 171 algal taxa, representing 5 divisions, were identified from the 13 saline lakes sampled in Esperance and Kambalda (Table 9). Thirty two genera and 82 species were identified from the division Bacillariophyta, 22 genera and 48 species from the division Cyanophyta, 23 genera and 33 species from the division Chlorophyta, one genus and two species of Euglenophyta and four genera and six species of Dinophyta were recorded. Iconographs of representative algal species are presented in Appendix 3.

One species, *Amphora coffeaeformis* occurred in all lakes in Esperance and Kambalda. Three species of cyanobacteria; *Microcoleus vaginatus*, *Phormidium* sp. 2 and *Spirulina major*, one species of chlorophyta; *Pediastrum boryanum*, and 12 species of bacillariophyta; *Amphora veneta*, *Amphora ventricosa*, *Navicella pusilla*, *Hantzschia amphioxys*, *Luticola mutica*, *Navicula cincta*, *Navicula cryptocephala*, *Navicula subinflatoides*, *Navicula sp1.*, *Nitzschia communis*, *Nitzschia* aff. *fonticola*, and *Triblionella apiculata*, occurred in more than 69% of lakes in Esperance and Kambalda.

A total of 132 algal taxa were recorded from lakes sampled in Esperance and 113 algal taxa were recorded from lakes in the Kambalda region. One species of cyanobacteria; *Chroococcus minutus*, 3 species of bacillariophyta; *Cocconeis placentula*, *Navicula elegans*, and *Rhopalodia musculus*, and 2 species of dinophyta; *Prorocentrum sp1.* and Dinoflagellate sp1. were found in all lakes in Esperance but not in Kambalda. One dinoflagellate; *Glenodinium* sp.1, was found in all lakes sampled in Kambalda.

Table 9: All algal species collected from saline lakes in the Esperance region (E) and in the Kambalda region (K), Western Australia during 1992-93, their voucher specimen details and their frequency of occurrence (% lakes). Diatom voucher specimens have been lodged in the International Diatom Herbarium, Curtin University and other taxa have been lodged with Environmental Biology Algal Collection, Curtin University.

Algal Species Name	Specimen Collection Details	Voucher#	% Lakes		
CYANOBACTERIA			E	K	All
Chroococcales					
Aphanocapsa elachista	Mullet Lake (B) 27/9/92	92-K-009	60	0	**23**
Aphanocapsa koodersi	Lake Wheatfield (P) 6/12/92	92-E-010	20	25	**23**
Aphanocapsa littoralis	Lake Wheatfield (P) 5/7/92	92-E-011	60	12	**31**
Aphanothece saxicola	Mullet Lake (Per) 27/9/92	92-E-002	20	0	**15**
	Lake Wheatfield (B) 6/7/92	92-E-013			
Chroococcidiopsis indica	Pink Lake (B) 17/4/93	93-E-020	20	38	**31**
Chroococcus limneticus	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	20	0	**8**
Chroococcus minutus	Lake Warden (B) 30/9/92	92-E-006	100	25	**54**
	Lake Wheatfield (P) 5/7/92	92-E-011			
Chroococcus turgidis	Pink Lake (B) 30/9/92	92-E-019	60	25	**38**
Dactylococcopsis rhaphiodiodes	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	20	0	**15**
Entophysalis sp.1	Lake Zot (B) 17/10/92	92-K-059	20	25	**31**
Gloeocapsa punctata	Lake Warden (B) 30/9/92	92-E-006	20	0	**15**
Gloeocapsa polydermatica	Mullet Lake (P) 14/2/93	93-E-023	20	0	**15**

Table 9 continued

Algal Species Name	Specimen Collection Details	Voucher#	% Lakes		
Gomphosphaeria aponina	Mullet Lake (P) 27/9/92	92-E-024	20	0	**8**
Gomphosphaeria lacustris	Lake Wheatfield (B) 14/2/93	93-E-025	20	0	**8**
Merismopedia punctata	Lake Wheatfield (P) 5/7/92	92-E-011	80	25	**62**
Microcystis aeruginosa	Lake Why (P) 18/7/93	93-K-064	0	25	**15**
Microcystis littoralis	Lake Wheatfield (P) 14/2/93	93-E-003	60	0	**23**
Microcystis pulverea	Mooreebar Dam (P) 17/10/92	92-K-066	0	12	**8**
Microcystis robusta	Binneridgie Road Marsh (Per) 17/10/92	92-K-065	0	12	**8**
Pluerocapsa minor	Lake Wheatfield (Per) 21/7/93	93-E-008	20	0	**8**
Pleurocapsa sp.1	Lake Warden (P) 13/2/93	93-E-041	40	38	**31**
Synechococcus aeruginosus	Pink Lake (B) 17/4/93	93-E-020	80	38	**54**
Oscillatoriales					
Lyngbya birgei	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	20	0	**8**
Lyngbya sp.1	Pink Lake (B) 30/9/92	92-E-019	20	12	**25**
	Mooreebar Dam (Per) 18/4/93	93-K-062			
Microcoleus vaginatus	Lake Warden (B) 8/7/92	92-E-030	40	88	**69**
	Lake Why (B) 13/1/93	93-K-063			
Microcoleus sp. 1	Pink Lake (B) 9/7/92	92-E-021	20	12	**25**
	Lake Zot (B) 18/7/93	93-K-058			
Oscillatoria agardii	Woody Lake Reserve Marsh (Per) 29/9/92	92-E-005	60	0	**23**
Oscillatoria limnetica	Lake Wheatfield (Per) 6/12/92	92-E-034	20	50	**38**
Oscillatoria sp.1	Lake Wheatfield (Per) 21/7/93	93-E-008	80	25	**46**
Oscillatoria sp.2	Pink Lake (B) 9/7/92	92-E-021	0	62	**38**
	Lake Zot (B) 18/7/93	93-K-058			
Phormidium fragile	Woody Lake Reserve Marsh (B) 2/7/92	92-E-016	80	0	**31**
Phormidium sp.1	Pink Lake (P) 17/4/93	93-E-026	60	0	**23**
Phormidium sp.2	Lake Wheatfield (Per) 14/2/93	93-E-038	80	75	**77**
Schizothrix sp.1	Pink Lake (B) 30/9/92	92-E-019	20	0	**8**
Schizothrix sp.2	Lake Lefroy (B) 18/7/93	93-K-071	0	62	**38**
Schizothrix sp.3	Mooreebar Dam (B) 18/7/93	93-K-072	0	12	**8**
Schizothrix sp.4	Lake Warden (Per) 8/7/92	92-E-050	20	0	**8**
Spirulina major	Pink Lake (B) 15/2/93	93-E-031	60	75	**69**
Spirulina subsalsa	Pink Lake (B) 17/4/93	93-E-020	20	12	**15**
Spirulina sp.1	Mullet Lake (Per) 27/9/92	92-E-004	80	50	**62**
Nostocales					
Anabaena spiroides	Lake Wheatfield (Per) 21/7/93	93-E-008	60	25	**38**
Anabaena sp.1	Mullet Lake (Per) 27/9/92	92-E-001	0	75	**46**
Anabaena musicola	Pink Lake (P) 15/2/93	93-E-017	40	0	**15**
Anabaena sp.2	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-007	20	50	**38**
Calothrix sp.1	Mullet Lake (Per) 27/9/92	92-E-002	80	0	**31**
	Lake Wheatfield (Per) 6/7/92	92-E-012			
Calothrix sp.2	Binneridgie Road Marsh (Per) 18/4/93	93-K-056	0	12	**8**
Nodularia sp.1	Lake Warden (B) 8/7/92	92-E-032	20	0	**8**
Nostoc sp.1	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	60	0	**23**
CHLOROPHYTA					
Volvocales					
Chlamydomonas sp.1	Lake Wheatfield (P) 21/7/93	93-E-045	60	0	**23**
Chlamydomonas sp.2	Mooreebar Dam (P) 18/4/93	93-K-075	20	38	**31**
	Lake Why (P) 24/10/93	93-K-076			
Dunaliella salina	Golf Lake (P) 18/4/93	93-K-080	20	50	**38**
Dunaliella viridis	Lake Zot (B) 18/4/93	93-K-081	20	25	**23**
Chlorococcales					
Akistrodesmus spiralis	Binneridgie Road Marsh (Per) 18/4/93	93-K-056	0	25	**15**
Botryococcus braunii	Lake Wheatfield (P) 5/7/92	92-E-011	60	38	**46**
Chlorella sp.1	Lake Wheatfield (Per) 14/2/93	93-E-046	20	0	**8**
Cladophora sp.1	Lake Warden (Per) 5/12/92	92-E-042	60	12	**31**
	Binneridgie Road Marsh (Per) 17/10/92	92-K-065			
Oocystis parva	Lake Warden (B) 30/9/92	92-E-006	80	50	**62**
	Binneridgie Road Marsh (Per) 18/4/93	93-K-056			
Pediastrum boryanum	Lake Why (P) 6/2/93	93-K-061	60	88	**77**
	Binneridgie Road Marsh (B) 17/10/92	92-K-068			
Scenedesmus quadricauda	Binneridgie Road Marsh (B) 17/10/92	92-K-068	60	50	**54**
Oedogoniales					
Oedogonium undulatum	Binneridgie Road Marsh (Per) 17/10/92	92-K-065	0	62	**38**
Oedogonium sp.1	Woody Lake Reserve Marsh (Per) 2/7/92	92-E-048	20	12	**15**
Uloticales					
Schizomeris sp.1	Lake Warden (P) 13/2/93	93-E-041	20	0	**8**
Microspora sp.1	Lake Warden (Per) 28/9/92	92-E-033	80	0	**31**

Table 9 continued

Algal Species Name	Specimen Collection Details	Voucher#	% Lakes		
Zygnematales					
Closterium pronum	Mooreebar Dam (B) 10/2/93	93-K-077	0	38	**23**
Closterium parvulum	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	20	62	**46**
Closterium acutum	Mooreebar Dam (P) 13/1/93	93-K-054	0	12	**8**
Cosmarium granatum	Woody Lake Reserve Marsh (P) 10/12/92	92-E-043	20	88	**62**
Cosmarium quadrifarium	Lake Why (P) 18/7/93	93-K-064	0	12	**8**
Cosmarium retusiforme	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	20	50	**38**
	Lake Why (B) 13/1/93	93-K-073			
Euastrum verrucosum	Lake Why (Per) 18/10/92	92-K-055	0	88	**54**
Mougeotia sp.1	Woody Lake Reserve Marsh (Per) 29/9/92	92-E-005	20	0	**8**
Mougeotia sp.2	Mooreebar Dam (B) 13/1/93	93-K-082	0	25	**15**
Pleurotaenium ehrenbergii	Binneridgie Road Marsh (Per) 18/4/93	93-K-056	0	50	**31**
Spirogyra sp.1	Mooreebar Dam (P) 17/10/92	92-K-066	0	12	**8**
Staustrum gracile	Binneridgie Road Marsh (Per) 17/10/92	92-K-065	0	50	**31**
Zygnema sp.1	Binneridgie Road Marsh (Per) 17/10/92	92-K-065	0	12	**8**
Tetrasporales					
Gloeocystis sp.1	Lake Wheatfield (P) 5/7/92	92-E-011	60	25	**38**
	Binneridgie Road Marsh (Per) 18/4/93	93-K-056			
Gloeocystis sp.2	Mullet Lake (Per) 27/9/92	92-E-004	20	0	**8**
Charales					
Lamprothamnium papulosum	Mullet Lake 6/12/92	92-E-014	80	12	**38**
Nitella lhotzkyi	Binneridgie Road Marsh 30/12/92	92-K-087	0	25	**15**
Nitella subtilissima	Lake Why 18/10/92	92-K-088	0	12	**8**
EUGLENOPHYTA					
Euglena sp.1	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-028	60	0	**23**
Euglena sp.2	Mooreebar Dam (P) 18/4/93	93-K-075	0	50	**31**
BACILLARIOPHYTA					
Achnanthes brevipes	Lake Warden (Per) 28/9/92	92-E-014	60	0	**23**
Achnanthes coarctata	Lake Warden (B) 28/9/92	92-E-013	20	0	**8**
Achnanthes lanceolata var dubia	Lake Warden (B) 28/9/92	92-E-013	80	12	**38**
Achnanthidium cruciculum	Lake Wheatfield 14/2/93	93-E-001	80	12	**38**
Achnanthidium minutissimum	Mooreebar Dam (Per) 17/10/92	92-K-027	0	25	**15**
Achnanthidium aff. *delicatulum*	Lake Wheatfield (B) 21/7/93	93-E-024	20	0	**8**
Amphora coffeaeformis	Lake Warden (B) 8/7/92	92-E-009	100	100	**100**
Amphora veneta	Woody Lake Reserve Marsh (Per) 2/7/92	92-E-007	80	62	**69**
Amphora ventricosa	Woody Lake Reserve Marsh (P) 14/2/93	93-E-019	80	75	**77**
Berkeleya rutilans	Woody Lake Reserve Marsh (P) 14/2/93	93-E-019	80	0	**31**
Berkeleya scopulorum	Lake Wheatfield (Per) 12/7/92	92-E-005	40	0	**15**
Brachysira aponina	Mullet Lake (Per) 12/7/92	92-E-003	20	0	**8**
Brachysira serians	Lake Wheatfield (P) 14/4/93	93-E-021	60	38	**46**
Caloneis bacillum	Mooreebar Dam (P) 13/1/93	93-K-034	0	25	**15**
Campylodiscus clypeus	Lake Wheatfield 14/2/93	93-E-001	40	0	**15**
Chaetoceros muelleri	Lake Wheatfield 14/2/93	93-E-001	20	12	**15**
Cocconeis placentula	Mullet Lake (Per) 12/7/92	92-E-003	100	0	**38**
Craticula cuspidata	Mooreebar Dam (B) 17/10/92	92-K-026	0	38	**23**
Ctenophora pulchella var lacerata	Mooreebar Dam (Per) 17/10/92	92-K-027	0	25	**15**
Cyclotella atomus	Lake Wheatfield (Per) 6/12/92	92-E-015	40	0	**15**
Cyclotella meneghiniana	Woody Lake Reserve Marsh (P) 29/9/92	92-E-012	60	12	**31**
Cyclotella stelligera	Mooreebar Dam (Per) 13/1/93	93-K-033	0	12	**8**
Cyclotella striata	Lake Wheatfield (P) 14/2/93	93-E-001	60	0	**23**
Cylindrotheca closterium	Lake Warden (B) 30/9/02	92-E-006	40	12	**23**
Diploneis ovalis	Lake Warden (B) 8/7/92	92-E-008	80	12	**38**
Entomoneis alata	Mullet Lake (P) 27/9/92	92-E-011	80	38	**54**
Eunotia pectinalis var undulata	Mooreebar Dam (B) 17/10/92	92-K-026	0	12	**8**
Staurosira construens	Lake Wheatfield (Per) 6/12/92	92-E-015	20	12	**15**
	Lake Why (P) 13/1/93	93-K-035			
Frustulia interposita	Lake Wheatfield (B) 21/7/93	93-E-024	20	0	**8**
Gomphonema gracile	Mooreebar Dam (B) 17/10/92	92-K-026	0	12	**8**
Gyrosigma balticum	Lake Wheatfield (P) 14/2/93	93-E-001	20	12	**15**
	Mooreebar Dam (B) 18/7/93	93-K-037			
Hantzschia amphioxys	Woody Lake Reserve Marsh (B) 2/7/92	92-E-006	100	88	**92**
Hantzschia aff. *amphioxys gracilis*	Mooreebar Dam (B) 17/10/92	92-K-026	0	38	**23**
Hyppodonta capitata	Lake Warden (Per) 5/12/92	92-E-043	20	0	**8**
Kobayasiella subtilissima	Mooreebar Dam (Per) 17/10/92	92-K-027	0	25	**15**

Table 9 continued

Algal Species Name	Specimen Collection Details	Voucher#	% Lakes		
Luticola mutica	Lake Warden (B) 28/9/92	92-E-013	60	88	**77**
Martyana martyi	Lake Wheatfield (P) 14/2/93	93-E-001	80	12	**38**
Mastogloia elliptica	Mullet Lake (B) 12/7/92	92-E-002	40	0	**15**
Mastogloia halophila	Mullet Lake (B) 12/7/92	92-E-002	60	0	**23**
Mastogloia pumila	Lake Wheatfield (Per) 6/12/92	92-E-015	80	25	**46**
Mastogloia pusilla	Woody Lake Reserve Marsh (B) 21/7/92	92-B-095	20	12	**15**
Mastogloia reimeri	Mullet Lake (P) 27/9/92	92-E-011	20	0	**8**
Mastogloia smithii	Mullet Lake (Per) 14/2/93	93-E-018	60	25	**38**
Navicella pusilla	Mullet Lake (B) 12/7/92	92-E-002	100	75	**85**
Navicula aff. *anglica*	Lake Wheatfield (B) 12/7/92	92-E-004	80	0	**31**
Navicula cincta	Woody Lake Reserve Marsh (B) 2/7/92	92-E-006	100	88	**92**
Navicula cryptocephala	Mooreebar Dam (B) 17/10/92	92-K-026	80	62	**69**
Navicula cryptocephala var. intermedia	Lake Warden (B) 28/9/92	92-E-013	20	0	**8**
Navicula directa	Lake Wheatfield (Per) 12/7/92	92-E-005	80	0	**31**
Navicula elegans	Woody Lake Reserve Marsh (B) 2/7/92	92-E-006	100	12	**46**
Navicula aff. *howeana*	Lake Warden (Per) 21/7/93	93-E-045	20	0	**8**
Navicula aff. *minusculus*	Lake Zot (P) 18/7/93	93-K-038	0	38	**23**
Navicula muralis	Lake Warden (B) 8/7/92	92-E-042	20	0	**8**
Navicula rhynchocephala	Lake Wheatfield (B) 21/7/93	93-E-024	20	0	**8**
Navicula subinflatoides	Lake Warden (B) 8/7/92	92-E-009	80	62	**69**
Navicula subrhynchocephala	Lake Wheatfield (Per) 6/12/92	92-E-015	20	0	**8**
Navicula tripunctata	Lake Wheatfield (Per) 6/12/92	92-E-015	80	25	**46**
Navicula sp.1	Lake Wheatfield (Per) 6/12/92	92-E-015	100	75	**85**
Nitzschia communis	Lake Zot (B) 17/10/92 Lake Warden (Peri) 8/7/92 Golf Lake (P) 18/10/92	92-K-028 92-E-010 92-K-025	60	75	**69**
Nitzschia aff. *fonticola*	Lake Wheatfield (Per) 6/12/92	92-E-015	80	75	**80**
Nitzschia lorenziana	Mooreebar Dam (P) 18/7/93	93-K-036	0	12	**8**
Nitzschia obtusa	Lake Warden (B) 8/7/92	92-E-009	20	0	**8**
Nitzschia palea	Woody Lake Reserve Marsh (Per) 10/12/92	92-E-017	80	38	**54**
Nitzschia punctata	Lake Warden (B) 8/7/92	92-E-008	40	0	**15**
Nitzschia sigma	Lake Wheatfield (Per) 6/12/92	92-E-015	80	38	**54**
Nitzschia sp.1	Mooreebar Dam (B) 17/10/92	92-K-026	0	38	**23**
Pinnularia biceps	Binneridgie Road Marsh (B) 18/7/93	93-K-041	0	12	**8**
Pinnularia borealis	Mooreebar Dam (B) 17/10/92	92-K-032	20	38	**31**
Pinnularia obscura	Woody Lake Reserve Marsh (P) 14/2/93	93-E-019	20	25	**23**
Pleurosigma salinarum	Woody Lake Reserve Marsh (P) 10/12/92	92-E-016	80	25	**46**
Rhopalodia gibba	Binneridgie Road Marsh (Per) 17/10/92	92-K-029	0	38	**23**
Rhopalodia musculus	Mullet Lake (B) 12/7/92	92-E-002	100	25	**46**
Stauroneis acuta	Lake Wheatfield (B) 21/7/93	93-E-024	20	0	**8**
Stauroneis anceps	Binneridgie Road Marsh (Per) 17/10/92	92-K-030	0	25	**15**
Stauroneis pachycephala	Lake Warden (P) 15/4/93	93-E-044	20	0	**8**
Stauroneis spicula	Mooreebar Dam (B) 18/4/93	93-K-040	40	12	**23**
Stauroneis sp.1	Pink Lake (P) 20/7/93	93-E-022	20	38	**31**
Surirella ovalis	Lake Warden (B) 21/7/93	93-E-023	20	0	**8**
Synedra acus	Mullet Lake (Per) 12/7/92	92-E-003	80	12	**38**
Tabularia fasciculata	Lake Wheatfield (Per) 6/12/92	92-E-015	80	25	**46**
Thalassiosira weissflogii	Woody Lake Reserve Marsh (P) 29/9/92	92-E-012	80	0	**31**
Triblionella apiculata	Mooreebar Dam (B) 17/10/92	92-K-026	60	75	**69**
DINOPHYTA					
Prorocentrum balticum	Golf Lake (P) 6/2/93	93-K-051	20	38	**31**
Prorocentrum sp.1	Mullet Lake (P) 27/9/92	92-E-024	100	0	**38**
Glenodinium sp.2	Golf Lake (P) 6/2/93	93-K-051	0	100	**62**
Glenodinium sp.3	Binneridgie Road Marsh (B) 17/10/92	92-K-068	0	12	**8**
Gymnodinium splendens	Mullet Lake (P) 12/7/92	92-E-039	60	0	**23**
Dinoflagellate sp.1	Pink Lake (P) 30/9/92	92-E-047	100	0	**38**

Where: Per = periphytic, P = planktonic and B = benthic samples

4.2.2 Benthic Microbial Mats

Three types of microbial mat were collected from lakes in the Esperance region during this study. One type of microbial mat was collected from Kambalda (Table 10). Two of the mats collected in Esperance, from Pink Lake and Woody Lake Reserve Marsh, were constructed in a similar way. Filaments of cyanobacteria were mechanically entangled, binding coccoid chlorophyta and bacillariophyta genera within the filaments. The mat collected from Lake Warden was constructed by the mechanical entanglement of filaments from chlorophyta genera, with bacillariophyta trapped within the filaments. The physical entanglement of filamentous cyanobacteria was coupled with the binding action of mucilage produced by coccoid cyanobacteria to construct the mat collected from Lake Zot in Kambalda. Bacillariophyta species were trapped within these filaments and mucilage.

Table 10: Physical description, *in situ* location and community composition of benthic microbial mats collected from lakes in Esperance and Kambalda.

Lake	Salinity	Mat Description	Algal Flora
Esperance			
Pink Lake	87.8ppT to 242ppT	Yellow-pink or black cohesive, laminated, rubbery mat, 1 to 5mm thick. Present on Lake floor and margins throughout duration of investigation. Constructed primarily from 5 genera of filamentous cyanobacteria with 2 genera of coccoid cyanobacteria and 2 species of pennate bacillariophyta bound within.	*Entophysalis* sp.1 *Lyngbya* sp. 1 *Microcoleus* sp.1 *Oscillatoria* sp.2 *Schizothrix* sp.1 *Spirulina major* *Synechococcus aeruginosus* *Navicula cincta* *Navicula* sp. 1
Woody Lake Reserve Marsh	10ppT	Thin, unlaminated, cohesive mat growing like carpet over Lake floor. Present during December 1992 sample collection. Constructed primarily from 4 genera of filamentous cyanobacteria with 4 genera of coccoid cyanobacteria, 9 pennate bacillariophyta and 4 genera of coccoid chlorophyta bound within. Filaments of 2 chlorophyta genera present too.	*Anabaena spiroides* *Calothrix* sp.1 *Chroococcus limneticus* *Dactylococcopsis rhaphidiodes* *Entophysalis* sp.1 *Gloeocapsa polydermatica* *Lyngbya birgei* *Nostoc* sp.1 *Achnanthidium* aff. *delicatulum* *Amphora coffeaeformis* *Amphora ventricosa* *Navicella pusilla* *Navicula cincta* *Nitzschia palea* *Nitzschia* aff. *fonticola* *Rhopalodia musculus* *Synedra acus* *Botryococcus braunii* *Cladophora* sp.1 *Euglena* sp.1 *Microspora* sp.1 *Pediastrum boryanum* *Scenedesmus quadricauda*

Table 10 continued

Lake	Salinity	Mat Description	Algal Flora
Lake Warden	28ppT to 67.3ppT	Thin, green, fibrous, unlaminated, cohesive mat on Lake floor in littoral zone. Present from July 1992 through to July 1993 sample collection. Constructed primarily from 3 genera of chlorophyta with 4 bacillariophyta species trapped within.	*Cladophora* sp.1 *Microspora* sp.1 *Schizomeris* sp.1 *Amphora coffeaeformis* *Cocconeis placentula* *Martyana martyi* *Tabularia fasiculata*
Kambalda			
Lake Zot	123ppt to 150ppT	Thick, rubbery, laminated, algal mat. Collected during October 1992 and July 1993 sample collections. Constructed from 5 genera of filamentous cyanobacteria and 2 species of coccoid cyanobacteria with 6 species of bacillariophyta bound within.	*Anabaena* sp.1 *Chroococcodiopsis indica* *Chroococcus minutus* *Microcoleus* sp.1 *Oscillatoria* sp.2 *Schizothrix* sp.2 *Spirulina major* *Amphora coffeaeformis* *Navicella pusilla* *Entomoneis alata* *Navicula cincta* *Navicula* sp.1 *Nitzschia* aff. *fonticola*

4.3 The Biota of Lakes in Esperance and Kambalda - Regional Differences

4.3.1 Lakes in the Esperance Region

There was no significant difference within the species diversity indices of lakes sampled from the Esperance region (Table 11). No specific lake was significantly more, or less, diverse than another during this study. There was also no significant difference between the species diversity indices calculated at different sampling times during the study (Table 11), indicating there was no detectable difference in species diversity within lakes in Esperance.

Table 11: Two-way ANOVA summary table of species diversity for Lakes within the Esperance region, relating to lake location and time of sampling (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Lake	4	0.51410	0.12852	2.03	0.138
Season	4	0.06194	0.01548	0.24	0.909
Error	16	1.01310	0.06332		
Total	24	1.58914			

There was a significant difference between the species richness of lakes sampled from the Esperance region at an alpha of 0.05, but no significant difference at an alpha of 0.01 (Table 12). There was no significant seasonal influence on species richness. No significant difference was indicated between species richness recorded from samples collected at different sampling time (Table 12).

Table 10 continued

Lake	Salinity	Mat Description	Algal Flora
Lake Warden	28ppT to 67.3ppT	Thin, green, fibrous, unlaminated, cohesive mat on Lake floor in littoral zone. Present from July 1992 through to July 1993 sample collection. Constructed primarily from 3 genera of chlorophyta with 4 bacillariophyta species trapped within.	*Cladophora* sp.1 *Microspora* sp.1 *Schizomeris* sp.1 *Amphora coffeaeformis* *Cocconeis placentula* *Martyana martyi* *Tabularia fasiculata*
Kambalda Lake Zot	123ppt to 150ppT	Thick, rubbery, laminated, algal mat. Collected during October 1992 and July 1993 sample collections. Constructed from 5 genera of filamentous cyanobacteria and 2 species of coccoid cyanobacteria with 6 species of bacillariophyta bound within.	*Anabaena* sp.1 *Chroococcodiopsis indica* *Chroococcus minutus* *Microcoleus* sp.1 *Oscillatoria* sp.2 *Schizothrix* sp.2 *Spirulina major* *Amphora coffeaeformis* *Navicella pusilla* *Entomoneis alata* *Navicula cincta* *Navicula* sp.1 *Nitzschia* aff. *fonticola*

4.3 The Biota of Lakes in Esperance and Kambalda - Regional Differences

4.3.1 Lakes in the Esperance Region

There was no significant difference within the species diversity indices of lakes sampled from the Esperance region (Table 11). No specific lake was significantly more, or less, diverse than another during this study. There was also no significant difference between the species diversity indices calculated at different sampling times during the study (Table 11), indicating there was no detectable difference in species diversity within lakes in Esperance.

Table 11: Two-way ANOVA summary table of species diversity for Lakes within the Esperance region, relating to lake location and time of sampling (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Lake	4	0.51410	0.12852	2.03	0.138
Season	4	0.06194	0.01548	0.24	0.909
Error	16	1.01310	0.06332		
Total	24	1.58914			

There was a significant difference between the species richness of lakes sampled from the Esperance region at an alpha of 0.05, but no significant difference at an alpha of 0.01 (Table 12). There was no significant seasonal influence on species richness. No significant difference was indicated between species richness recorded from samples collected at different sampling time (Table 12).

Table 12: Two-way ANOVA summary of species richness for Lakes within Esperance, relating to lake location and time of sampling (alpha = 0.05 and 0.01).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Lake	4	1530.0	382.5	3.69	0.026
Season	4	123.2	30.8	0.30	0.876
Error	16	1658.8	103.7		
Total	24	3312.0			

4.3.2 Lakes in the Kambalda Region

There was a significant difference within the species diversity indices of lakes from the Kambalda region (Table 13). Binneridgie Road Marsh supported the most diverse algal flora (Table 14). While not significantly more diverse than Lake Why, Mooreebar Dam, Lake Eaton North and Lake Zot, Binneridgie Road Marsh was significantly more diverse than Golf Lake, Victory Lake and Lake Lefroy. Lake Lefroy and Victory Lake were the least diverse of lakes sampled (Table 14). Their species diversity was not significantly different from Golf Lake and Lake Zot but, in addition to Binneridgie Road Marsh, they were significantly less diverse than Lake Eaton North, Mooreebar Dam, and Lake Why.

Table 13: One- way ANOVA summary table of species diversity for Lakes within the Kambalda region, relating to lake location (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Lake	7	4.9001	0.7000	16.47	0.000
Error	28	1.1903	0.0425		
Total	35	6.0904			

Table 14: Scheffe` Test Summary Table of the mean species diversity indices for Lakes sampled within the Kambalda region. Underscoring indicates means that do not differ significantly at alpha 0.05.

Lk Lefroy	Victory Lk	Golf Lk	Lk Zot	Lk Eaton	Mooreebar Dam	Lk Why	Binneridgie Marsh
(0.252)	(0.238)	(0.315)	(0.836)	(0.860)	(1.074)	(1.074)	(1.172)

There was no significant difference within the species diversity indices of the lakes from Kambalda at different sampling times during the study (Table 15) indicating there was no significant seasonal difference in species diversity.

Table 15: One-way ANOVA summary table of species diversity for Lakes within the Kambalda region, relating to sampling time (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Season	4	0.255	0.064	0.34	0.850
Error	31	5.835	0.188		
Total	35	6.090			

The species richness of lakes sampled from the Kambalda region were significantly different (Table 16). Binneridgie Road Marsh was the most species rich lake sampled in the Kambalda region (Table 17). It did not support significantly more algal species than Mooreebar Dam and Lake Why but did support significantly more species than Lake Eaton, Lake Zot, Lake Lefroy, Golf Lake and Victory Lake. Lakes Victory, Golf, Lefroy and Zot were the least species rich lakes sampled during this investigation (Table 17).

Table 16: One-way ANOVA summary table of species richness for Lakes within the Kambalda region, relating to lake location (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Lake	7	7216.4	1030.9	22.01	0.000
Error	28	1311.7	46.8		
Total	35	8528.0			

Table 17: Scheffe` Test Summary Table of the mean species richness for Lakes sampled within the Kambalda region. Underscoring indicates means that do not differ significantly at alpha 0.05.

Victory Lk	Golf Lk	Lk Lefroy	Lk Zot	Lk Eaton	Lk Why	Mooreebar Dam	Binneridgie Marsh
(5.40)	(7.25)	(8.50)	(20.00)	(23.25)	(34.00)	(39.60)	(44.25)

There was no significant seasonal influence on the species richness of lakes sampled from the Kambalda region. There was no significant difference within the species richness of lakes at different sampling times (Table 18).

Table 18: One-way ANOVA summary table of species richness for Lakes within the Kambalda region, relating to sampling time (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Season	4	521	130	0.50	0.733
Error	31	8007	258		
Total	35	8528			

4.3.3 Regional Differences

In terms of species diversity and species richness, lakes from the Esperance region were significantly different from lakes in the Kambalda region. Lakes in Esperance were significantly more diverse (Table 19), and significantly more species rich (Table 20), than those in Kambalda.

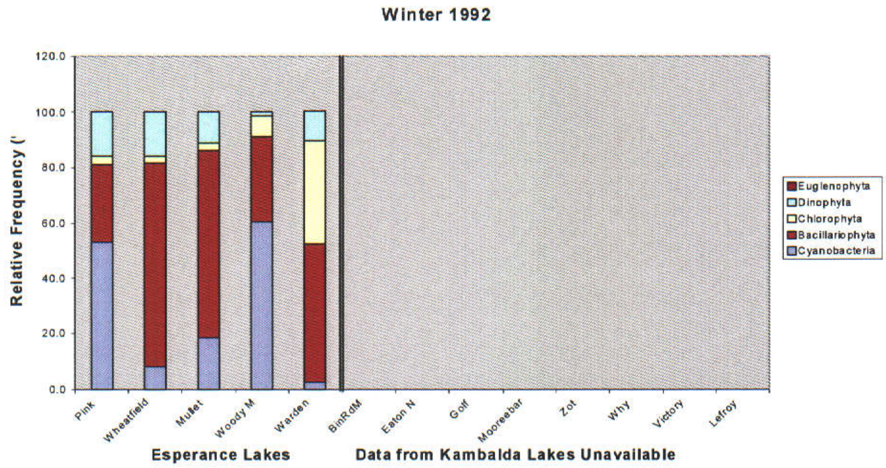
Table 19: One-way ANOVA table summary of species diversity, relating to lake location (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Factor	1	0.1440	0.1440	13.52	0.006
Error	8	0.0852	0.0106		
Total	9	0.2292			

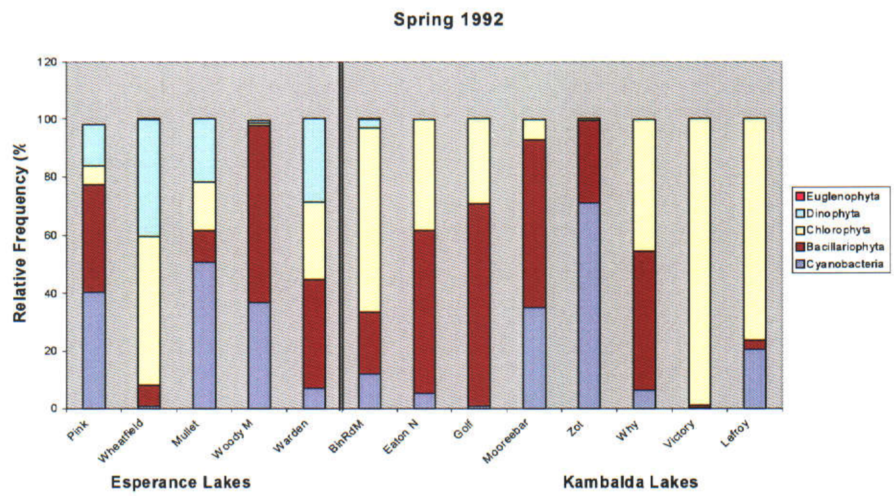
Table 20: One-way ANOVA table summary of species richness, relating to lake location (alpha = 0.05).

Source of Variation	DF	Sum of Squares	MS	F cal	P
Factor	1	291.6	291.6	13.50	0.006
Error	8	172.8	21.6		
Total	9	464.4			

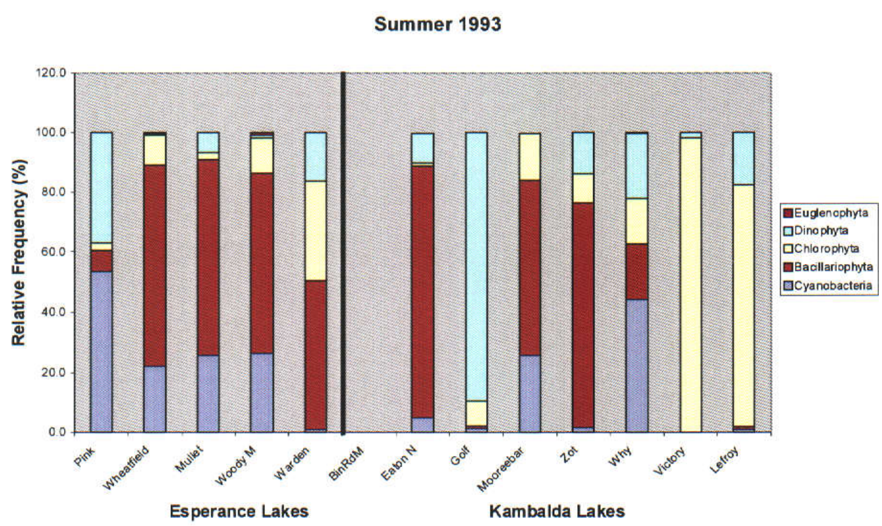
The relative frequency of species recorded during this study from lakes in Esperance and Kambalda are presented in Figures 14 (a, b & c) and 15 (a, b & c). While species diversity and richness did not vary significantly from season to season, species composition did. The most abundant algal division varied between lakes, and within each lake, from season to season. Only Pink Lake was dominated by the same division (cyanobacteria) at each sampling time.



a)

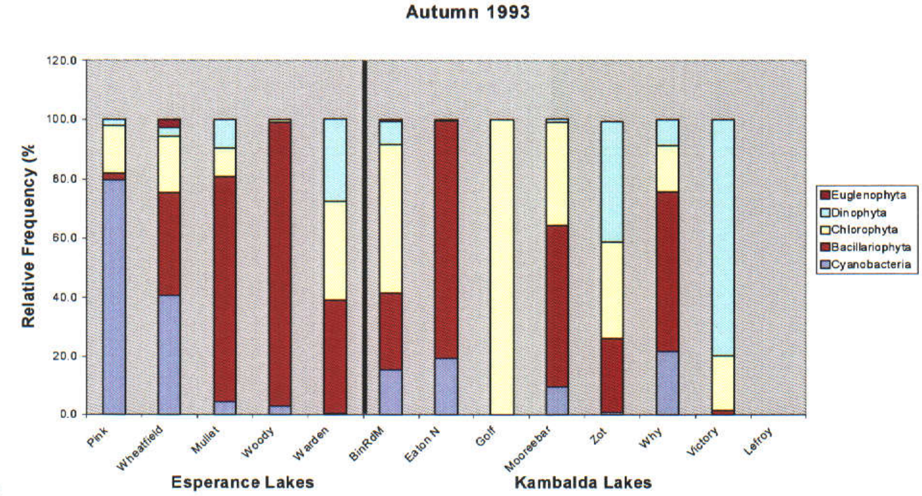


b)

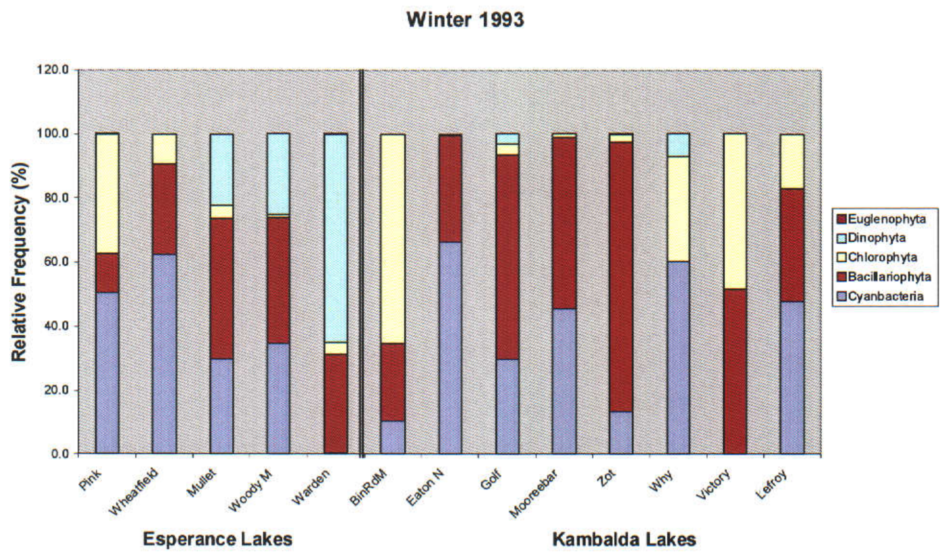


c)

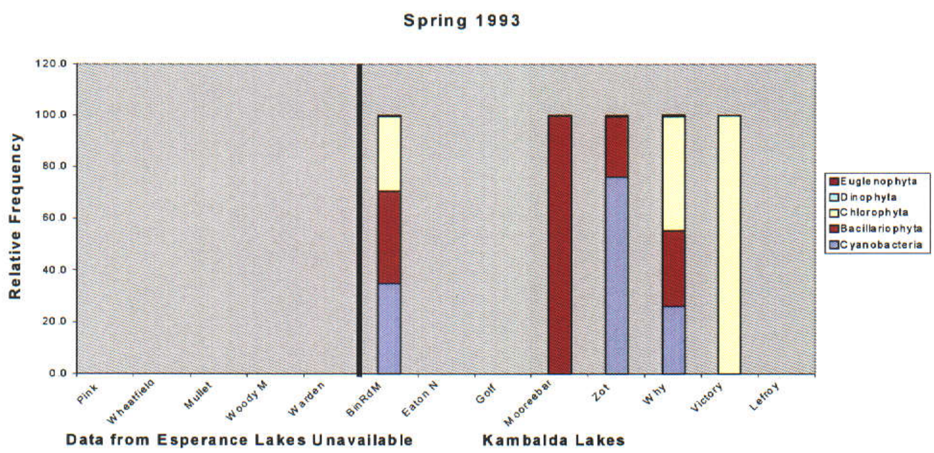
Figure 14: Relative frequency of algal divisions recorded from salt lakes in Esperance and Kambalda in winter 1992 (a), spring 1992 (b) and summer 1993 (c).



a)



b)



c)

Figure 15: Relative frequency of algal divisions recorded from salt lakes in Esperance and Kambalda in autumn (a), winter (b) and spring (c) 1993.

4.4 The Influence of Environmental Parameters on Algal Flora in Lakes in Esperance and Kambalda

4.4.1 The Influence of Salinity, Water Depth and pH on Species Diversity and Species Richness

Algal flora species diversity was inversely correlated to salinity, the correlation coefficient being -0.805. As salinity increased, species diversity decreased to zero at salinities in excess of 270ppt (Figure 16). The maximum species diversity index recorded was 1.36 at a salinity of 1ppt. Species diversity index ranged from 0 to 1.36 over a salinity range of 1 to 364ppt.

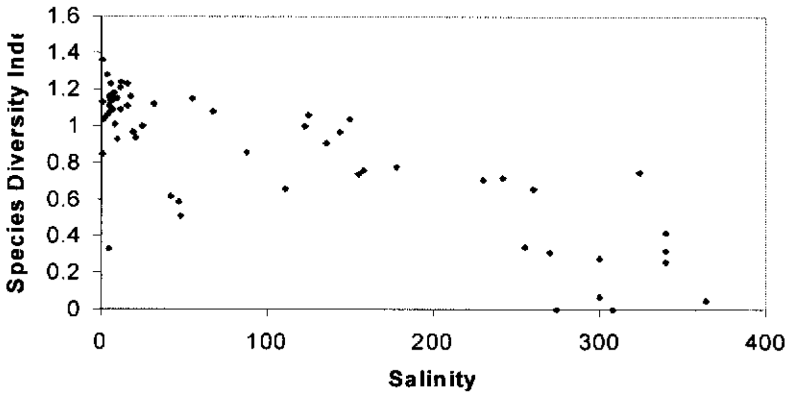


Figure 16: Species diversity of algal flora recorded from lakes in Esperance and Kambalda, Western Australia at varying salinity levels (ppt).

Algal flora species richness was inversely correlated to salinity, the correlation coefficient being -0.829. As salinity increased, species richness decreased as low as one (Figure 17). At salinities in excess of 300ppt species richness did not exceed 13. The maximum species richness recorded was 54 at a salinity of 8.6ppt. The minimum species richness recorded was 1, recorded at a salinity of 274 and 308ppt. Species richness ranged from 54 to 1 over a salinity range of 1 to 364ppt.

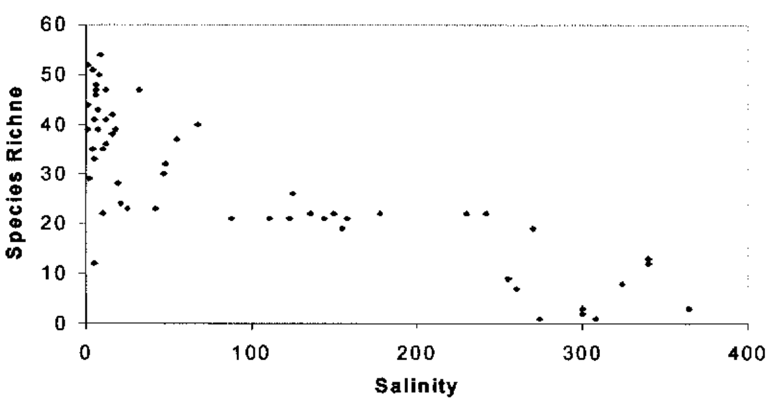


Figure 17: Species richness of algal flora recorded from lakes in Esperance and Kambalda, Western Australia at varying salinity levels (ppt).

Neither species diversity or species richness were correlated with water depth, the correlation coefficients being 0.149 and 0.363 respectively. There was a relationship between species diversity and pH, though not as strong as the relationship between species diversity and salinity. The correlation coefficient was 0.560. As pH increased so did species diversity (Figure 18). Most of the 13 lakes sampled were neutral or alkaline during this study. Two lakes were consistently weakly acidic and two lakes were weakly acidic at one sampling time.

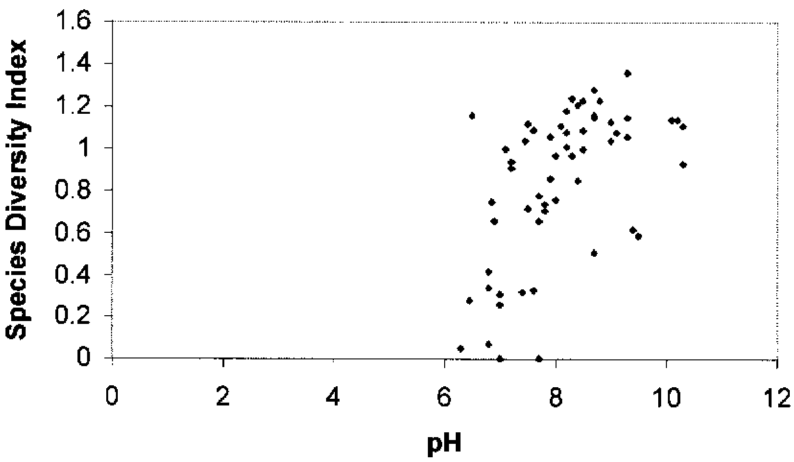


Figure 18: Species diversity index of algal flora recorded from 5 lakes in Esperance and 8 lakes in Kambalda, Western Australia at varying pH.

There was a positive relationship between species richness and pH, though again not as strong as the relationship with salinity. The correlation coefficient was 0.643. As pH increased so did species richness (Figure 19).

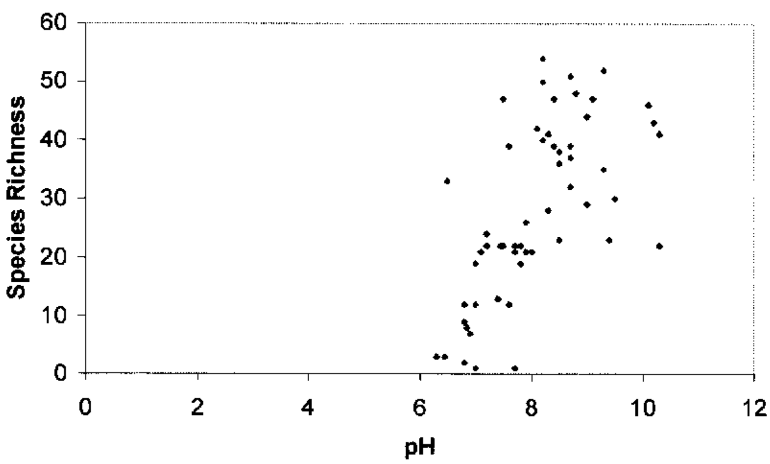


Figure 19: Species richness of algal flora recorded from 5 lakes in Esperance and 8 lakes in Kambalda, Western Australia at varying pH.

4.4.2 The Influence of Environmental Parameters on Algal Community Composition

Results from axes 1 and 2 have been plotted, for each sampling time. Axes 1 and 2 explained more of the species-environment variation than axis 3, as indicated by the correlation coefficients calculated between species frequency and environmental variables recorded, including salinity, pH, water depth, and major anions and cations and axes 1, 2 and 3 (Tables 21, 22, 23, 24, and 25). Geographical location was included as a factor by keeping specific lakes identified, thus identifying lakes in the coastal region of Esperance and lakes in the inland region of Kambalda. The scores from axes 1 and 2 are presented in Figure 20 for winter 1992, Figure 21 for spring 1992, Figure 22 for summer 1993, Figure 23 for autumn 1993, and Figure 24 for winter 1993. The scores from axes 1 and 2, with "species" plotted rather than "lake", are presented in Appendix 2. Figures 20-24 indicate that salinity and pH were significant factors in the clustering of sites based on algal flora assemblages.

Lakes Wheatfield (Wheat) and Mullet (Mullet) clustered together in Figure 20. Both lakes were dominated by *Navicula* sp.1, *Tabularia fasciculata*, *Amphora ventricosa* and *Cocconeis placentula, Aphanocapsa littoralis* and *Merismopedia punctata*. *Cyclotella atomus* and *Martyana martyi* were dominant species in Lake Wheatfield but were not present in Mullet Lake. *Navicella pusilla*, *Mastogloia elliptica* and *Mastogloia halophila* were dominant in Mullet Lake but not present in Lake Wheatfield.

Woody Lake Reserve Marsh (WLRM) did not cluster with other lakes and was dominated by *Phormidium fragile* and *Oscillatoria* sp.1 and *Navicula elegans* (Figure 20). Pink Lake (Pink) and Lake Warden (Warden) did not cluster with other lakes in winter 1992 either (Figure 20). Pink Lake was dominated by mat forming cyanobacteria including *Microcoleus* sp.1, *Synechococcus aeruginosus* and *Schizothrix* sp.1. *Dunaliella viridis* was also significant. Lake Warden was dominated by *Amphora coffeaeformis*, *Achnanthidium* aff. *delicatulum*, *Nitszchia obtusa* and *Martyana martyi* and the filamentous *Microspora* sp.1 and *Schizomeris* sp.1.

Table 21: Pearson and Kendall Correlations with ordination axes for canonical correspondence analysis of algal flora species and environmental parameters recorded from 5 lakes in Esperance in winter 1992.

Environmental Parameter	Axis 1		Axis 2		Axis 3	
	r	tau	r	Tau	r	tau
Salinity	.484	.600	-.847	-.400	-.218	-.200
pH	.114	.000	.944	.894	.307	.224
Depth	-.594	-.600	-.128	.000	.794	.600

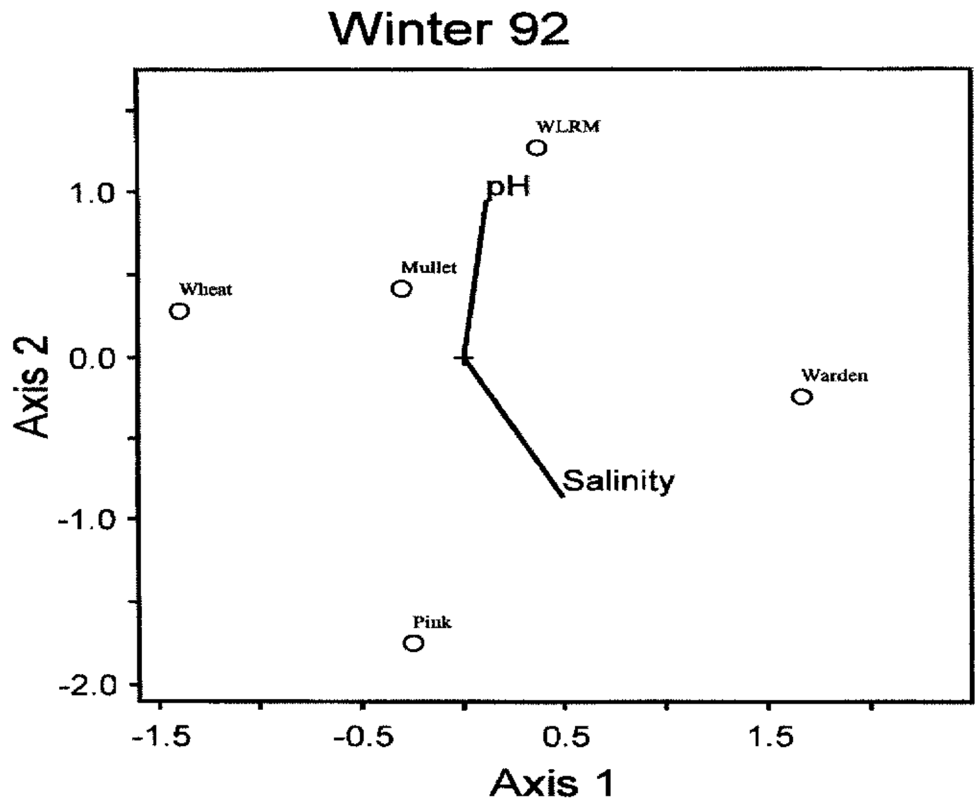


Figure 20: Canonical correspondence analysis of algal flora species and related environmental parameters recorded from 5 lakes in Esperance in winter 1992.

Victory Lake (Victory) did not cluster closely with the other lakes sampled in Kambalda or Esperance in spring 1992 (Figure 21). The Lake was dominated by *Dunaliella salina,* was the most hypersaline of those sampled and had the lowest pH recorded (6.4). Golf Lake (Golf) was the lake closest to Victory Lake in Figure 21 and was dominated by *Dunaliella salina. Nitzschia communis* was also abundant in Golf Lake. Golf Lake was hypersaline and had the second lowest pH (6.8) of those sampled. Lakes Zot (Zot) and Pink also did not cluster with any other lakes in Figure 21. Both were hypersaline but Lake Zot dominated by *Chroococcus minutus, Chroococcodiopsis* sp.1, *Microcoleus* sp.1 and *Oscillatoria* sp.2 and *Nitzschia* aff. *fonticola.* Pink Lake was dominated by *Lyngbya* sp.1, *Chroococcus turgidis* and *Schizothrix* sp.4.

Lake Why (Why) and Binneridgie Road Marsh (BRM) clustered together in Figure 21. Both lakes had the highest pH recorded, were subsaline and were dominated by *Navicula cryptocephala.* Mooreebar Dam (Mooreebar) clustered loosely with these lakes (Figure 21). Mooreebar Dam was subsaline, but had a lower pH (8.4) than the latter two. Mooreebar Dam was dominated by *Achnanthidium minutissimum, Amphora ventricosa, Gomphonema gracile,* and *Nitzschia lorenziana.* Lake Eaton North (LEN) from Kambalda and Lakes Wheatfield, Warden and Mullet from Esperance clustered closely together (Figure 21). All four had a similar pH levels, close to neutral, and all four were hyposaline.

Woody Lake Reserve Marsh did not cluster with any other lakes (Figure 21). This lake had the lowest pH (6.5) of those that were subsaline in spring 1992, and was dominated by *Phormidium* sp.1, *Anabaena* sp.2, *Oscillatoria agardii*, *Calothrix* sp.1 and *Synedra acus*.

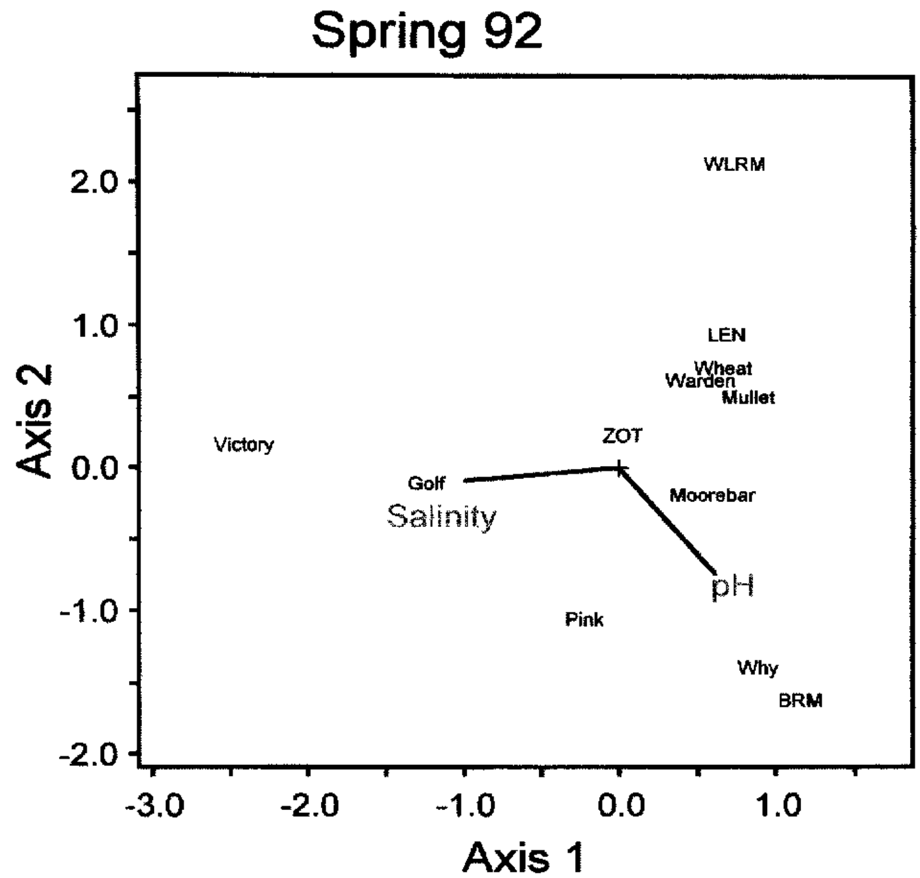


Figure 21: Canonical correspondence analysis of algal flora species and related environmental parameters recorded from lakes in Esperance and Kambalda in spring 1992.

Table 22: Pearson and Kendall Correlations with ordination axes for canonical correspondence analysis of algal flora species and environmental parameters recorded from lakes in Esperance and Kambalda in spring 1992.

Environmental	Axis 1		Axis 2	
Parameter	r	tau	r	tau
Salinity	-.980	-.708	-.081	.031
pH	.621	.492	-.755	-.462

Victory Lake and Lake Lefroy (Lefroy) clustered together in Figure 22. These lakes were dominated by *Dunaliella salina*, and both were hypersaline and slightly acidic. Pink Lake clustered loosely with these two lakes. It was hypersaline, weakly alkaline and contained *Dunaliella salina* but was dominated by mat forming cyanobacteria *Microcoleus* sp.1, *Synechococcus aeruginosus* and *Schizothrix* sp.4.

Lake Zot did not cluster closely with other lakes in Figure 22 but it did occur within the same quadrat as Lake Eaton North, Lake Wheatfield, Mullet Lake and Woody Lake Reserve Marsh. *Navicula cincta, Navicella pusilla, Navicula* sp.1 and *Entomoneis alata* were present in all five of these lakes. Lake Zot was dominated by *Nitzschia communis.*

Lake Eaton North, Lake Wheatfield, Mullet Lake and Woody Lake Reserve Marsh clustered together in Figure 22. The salinity range between these four lakes was large; 12ppt to 136ppt but all were weakly alkaline. Dominant species in this group were *Amphora coffeaeformis, Pluerosigma salinarum, Rhopalodia musculus, Nitzschia* aff. *fonticola, Mastogloia pumila* and the charophyte *Lamprothamnium papulosum.*

Mooreebar Dam did not cluster with any other lake sampled in summer 1993 (Figure 22). It was the deepest of the lakes sampled, slightly alkaline, subsaline and dominated by *Navicula cryptocephala, Navicula subinflatoides, Cyclotella stelligera, Achnanthidium minutissimum*, and *Closterium pronum.*

Lakes Warden and Why clustered loosely in Figure 22. Both lakes were alkaline and similar in depth. Salinity was vastly different, Lake Warden was mesosaline and Lake Why was hyposaline. The diatom *Tabularia fasiculata* was common to both lakes and both were dominated by green algae. In Lake Why *Oedogonium undulatum, Cosmarium retusiforme, Cosmarium granatum, Botryococcus braunii* and *Nitella subtillissima* were abundant. In Lake Warden *Microspora* sp.1, *Schizomeris* sp.1, *Cladophora* sp.1 and *Lamprothamnium papulosum* were dominant.

Table 23: Pearson and Kendall Correlations with ordination axes for canonical correspondence analysis of algal flora species and environmental parameters recorded from lakes in Esperance and Kambalda in summer 1993.

Environmental Parameter	Axis 1		Axis 2		Axis 3	
	r	tau	r	tau	r	tau
Salinity	-.964	-.786	-.179	.071	.004	-.429
pH	.657	.691	.466	.327	.198	.182
Depth	.649	.667	.266	.000	.631	.741
Sodium (Na)	-.971	-.714	.091	.143	.197	-.357
Potassium (K)	-.969	-.764	.116	.109	.196	-.327
Calcium (Ca)	-.270	-.714	-.898	.000	-.043	-.357
Magnesium (Mg)	-.968	-.786	.132	.071	.196	-.286
Chloride (Cl)	-.969	-.714	.115	.143	.199	-.357
Bicarbonate (HCO3)	-.929	-.500	.279	.214	-.034	-.143
Carbonate (CO3)	-.027	-.231	.266	.463	-.140	-.309
Nitrate (NO3)	-.164	-.309	.317	.617	-.896	-.231
Sulphate (SO4)	-.982	-.764	-.094	.109	.103	-.327
Silicon (Si)	-.800	-.546	.285	.182	-.168	-.255

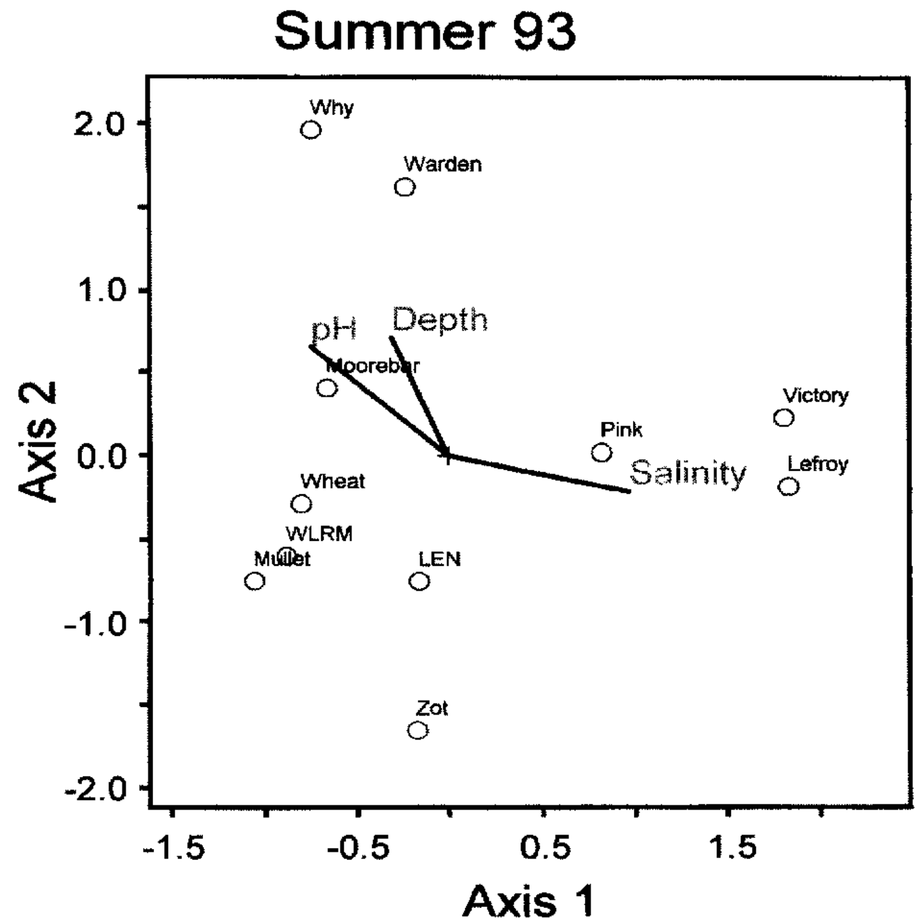


Figure 22: Canonical correspondence analysis of algal flora species and related environmental parameters recorded from lakes in Esperance and Kambalda in summer 1993.

Lake Warden did not cluster with any other lakes sampled in autumn 1993 (Figure 23). The lake was mesosaline, alkaline and 1.65m deep. *Lamprothamnium papulosum* was dominant. Pink Lake also did not cluster with other lakes in Figure 23. The Lake was hypersaline, very shallow and had a pH of 7.5, the lowest of lakes sampled in Esperance. Mat forming cyanobacteria species *Schizothrix* sp.1, *Microcoleus* sp.1, *Synechococcus aeruginosus* and *Oscillatoria* sp.1 were dominant.

Lakes Eaton North and Zot, both from the Kambalda region, clustered closely together in Figure 23 and were dominated by *Navicula* sp.1. Both were hypersaline, very shallow and weakly alkaline. *Chroococcus turgidis* and *Rhopalodia musculus* were also especially abundant in Lake Eaton North and *Dunaliella viridis* and *Dunaliella salina* were also dominant in Lake Zot.

Lake Why did not cluster with other lakes in Figure 23. The lake was hyposaline, 1.0m deep and the most alkaline of all lakes sampled with a pH of 10.2. *Amphora coffeaeformis* was particularly abundant, as was *Amphora veneta*, *Hantzschia amphioxys*, *Navicula subinflatoides*, *Triblionella apiculata*, *Nitzschia sigma*, *Anabaena* sp.1, *Microcoleus vaginatus*, and *Spirulina major.*

Binneridgie Road Marsh in Kambalda and Mullet Lake in Esperance clustered together in Figure 23. The salinity of the two lakes was different, Binneridgie Road Marsh was subsaline, Mullet Lake was hyposaline, but both lakes were around 70cm deep and both were alkaline. *Navicella pusilla*, *Navicula cincta*, *Nitzschia palea* and *Botryococcus braunii* were dominant in both lakes. In addition to *Botryococcus braunii*, *Oocyctis parva* and *Ankistrodesmus spiralis* were common in Binneridgie Road Marsh. *Entomoneis alata* and *Mastogloia pumila* were significant in Lake Mullet.

Mooreebar Dam in Kambalda and Lake Wheatfield in Esperance also clustered together in Figure 23. Both were hyposaline, just over 1.0m deep and alkaline. *Amphora ventricosa*, *Navicula cincta* and *Nitzschia* aff. *fonticola* were abundant in both lakes. In addition, *Nitzschia* sp.1, *Nitzschia lorenziana*, *Navicula mutica*, *Gomphonema gracile*, *Eunotia pectinalis* var. *undulata*, *Cyclotella stelligera* and *Achnanthidium minutissimum* were abundant in Mooreebar Dam. *Merismopedia punctata* and *Euglena* sp.1 were prominent in Lake Wheatfield.

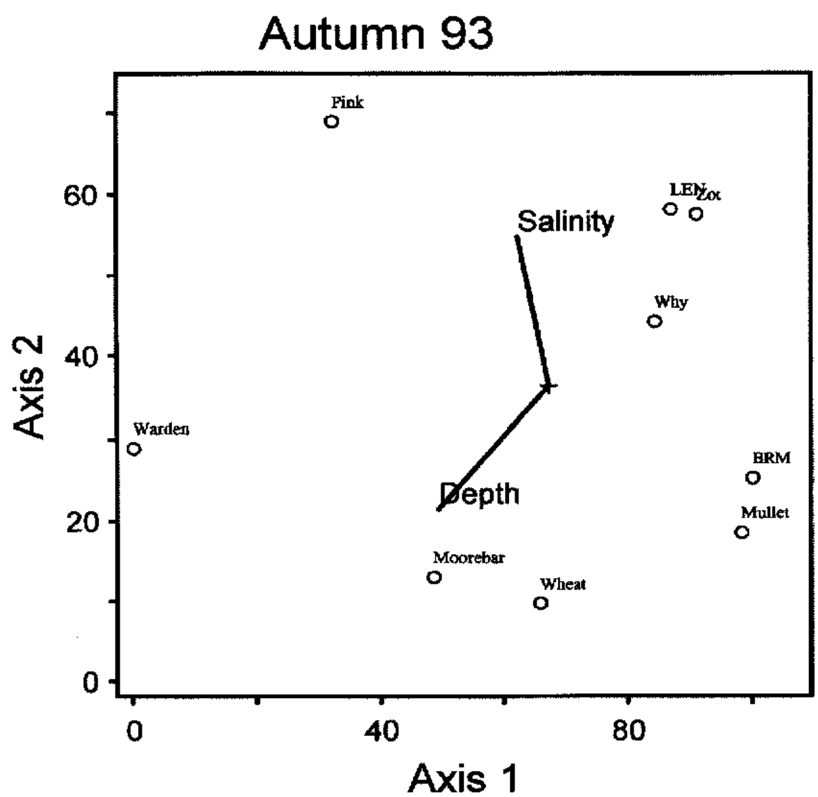


Figure 23: Canonical correspondence analysis of algal flora species and related environmental parameters recorded from lakes in Esperance and Kambalda in autumn 1993.

Table 24: Pearson and Kendall Correlations with ordination axes for canonical correspondence analysis of algal flora species and environmental parameters recorded from lakes in Esperance and Kambalda in autumn 1993.

Environmental Parameter	Axis 1		Axis 2		Axis 3	
	r	tau	r	tau	r	tau
Salinity	-.153	-.197	.889	.704	.423	.254
pH	-.044	.000	-.569	-.278	-.814	-.667
Depth	-.536	-.389	-.733	-.444	-.405	-.278

In Figure 24 Golf Lake, Victory Lake and Lake Lefroy clustered together. These lakes were hypersaline, less than 0.80m deep and slightly acidic. *Dunaliella salina* was the dominant alga. While not clustering closely to this group, Pink Lake and Lake Zot were adjacent to them in Figure 24. Both were also hypersaline and shallow, but their pH was 7.8 and 7.4 respectively. *Dunaliella salina* was present in Pink Lake but it was not dominant, *Schizothrix* sp.1 and *Synechococcus aeruginosus* were. Lake Zot was dominated by *Dunaliella viridis,* as well as *Navicula* aff. *minusculus*.

Lake Eaton North did not cluster with other lakes in Figure 24. The lake was hypersaline, 0.02m deep, close to neutral (pH 7.7) and dominated by *Phormidium* sp.2. Lake Warden also did not cluster closely with other lakes. It was mesosaline, 1.92m deep, alkaline and *Gymnodinium splendens* was most abundant.

Lake Why did not cluster with other lakes in Figure 24. It was hyposaline, 1.5m deep and alkaline. *Amphora coffeaeformis*, *Amphora veneta*, *Navicella pusilla*, *Navicula subinflatoides, Nitzschia* aff. *fonticola* and *Cosmarium granatum* were dominant. Woody Lake Reserve Marsh also did not cluster with other lakes. It was mesosaline, 0.30m deep, alkaline and the algal flora was dominated by *Phormidium* sp.1 and *Amphora ventricosa*.

Mooreebar Dam was adjacent to Woody Lake Reserve Marsh in Figure 24. Cyanobacteria and diatoms were abundant in both lakes but Mooreebar Dam was dominated by *Anabaena* sp.1, *Microcoleus vaginatus, Schizothrix* sp.3, *Achnanthidium minutissimum*, *Mastogloia smithii*, *Navicula cryptocephala*, *Nitzschia lorenziana* and *Rhopalodia gibba*. Mooreebar Dam was less saline than Woody Lake Reserve Marsh (hyposaline), 0.03m deep and pH was 8.5.

Mullet Lake and Lake Wheatfield clustered together in Figure 24. Both of the lakes were hyposaline, over 1.0m depth, alkaline (pH 8.1-8.2) and dominated by cyanobacteria, particularly *Oscillatoria* sp.1, *Merismopedia punctata* and *Calothrix* sp.1.

Binneridgie Road Marsh clustered with no other lakes in Figure 24. The lake was hyposaline, 0.40m deep and the most alkaline of all lakes sampled in this season (pH 10.1). *Ankistrodesmus spiralis*, *Oocytis parva*, *Staurastrum gracile*, *Scenedesmus quadricauda*, *Closterium parvulum*, *Cosmarium* *retusiforme* and *Euastrum verrucosum* were particularly abundant and the lake floor was covered by *Nitella lhotzyi*, which was found at only one other lake, Mooreebar Dam, in this study.

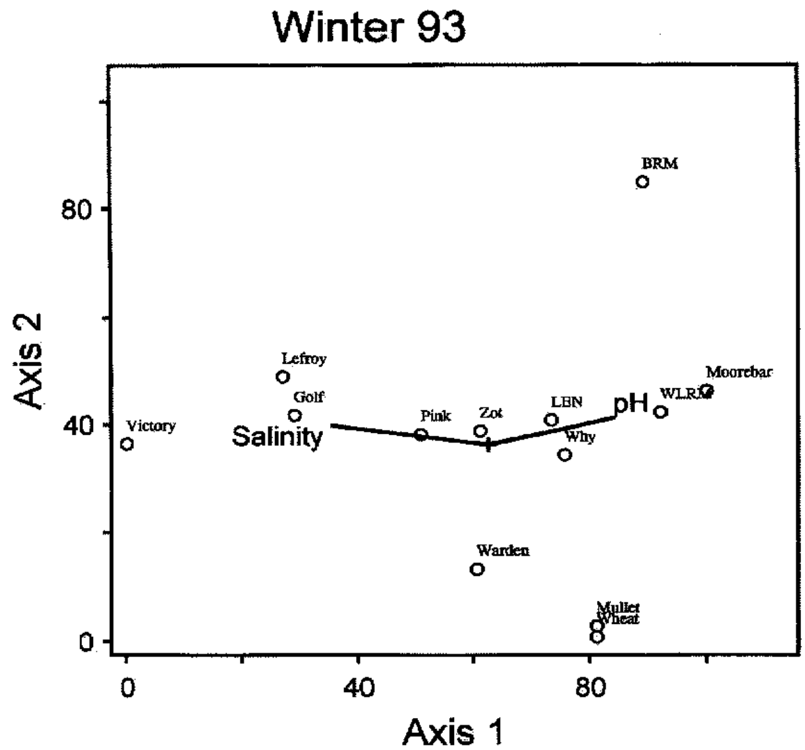


Figure 24: Canonical correspondence analysis of algal flora species and related environmental parameters recorded from lakes in Esperance and Kambalda in winter 1993.

Table 25: Pearson and Kendall Correlations with ordination axes for canonical correspondence analysis of algal flora species and environmental parameters recorded from lakes in Esperance and Kambalda in winter 1993.

Environmental Parameter	Axis 1		Axis 2		Axis 3	
	r	tau	r	tau	r	tau
Salinity	-.947	-.718	.164	.077	-.274	-.179
pH	.751	.581	.238	-.013	.614	.323
Depth	.085	-.090	-.683	-.555	.723	.684

5.0 DISCUSSION

The results of the present study attempt to characterise the physical limnology and algal flora of 13 saline lakes in Western Australia, five from the coastal Esperance region and eight from the inland Kambalda region. Previous published work on the physicochemical limnology and algal flora of these lakes is very limited, and was even more so when this project was initiated in 1992. In particular, no previous literature has been published on algal flora of the lakes investigated from the Esperance region, and only Lake Lefroy from the Kambalda region has the subject of preliminary surveys of aquatic biota (Chaplin, 1999; John, 1999).

Biodiversity in these 13 salt lakes, while less than that of freshwaters, was relatively high, except at salinities in excess of 100ppt, comprised a wide variety of taxa and displayed distinct geographical differences between the coastal and inland regions.

5.1 Characterising Lakes on the Basis of Physicochemical Properties and Algal Flora

5.1.1 Physicochemical Characteristics of Lakes in Esperance

The physicochemical limnology of salt lakes investigated in the Esperance region can be considered as seasonally variable. The water regime of all lakes sampled was strongly seasonal, defined by climatic variation in rainfall, exhibiting a reliable cycle of filling during winter and spring and drying out in summer. This seasonal pattern of rainfall and evaporation is consistent with other locations of this latitude on the south coast of Western Australia (Paijmans et al., 1985).

Water depth and salinity were heterogeneous both within each lake, from season to season, and between lakes in the region. Seasonal variability was least influential on the salinity of Lake Wheatfield, most likely because the variation in lake volume, as depth changed, was insufficient to markedly concentrate or dilute salts. While pH varied in all lakes with seasonal fluctuation in water depth, and subsequent concentration and dilution of solutes, pH was consistently alkaline, reflecting the alkaline geochemistry of the lakes' sediment and their catchments (CALM, 1997).

While the depth of lakes in the Esperance region was variable only one lake, Woody Lake Reserve Marsh, dried out completely during this study. One can infer, therefore, that while the biota of these temporary lakes must be able to withstand periods of desiccation, these periods are relatively short and do not occur frequently. It is likely that Woody Lake Reserve Marsh dries out more regularly than other lakes in the region due to its small surface area and relatively flat bathymetry. This morphology results in a relatively small water holding capacity, thus the lake takes only a short time to dry out.

The marked influence of seasonal rainfall on the depth of all lakes sampled in the region indicates their water regimes are largely dictated by surface water runoff. That said, the delay recorded in attaining maximum depth in Pink Lake and Lake Warden, following peak rainfall periods, suggests that groundwater flows are likely to have a role in the hydrological processes of these lakes as well. This is not unexpected given the influence of marine groundwater on the hydrology of other coastal lakes in Western Australia (Moore, 1993). The salinity of Pink Lake provides further evidence for this groundwater interaction. Pink Lake was the most saline of all lakes sampled in the Esperance region, and while salinity varied on a seasonal basis, the lake was consistently hypersaline. Because Pink Lake supports a salt crust when dry, the volume of rain water received was not sufficient to dilute surface waters significantly. The hydrological interaction of Pink Lake's surface water and marine groundwater is likely to be responsible for the presence of this salt crust (CALM, 1997).

The ionic composition recorded from lakes in the region had the same ionic spectrum as sea water, reflecting the geological and hydrological histories of the lakes (McComb and Lake, 1990). This lake system was separated from the ocean relatively recently, in geological terms, and Mullet Lake and Pink Lake retain a connection with waters of marine origin. Mullet Lake through direct connection with the Southern Ocean via Bandy Creek and Pink Lake through interaction with groundwater of marine origin.

None of the lakes were stratified at any time with respect to either dissolved oxygen or temperature. All were well mixed to the bottom, and none of the levels recorded would be likely to impede algal growth (Williams, 1985). This is in keeping with the general trend for salt lakes reported by John (2002) in which he indicated 8-9 mgL^{-1} of dissolved oxygen was a common range for salt lakes. The large surface area of each of the lakes sampled in relation to their volume, and exposure of the surface to agitation by wind and rain, was most likely responsible for the lakes being well mixed to the bottom In all cases, lower dissolved oxygen levels were recorded in the hypersaline lakes than the meso- or hyposaline lakes. The inverse relationship between dissolved oxygen and salinity, reported often before, is based on the filling of intermolecular spaces by dissolved salts, reducing the space available for oxygen (Colburn, 1988; Stephens, 1990).

Supersaturated dissolved oxygen levels were recorded at times throughout this study, each recording corresponding with prolific growth of benthic aquatic macrophytes and/or charophytes. Woody Lake Reserve Marsh supported the aquatic macrophyte *Lepilaena cylindrocarpa* and charophyte *Lamprothamnium papulosum,* and the sediment of Lake Warden was covered by *Lamprothamnium papulosum* throughout most of this study. Such high oxygen saturation levels can be attributed to both the mixing of air into the water column by wind and photosynthetic oxygen production by these dense growths of aquatic plants, illustrating the role algal flora can play in determining the physicochemical character of salt lakes (De Deckker, 1988).

Although nutrient data were not collected from any of the lakes in the Kambalda region (due to financial constraints), the nutrient status of lakes in the Esperance region ranged from mesotrophic to eutrophic, based on the OECD boundary values (tabulated in Appendix 1). Pink Lake and Lakes Warden and Wheatfield were eutrophic while Woody Lake Reserve Marsh and Mullet Lake were mesotrophic with respect to total phosphorus, and eutrophic with respect to total nitrogen. These nutrient levels are higher than those reported for a number of Australian salt lakes, especially those in inland regions with limited anthropogenic nutrient inputs (John, 2002).

One can infer from the high nutrient values recorded that the agricultural and urban development practices occurring in the sandy soils of the catchments of lakes in the region, particularly the application of nitrogen and phosphorus fertilisers, could be affecting their physicochemical, and most likely biological, character (Blinn and Bailey, 2001). The influence of catchment management practices on the physicochemical and biological character of salt lakes has been reported previously (Williams, 2001). For example, the leaching of fertilisers from the catchment into Pink Lake could exacerbate nutrient loading in the lake, indirectly leading to inhibition of growth of the benthic microbial communities that dominate the algal community of this lake, by promoting epiphytic algae and planktonic blooms of green algae or cyanobacteria. This man-induced shift in algal community structure has been reported to have occurred in the coastal Lake Clifton in Western Australia, impacting the microbialite structures so characteristic of the lake (Moore, 1991).

5.1.2 Characteristic Algal Flora of Lakes in Esperance

Diatoms and cyanobacteria dominated the algal communities of coastal salt lakes in the Esperance region. Green algae, dinoflagellates and euglena species were present, but not in high abundance, except in Lake Warden. All algal species recorded in Esperance are known for their wide distribution, some from both inland and coastal regions of Australia and some only from coastal geographic locations. For example, *Achnanthes brevipes, Achnanthes coarctata, Achnanthes lanceolata* var. *dubia, Achnanthidium cruciculum, Campylodiscus clypeus, Cyclotella atomus, Cyclotella meneghiniana, Cyclotella striata, Mastogloia elliptica, Mastoglia pumila, Nitzschia punctata and Thalassiosira weissflogii* were all distinctive elements of the algal communities of Lake Warden, Lake Wheatfield, Woody Lake Reserve Marsh and Mullet Lake and all have been reported to be characteristic of other coastal saline waters (Blinn, 1993; Round *et al.*, 1990). These species were not abundant in Pink Lake, however, most likely because salinity in this lake was consistently higher than their tolerance.

Thick, laminated benthic microbial mats made by filamentous and coccoid cyanobacteria, with a few species of diatoms trapped within, characterised the algal flora of Pink Lake. All species recorded have previously been reported to occur in saline waters, and thick algal mats constructed by cyanobacteria have been described as key biological elements of a number of coastal hypersaline lake environments, similar to Pink Lake, along the coastline of Western Australia from Yalgorup (Moore, 1987), to Rottnest Island (John, 1984; Playford, 1988), to Cervantes (Grey *et al.*, 1990), to Shark Bay (Bauld, 1986). The persistence of these benthic microbial mats in Pink Lake is likely to be determined by the groundwater interaction characteristic of the lake's water regime. Grey *et al.* (1990) suggests that for any thickness of benthic microbial mat to remain on the floor of a lake, sedimentation rates must be high. This requires considerable rainfall or substantial groundwater discharge, and given rainfall was not high in the Esperance region, one can infer groundwater discharge is important in determining their distribution.

The algal community of Lake Warden was dominated by benthic green algal species. *Lamprothamnium papulosum,* a charophyte widely distributed in saline waters throughout Australia (Brock and Casonova, 1991), covered most of the lake floor throughout the duration of this study. Further, a fibrous, unlaminated, cohesive mat, constructed by filaments of *Cladophora* sp.1, *Microspora* sp.1 and *Schizomeris* sp.1 was prominent in the littoral zone of the lake, at a salinity range of 28ppt to 67.3ppt. It is most likely that algal community composition in Lake Warden deviated from those of other lakes in the region as a function of the high levels of nutrients that occurred in the lake. Fertiliser application to semirural properties immediately adjacent to the lake, and on agricultural properties in the lake's catchment, is the most likely source of this eutrophication. The stimulation of green algal growth by high levels of nitrogen and phosphorus has been reported from waters in Australia, and throughout the world (John, 1994; Rader and Richardson, 1992). The abundance of the diatom *Martyana martyi* provides further biological evidence of the lake's high nutrient levels. This diatom species has been noted for its wide distribution in the benthos of mesotrophic and eutrophic waters (Patrick and Reimer, 1975).

The algal flora of Lake Wheatfield was similar to Lake Warden, Woody Lake Reserve Marsh and Mullet Lake in seasons when their salinities were within the hyposaline salinity limits recorded in Lake Wheatfield. Not surprisingly then, the algal flora of the lake was characterised by widely dispersed diatom and cyanobacteria species. One distinct element of the algal community in Lake Wheatfield was, however, the prominence of truly planktonic diatom species including the structurally delicate *Chaetoceros muelleri* (Rushforth and Johansen, 1986). It is likely that the presence of these diatoms is a reflection of the availability of suitable habitat, given that the lake was consistently deep enough for truly planktonic species to establish.

As discussed earlier, Woody Lake Reserve Marsh was the only lake in Esperance to dry out fully in this study, and the impacts of the drying and filling cycle on the lake's algal community structure was dramatic. In winter 1992, when the lake was very shallow and hyposaline, the algal community was characterised by cyanobacteria species, including *Phormidium fragile* and *Oscillatoria* sp.1. *Navicula elegans*, a widely distributed diatom in mesosaline, nutrient rich waters was also characteristic (Caljon, 1983). By spring 1992 the lake had filled, following late winter rains, and salinity had dropped to subsaline levels. Under these physicochemical conditions, *Synedra acus*, a widely distributed diatom species in saline, neutral-weakly alkaline waters (Patrick and Reimer, 1975), and cyanobacteria including *Phormidium* sp.1, *Anabaena* sp.2, *Oscillatoria agardii* and *Calothrix* sp.1 were dominant.

In summer 1993, the lake dried to 1.0m depth, salinity increased to hyposaline levels and diatoms including *Amphora coffeaeformis, Navicella pusilla*, *Pluerosigma salinarum*, *Rhopalodia musculus*, *Nitzschia* aff. *fonticola* and *Mastogloia pumila* were the most abundant algae recorded. All of these species are known for their wide distribution in saline waters (Gell and Gasse, 1990; Gell, 1997). Notably, green algal abundance increased under these conditions, in this lake, and the third type of algal mat collected from the Esperance region; a thin, unlaminated, cohesive mat growing like a carpet over the lake floor, appeared. The mat was constructed by filamentous and coccoid cyanobacteria, diatoms, and filamentous and coccoid green algae. A green algal mat similar in composition to this one has been collected from coastal salt lakes in Bunbury, Western Australia (J. John, pers. comm.). By autumn 1993 the lake virtually dried and was hypersaline. The cosmopolitan diatom *Amphora ventricosa* and cyanobacteria *Phormidium* sp.1 dominated the algal community under these conditions.

The composition of the algal flora community in Mullet Lake was very distinctive, clearly reflecting a degree of marine influence. Diatom species characteristic of marine coastal waters including *Mastogloia halophila, Mastogloia reimeri*, *Bracysira aponina*, and *Berkelya scopulorum* were common (Round et al., 1990). The sea constitutes an enormous reservoir of species, some of which may become established in a basically foreign environment, providing it happens at the time and the right order of salinity exists (De Deckker, 1983). This has clearly been the case in Mullet Lake which is connected with the Southern Ocean in wetter years via Bandy Creek. When lake depth reached its maximum and salinity decreased to 8ppt in Mullet Lake the lake's algal community composition shifted from a diatom dominated community to one dominated by cyanobacteria species including the coccoid *Aphanocapsa elachista* and *Gomphosphaeria aponina.*

5.1.3 Physicochemical Characteristics of Lakes in Kambalda

The water regime of lakes in the Kambalda region were much less predictable than those of lakes in the Esperance region, affected by seasonal variability in rainfall and evaporation but also determined by summer cyclonic rainfall events that were unpredictable from year to year. Rainfall in the semi-arid and arid inland regions of Australia is reported to be highly variable in terms of timing, duration and intensity, and as such hydrological processes are highly variable in time and space (Roshier et al., 2001).

The influence of climatic variation on the depth of lakes in the region suggests their water regimes are greatly influenced by surface water flows. Binneridgie Road Marsh exhibited the most responsive water regime to rainfall events. This may have been a function of local spatial variation in rainfall. If this is a factor in the region, then it is likely that although the lakes are located in the same geographic region, they may have different hydrological histories. It may also have been a function of the lake's individual hydrological processes. Binneridgie Road Marsh has a small surface area and overland flooding is common in its catchment, hence the volume of surface water required to fill the lake, and the time taken to do so, is small. All catchments in the Kambalda region are susceptible to overland flows as the rainfall rate is often greater than the penetration rate of water into the catchment soils but the very large, flat nature of many lakes in the region mean that large volumes of surface runoff result in depth changes of only a few centimetres, hence the impact of rainfall events is less dramatic.

The water regime of all lakes sampled in Kambalda, except Lakes Why and Eaton North, also appear to be heavily impacted by human activities related to gold and nickel mining. The man-made Mooreebar Dam was the most directly impacted. The purpose of Mooreebar Dam was to impound the relatively fresh flows of Mooreebar Creek, which would naturally have flowed into the northern margins of Lake Lefroy, for use in Western Mining Corporation's (WMC) mineral processing operations. During this study the filling phase of Mooreebar Dam was dependent on natural rainfall events and the drying phase was determined by the rate of water extraction by WMC.

The impact of impeding freshwater inflows on the ecology of Mooreebar Creek and Lake Lefroy is unknown. It is unlikely that the volume of water prevented from reaching Lake Lefroy has a dramatic effect on the total water budget of Lake Lefroy, given the vast size of the lake and the relatively small scale of Mooreebar Creek. Further research is required on the hydrological processes of Mooreebar Creek and Lake Lefroy before the impact of Mooreebar Dam can be quantified and recommendations can be made relating to the long term management of the dam. Given the inverse relationship between species richness and salinity, the section of Lake Lefroy that would previously have received Mooreebar Creek's fresh waters may have supported more species than the total lake itself (Timms, 2001).

The water regimes of Golf Lake, Binneridgie Road Marsh, Lake Zot and Lake Lefroy may also be impacted by the construction of structures that affect their hydrological processes. In their case it appears to be the construction of a road either in close proximity to, or directly through, each of the lakes creating a disconnect within the lakes, effectively creating two systems within one lake. Field observations suggest that the depth of these lakes is higher on one side of the road (or causeway) and lower on the other side, and although hydrological processes were not investigated within the scope of this primarily biological study, it is important to note that these roads may be impacting the hydrological processes within each lake. Aspects such as total water budget, duration water persists for, and surface water circulation patterns (despite the use of large culverts) may be affected. If these roads are impacting hydrological processes then it is highly likely that they also impact physicochemical and biological characteristics as well. More research, particularly on the hydrological processes of lakes in the region, is required to establish if this is the case. It may be that the location of each road, and the scale of impact within the context of the total limnology of these lakes, means the impact of these roads is negligible.

Salinity varied in accordance with drying and filling in all lakes except the most hyersaline; Lakes Lefroy, Victory and Golf. The changes in salinity exhibited can be attributed to concentration through evaporation and subsequent dilution by rainwater (Boulton and Brock, 1999). The lack of correlation between water depth and salinity in the most hypersaline lakes in the region reflect the influence of the extensive surface salt crusts they each supported when dry. The volume of rain water received was insufficient to dilute surface waters significantly.

The ionic composition of lakes in the region exhibited the same spectrum as sea water. It can be inferred then, that the source of salts in this region are relict marine deposits (connate salts), or atmospherically transported oceanic salts (Hart and McKelvie, 1986). Relict marine deposits, or connate salts, are the major source of salts in Australian salt lakes (De Deckker, 1983). In addition, calcium levels were significantly higher in lakes in the Kambalda region when compared with lakes in the Esperance region. This can be attributed to weathering of calcium rich catchment sediments (Drever, 1982).

The results of this investigation indicate that photosynthetically usable radiation was not a limiting factor for algal growth in any of the lakes sampled in Kambalda, light penetration to the lake bottom being recorded in all lakes on all sampling occasions. This was a potential factor affecting algal growth in lakes in the Kambalda region given the very shallow nature of a number of them. The potential for wind action to increase turbidity, and thus limit light penetration, in shallow lakes has been reported previously (Boulton and Brock, 1999).

Further, both dissolved oxygen and temperature were also shown not to be present at levels that would limit algal growth and none of the lakes exhibited stratification. The large surface area of each of the lakes sampled in relation to their volume, and exposure of the surface to agitation by wind and rain ensured waters in the region were well mixed. It should be noted, however, that no summer surface water temperatures were recorded in Kambalda. It is most likely that if temperatures were to approach lethal limits for aquatic biota it would have occurred in summer, when maximum air temperatures were reached. It is also likely that if water temperatures were measured over a 24 hour period they would have been shown to vary diurnally, especially in those lakes that were very shallow, given it has been reported previously that the water temperature of shallow saline lakes is very close to atmospheric temperature (John, 2002).

Supersaturated dissolved oxygen levels were recorded in Binneridgie Road Marsh, Lake Why and Mooreebar Dam at different times throughout this study. In each case the lake's floor was covered by a dense meadow of aquatic macrophytes and/or charophytes. The floor of both Mooreebar Dam and Binneridgie Road Marsh was covered by the charophyte *Nitella lhotzkyi*, while in Lake Why the aquatic macrophyte *Zannichellia palustris* or the charophyte *Nitella subtilissima* was abundant. Such high oxygen saturation levels can be attributed to both the mixing of air into the water column by wind and photosynthetic oxygen production by these dense growths of aquatic plants.

5.1.4 Characteristic Algal Flora of Lakes in Kambalda

At first glance, lakes of the Kambalda region may appear to be hostile to algal growth and barren most of the time. They do, however, support a distinctive algal flora dominated by diatoms and cyanobacteria that are adapted to the temporary water regimes and variable salinity that are characteristic of lakes in this region. The prominence of diatoms and cyanobacteria in lakes in the region is consistent with other salt lakes in the south-eastern interior of Western Australia (Chaplin and John, 1999; John, 1999; 2002; John et al., 2000). Many of the cyanobacteria recorded consist of motile forms and the diatoms have raphe, which facilitates movement. Motility is a necessary adaptation to life in the temporary lakes of the Kambalda region since algae must be able to migrate within surface sediments to avoid high air temperatures and light intensity in summer.

The unpredictable and temporary nature of lakes in the Kambalda region is likely to be a major factor determining the distribution of algal species. Algal species must be able to withstand long, and unpredictable, periods of desiccation. Not surprisingly then, none of the algal taxa recorded from the region were regionally restricted, all noted previously in the literature to have wide geographic distributions, and to be tolerant of a wide range of physicochemical conditions. It is likely, therefore, that the algal flora of lakes in the region have evolved elsewhere and occur there only because they have good dispersal mechanisms which enable them to take rapid advantage of the presence of suitable habitats, as well as mechanisms to survive periods of desiccation (Williams, 1998).

Characteristic algal communities were evident from lakes in the region, within specific salinity concentration ranges. Three lakes, Lake Lefroy, Victory Lake and Golf Lake were consistently hypersaline, salinities ranging from 255ppt to 340ppt, and were weakly acidic to neutral. Under these conditions species diversity was the lowest of the lakes sampled, and *Dunaliella salina* was found to be a dominant algal element. *Dunaliella salina* has previously been reported to thrive in extremely saline environments like these, such as the northern arm of the Great Salt Lake in Utah, which has a salinity of 330ppt (Oren, 2002), the coastal lakes of Rottnest Island in Western Australia (John, 1984) and Lake Dowerin, an inland temporary salt lake in Western Australia which has a salinity of 240ppt (John, pers.comm.).

The algal flora of Lake Zot, whose salinity ranged from 123ppt to 158ppt, was similar to the more saline Lake Lefroy, Victory Lake and Golf Lake in that when salinity was at its highest, *Dunaliella salina* was most abundant. *Dunaliella viridis* was, however, collected more often in Lake Zot than *D. salina*. D. *viridis* has been reported to be a dominant component of slightly less saline environments than those *D. salina* is known to thrive in, including the Great Salt Lake, Utah when salinity was around 120ppt (Post, 1981).

One additional distinctive element of the algal flora of Lake Zot was the presence of a thick, rubbery, laminated benthic algal mat constructed by filamentous and coccoid cyanobacteria with diatoms trapped within. *Chroococcus minutus, Chroocoocodiopsis indica, Microcoleus* sp.1, *Oscillatoria* sp.2, *Schizothrix* sp.2, and *Spirulina major* constructed the mat, with widespread, salt tolerant diatom species including *Amphora coffeaeformis, Cymbella pusilla, Entomoneis alata, Navicula cincta, Navicula* sp.1 and *Nitzschia* sp. aff. *fonticola* trapped within (John, 1998; 2000).

The presence of this benthic microbial mat in Lake Zot suggests that the lake is subject to considerable groundwater discharge. As discussed earlier, for any thickness of algal mat to remain on the floor of temporary lakes sedimentation rates must be high. This requires considerable rainfall, which is clearly not the case in Kambalda, or substantial groundwater discharge (Grey *et al.*, 1990). This may explain why the same species are present in other lakes in the region but benthic mats are not. Although microbial mats were only collected from Lake Zot, John (1999) reported the presence of *Schizothrix* algal mats in Lake Lefroy and noted the functional role they were likely to play in the ecology of the system. However, such mats were not collected in this investigation.

During this study Lake Eaton North exhibited limnological changes associated with the drying phase of the lake's water regime. Algal community composition remained dominated by cosmopolitan, salt tolerant species including *Amphora coffeaeformis*, *Pluerosigma salinarum*, *Rhopalodia musculus*, *Nitzschia* aff. *fonticola*, and *Mastogloia pumila*. However, when the lake was at it most hypersaline, just before drying out completely, the benthic cyanobacteria *Phormidium* sp.2 was dominant. Cyanobacteria are well known to survive, and even thrive, in such variable and extreme conditions (Vincent and Howard-Williams, 2001).

Mooreebar Dam, Binneridgie Road Marsh and Lake Why were the least saline, most alkaline and most diverse of the eight lakes sampled in the Kambalda region. There was no significant difference within the species diversity and species richness of these three lakes, and green algae and diatoms were characteristic components of their algal communities.

Of the green algae, *Ankistrodesmus spiralis, Botryococcus braunii*, *Chlamydomonas* sp.2, *Oocyctis parva, Oedogonium undulatum,* and *Cosmarium retusiforme* were most abundant. Diatom flora included a number of species that have been reported to be widespread and characteristic of alkaline waters of low to medium salinity including *Achnanthidium minutissimum, Caloneis balticum, Navicula cryptocephala* and *Craticula cuspidata* (Gell and Gasse, 1990). Each of these lakes was deep enough during this study to support a number of truly planktonic species, such as *Chaetoceros muelleri*. *C. muelleri* is also indicative of subsaline to hyposaline waters, having been recorded from lakes in Western Victoria at salinities less than 20ppt (Blinn, 1995). The presence of algae such as *Oedogonium* and *Chaetoceros muelleri* appear to be indicative of hyposaline lakes in this inland region of Western Australia as both of these species have also been recorded from Lake Miranda, a temporary seasonal or intermittent saline lake 500km north-east of Perth (John et al., 2000).

In addition, Mooreebar Dam, Binneridgie Road Marsh and Lake Why were the only lakes in this region from which species of the charophyte genus *Nitella* were recorded. Dense meadows of *Nitella lhotzkyi* were found in both Mooreebar Dam and Binneridgie Road Marsh. While only being recorded from these two lakes in this study, *N. lhotzkyi* is reported to be widespread in Australia, from Queensland, Victoria, Western and South Australia (Wood and Imahori, 1965). *Nitella subtillissima* was recorded from Lake Why, the entire floor being covered in large, gelatinous plants in spring 1992 and summer 1993. This species has been reported from a number of locations in Western Australia including the Swan River (Wood and Imahori, 1965). It is likely that the rest of the lakes sampled in the region were too saline for *Nitella* to tolerate. Charophytes are well known to tolerate fluctuations in water permanence and to survive extended periods of desiccation, but they are not known for their capacity to tolerate salinities in excess of 70ppt (Brock and Casanova, 1991; Burne et al., 1980).

5.2 Comparing and Classifying the Esperance and Kambalda Lake Systems

While lakes in the Esperance and Kambalda regions displayed physicochemical and algal characteristics specific to each lake there were some similarities in algal community composition, Sorensen's Index of Similarity between the two systems of lakes being 60%. Of the algal divisions recorded, Sorensen's Index of Similarity for the 82 diatom species was 64%. The source of this similarity is most likely the cosmopolitan, salt tolerant nature of most of the diatoms recorded in this study (Blinn, 1993; Gell, 1997; John, 1999; 2002; Vyvermam, 1991). Most species recorded were able to tolerate a wide and fluctuating range of physiochemical conditions. This is not unusual for this algal division, with many diatom species noted to inhabit waters of a similar and wide-ranging physicochemical nature around the world (Juggins et al., 1994). The 33 green algae recorded from both regions were 60% similar, and the 48 cyanobacteria species were 59% similar. These results suggest that the algal flora of lakes in both of these regions have evolved elsewhere and occur there because they have good dispersal mechanisms which enable them to take advantage of the presence of suitable habitat.

Further, the level of similarity in algal community composition is not surprising when one considers the similarities in physicochemical constraints on algal flora in these two lake systems. They are effectively unified by salinity, despite being geographically separate, and thus experiencing different climatic conditions. Regardless of the role of climatic and hydrological processes play in determining the existence of salt lakes, when it comes to the distribution of algal species the presence of salt requires the ability for organisms to osmoregulate. The results of this study suggest that this requirement has an important influence on algal species diversity, richness and composition. In addition, all lakes in this study exhibited temporary water regimes. As such, adaptation of algal species to temporary conditions, which includes the ability to survive periods of desiccation, is necessary for species to thrive in these saline ecosystems. Canonical correspondence analysis supports this, indicating that pH, water depth and salinity overrode differences in geographical location between Esperance and Kambalda.

This is not to say, however, that there were not differences between lakes in the two regions. Most notably, algal communities in Esperance were significantly more diverse, and species rich, than those from lakes in Kambalda. This is not unexpected when the difference in reliability and permanence of lake water regime, and the influence this has on physicochemical conditions in the lakes, is considered. Water regimes in the Esperance region were more predictable, and rainfall was higher and spatially consistent, hence lake water regimes were less temporary, leading to less variable physicochemical conditions as lakes dried and filled. As a consequence biota needed to withstand less variability and shorter periods of desiccation in Esperance than in Kambalda. Lakes in the Kambalda region are also isolated, whereas lakes in Esperance are in close proximity to the ocean, and thus a large reservoir of marine species that could potentially survive in saline lakes.

Such limnological changes, be they physicochemical or biological, on either a cyclical or irregular basis, are an intrinsic feature of many Australian salt lake systems (Brock, 1986). As a consequence, any attempt to broadly classify salt lakes in these two regions must account for such variation in delineation of categories, a consideration compounded by the continuum along which the transition between wet and dry environments lie (Paijmans *et al.*, 1985). In addition, any classification system used must be easy to apply within a broader Australian context and robust enough to encompass all of the salt lake types likely to be encountered within the full range of climatic and physiographic settings that exist on the Australian continent (Semeniuk and Semeniuk, 1993).

Classification systems have, in the past, been based on criteria pertaining to a range of disciplines from biological, physical and genetic, chemical, ontogenetic or other characteristics. In view of the variability of salt lakes in Australia and the lack of detailed information for many aspects over large areas of the continent, only a simple and rather loosely defined classification system has been possible to date, based on the predictability and duration of filling.

Table 26: Salt Lake Classification System (from Paijmans *et al.*, 1985; Boulton and Brock, 1999).

Salt Lake Type	Predictability and Duration of Filling
Ephemeral	Only filled after unpredictable rainfall and runoff. Surface water dries within days of filling and seldom supports macroscopic aquatic life.
Episodic	Annual inflow is less than the minimum annual loss in 90% of years. Dry most of the time with rare and very irregular wet phases that may persist for months.
Intermittent	Alternatively wet and dry but less frequently and regularly than seasonal wetlands. Surface water persists for months to years.
Seasonal	Alternatively wet and dry every year, according to season. Usually fills during the wet part of the year, and dries predictably and annually. Surface water persists for months, long enough for some macroscopic plants and animals to complete the aquatic stages of their life cycles.
Permanent and near-permanent	Predictably filled although water levels may vary. Annual inflow greater than minimum annual loss in 90% of years. During extreme droughts, these lakes may dry. Much of their biota cannot tolerate desiccation.

When one considers the data collected during this study in the context of Table 26 it is evident that four of the five lakes in the Esperance region can be classified as near-permanent and one, Woody Lake Reserve Marsh as seasonal. The depth of all lakes in the region predictably increased and decreased on a seasonal basis and only Woody Lake Reserve Marsh filled and dried completely on a seasonal basis. To be definitive in this classification the 18 month duration of this study would need to be prolonged, to between 3 and 4 years, to ensure interannual variation was established.

Classification of salt lakes in the Kambalda region is less clear in some cases. Water depth data suggests that four of the eight lakes sampled in the region were intermittent, and a fifth lake, Binneridgie Road Marsh, appears to be intermittent, with the caveat that filling may occur on a more regular basis than seasonally, but not predictably so. This is likely to be a function of the lake's bathymetry and its size relative to its catchment, which makes it very responsive to seasonal and unpredictable cyclonic rainfall events.

On the basis of the water depth data collected, Lake Why appeared to be near-permanent. This is, however, highly unlikely given the low and variable rainfall known to occur in the region. In addition, the prominence of the charophyte *Nitella* suggests that this lake is likely to dry out as these algae are renowned for their ability to thrive in habitats that experience extended periods of desiccation (Brock and Casanova, 1991; Burne *et al.*, 1980). What is most likely is that the lake is intermittent and what was observed during this study was an extended period of inundation. To be certain, however, the lakes would need to be studied for between 3 and 4 years.

The man-made Mooreebar Dam could not be classified using this system, given the overriding influence of Western Mining Corporation's "total water extraction" management practice. Similarly, the water regime of Victory Lake is unclear as the lake is currently maintained as permanent due to active groundwater discharge into the lake by WMC. Given the extremely hypersaline conditions of the lake there is no biological evidence to confirm whether the natural water regime of this lake would be permanent, or intermittent, like the other lakes in the region.

5.3 The Influence of Selected Environmental Parameters on Algal Species Diversity and Richness

Ecological communities do not all contain the same number of species, and one of the areas of research in community structure and ecology is the study of species diversity. Once diversity has been quantified a common problem encountered is the analysis of the multitude of responses of biota to external environmental factors (Ter Braak, 1987). Analysis of the influence of physical parameters is especially important in temporary saline lakes as biota are exposed to wide fluctuations in physicochemical parameters, as well as extreme levels of each (Boulton and Brock, 1999).

Canonical correspondence analysis showed that, of the physicochemical parameters that were investigated in this study, both salinity and pH interacted in determining algal community structure. Both of these attributes were correlated with water depth, which varied according to climatic conditions in a seasonal drying and filling cycle.

The general relationship between species richness and pH and salinity, and species diversity and pH and salinity was simple and linear. With increasing pH and salinity, species diversity and species richness decreased. This finding is similar to the relationship reported from other salt lakes, indicating that in general, increasing salinity and decreasing pH results in decreased species diversity in saline lakes throughout the world (Williams, 1998). In particular, salinity has been reported to be one of the most important predictors of algal community structure in the saline lakes of south-east Western Australia (John, 2002), North America (Blinn, 1993) and Western Victoria (Blinn, 1995). This study differs from these latter two studies, however, in that they indicated pH had no relationship with diatom community structure.

What was less simple, and non-linear, was the nature of the relationship between species diversity and salinity, and species richness and salinity within more narrowly defined ranges of salinity. Across the total spectrum of salinities recorded during this study (1ppt to 350ppt) species diversity and richness dramatically declined, but within smaller salinity ranges the relationship was less significant.

As salinity increased from <1ppt to 30ppt there was a dramatic reduction in species richness and diversity, then, as salinity increased from 30ppt to 100ppt the rate of decrease reduced. Between 100ppt and 250ppt there was almost no relationship between species richness and salinity and species diversity and salinity, but after 250ppt both species diversity and species richness declined markedly. One possible basis for this non-linear relationship is that the algal species typical of low to moderate salinities (below 30ppt) have relatively narrow salinity tolerance ranges, whereas those species more typical of salinities in excess of 30ppt have broad salinity tolerances (Williams *et al*,. 1990). Once a salt tolerant algal species is able to survive the initial physiological problem of osmoregulatory stress, it is able to occupy a wide salinity range. Within this range factors such as ability to survive desiccation, nutrient availability, temperature, light penetration, competition and other forms of biological interaction, rather than salinity itself seem more likely to determine whether it persists or not (Williams, 1998).

5.4 Limitations to Analyses

There are a number of caveats on the findings presented here. Firstly, while the results of this study suggest salinity, pH and water depth variability influence the distribution of algal species in salt lakes in both Esperance and Kambalda, other factors such as solute composition have been reported previously to play a role in shaping the distribution of many organisms inhabiting salt lakes (Herbst, 2001). Nutrient levels and anionic ratios of chloride, bicarbonate-carbonate, and sulphate in particular appear to be important determinants of algal species distribution. Total phosphorus is often reported to be low in temporary Australian salt lakes, although concentrations may increase as lakes dry out and soluble reactive phosphorus, nitrite and nitrate are also usually low. Total nitrogen is generally higher than total phosphorus and often increases as lakes dry out (John, 2002). It is as yet unclear whether this is the case for lakes in Esperance and Kambalda.

In addition, although this project indicated pH played a role in determining species distribution, it did not establish whether this is a direct causal relationship or a function of the control pH has over the chemical state of a number of parameters such as carbon dioxide, phosphate, ammonia, iron, and trace metals. For example, the solubility of particulate amphorous silica, which is important for diatom distribution, is inversely related to pH at values between 3 and 7, increasing at alkaline values to a pH of 9. Funds for chemical analyses were insufficient to investigate fully such water quality parameters but this research is required to establish the role of chemical parameters in determining the distribution of algal species in these lakes.

Secondly, investigation of the hydrological processes of lakes in both regions is vital. Little is known at present about the influence of groundwater flows on their water regimes. It is likely that the water regime of a number of these lakes is influenced by groundwater. The results of this study have indicated that it is likely Pink Lake, Lake Warden and Lake Zot at least receive significant groundwater inflows, and large playa lakes like Lake Lefroy are often described as groundwater lenses, but this requires further investigation. A clear understanding of the role of groundwater in lake water budgets is especially important for all lakes in Esperance and Lakes Lefroy, Zot and Mooreebar Dam in Kambalda as they are all subjected to alteration of groundwater regimes or groundwater extraction. At present, groundwater management decisions are made in the catchments of the lakes, and at the lakes themselves, in the absence of such hydrological information.

Thirdly, the physicochemical and biological changes that take place during the drying and filling cycles of each of these temporary saline lakes is an important aspect of their ecology. It was not possible to be definitive about such issues in this relatively short-term study, however. The sampling period was not long enough to uncover all parts of their drying and filling cycles. The 18 month duration of this study would need to be prolonged to between 3 and 10 years if the interannual variation that is so characteristic of temporary saline lakes, especially those that are intermittent, is to be established. This is required if any real comparison of these lakes is to be made, particularly in the case of Lake Why in which it appears water persists for a few years at a time before drying.

Further, in fluctuating environments like these, numerous fortnightly *in situ* collections are needed to characterise them but the long distances between each of these lake systems, and their location hundreds of kilometres from laboratory facilities made this prohibitively expensive and logistically challenging. A number of physical parameters, such as nutrient concentrations, salinity and pH vary according to the stage the lakes are in during their hydric cycle, which in turn affects species composition. Boulton and Brock (1999) indicate that often the period of maximal chemical variance occurs when temporary wetlands first fill or while they are drying. It is imperative that this cycle of change be investigated if the ecological character of these lakes is to be understood and the impacts of the surrounding activities is to be assessed and adaptively managed to ensure the ecological integrity of temporary saline lakes in the Esperance and Kambalda regions is to be maintained.

Fourthly, a major difficulty for managers in these regions in deciding how to minimise the impact of human activities on the ecological integrity of the lakes, is uncertainty about current levels of water availability, how these compare with previous decades and likely scenarios for the future. All of these salt lakes rely on surface waters flows to fill them, so they are clearly vulnerable to any change in frequency or magnitude of flood events. The key to understanding these issues is knowledge of the distribution and persistence of lakes in the region and the weather and climatic conditions that drive their filling and drying events.

Finally, more research needs to be conducted to identify important indicator species at varying salinity and nutrient levels that may be used to generate a predictive model which should be incorporated into future management plans for the mitigation of salinisation and eutrophication in the catchments of Esperance. The algal flora of Lake Warden in particular highlights the current eutrophic status of lakes in the region. This is particularly important given the international importance of these Ramsar listed wetlands, and the legal requirement under the Environment Protection and Biodiversity Conservation Act (1999) to maintain their ecological integrity. The same indicator species could also be used to monitor the effectiveness of any remediation measures undertaken to combat these issues.

Nonetheless, the concordance between the results presented here and other published studies on the physicochemical and biological limnology of salt lakes in Australia is high. This indicates the adequacy of the methodology employed to establish baseline information on algal communities in temporary salt lakes in the Esperance and Kambalda regions, and to provide preliminary insights to the influence of characteristic physicochemical parameters on algal species distribution.

6.0 CONCLUDING REMARKS

This investigation focussed on the distribution pattern of algal flora in five saline lakes on the southern coast in Esperance and eight inland saline lakes in the Kambalda region. Algal flora of lakes in the Esperance region were more diverse and more species rich than algae from lakes in the Kambalda region. Factors responsible for this include the more persistent and seasonally reliable nature of lake water regimes in Esperance, the result of the region's less variable coastal climate. Rainfall in the Kambalda region was lower and more variable, both temporally and spatially, hence lakes in the Kambalda region filled less predictably and periods of desiccation were more common, and longer.

Secondly, the more extreme variation in water depth in lakes of the Kambalda region meant that the physicochemical conditions algae were required to tolerate to survive were more variable. In addition, proximity to the ocean, and thus a potential reservoir of marine species, also played a role in determining the algal characteristics of lakes in the Esperance region compared to lakes in Kambalda. For example, Mullet Lake supported a number of diatom species characteristic of marine coastal waters including *Mastogloia halophila*, *Mastogloia reimeri, Bracysira aponina, and Berkelya scopulorum*, reflecting its connection with the Southern Ocean in times of high rainfall.

Despite these differences there was, however, a high degree of overlap between the algae recorded, 64% of species being common to both geographical regions. This level of similarity is not surprising when one considers the likeness in physicochemical constraints on algal flora in these two lake systems. They are effectively unified by salinity, despite being geographically separate, and thus experiencing different climatic conditions. Regardless of the role climatic and hydrological processes play in determining the existence of salt lakes, when it comes to the distribution of algal species the presence of salt requires the ability for organisms to osmoregulate. The results of this study suggest that this requirement has an important influence on algal species diversity, richness and composition. In addition, all lakes in this study exhibited temporary water regimes. As such, adaptation of algal species to temporary conditions, which includes the ability to survive periods of desiccation, is necessary for species to thrive in these saline ecosystems.

Further, the algal taxa collected in this study were similar in composition to those reported for inland and coastal saline lakes throughout Australia (Blinn, 1993; Brock and Casanova, 1991; Gell, 1997; John, 1999; John *et al.*, 2000; Moore, 1993). All of the taxa recorded have been reported to have wide geographic distributions. It is likely, therefore, that the algal flora of lakes in both of these regions in Western Australia has evolved elsewhere and occurs there only because it has good dispersal mechanisms which enable it to take rapid advantage of the presence of suitable habitats, as well as mechanisms to survive periods of desiccation and fluctuations in physicochemical conditions.

One species, *Amphora coffeaeformis* occurred in all lakes in Esperance and Kambalda, across a salinity range of 1ppt to 308ppt and a pH range of 6.5 to 10.1. While this is a broad salinity and pH range for this species to tolerate, *A. coffeaeformis* is known to be a widely distributed benthic and epiphytic species in saline waters in both coastal and inland areas (John, 1998). The green alga *Dunaliella salina* was the most halophilic species collected, being recorded in bloom proportions from Pink Lake in the Esperance region and Lake Lefroy, Victory Lake, Golf Lake and Lake Zot in the Kambalda region, at salinities from 158ppt to 340ppt. To thrive in such high salinities *Dunaliella salina* employs a physiological strategy of accumulating a high intracellular concentration of compatible solute (glycerol) to balance the concentration of salts in the external medium (Oren, 2001).

The differences in reliability and duration of filling of salt lakes in the Esperance region, compared to those of the Kambalda region, was used as a basis for their classification into different categories. Four lakes in the Esperance region were classified as near-permanent and one was seasonal. Of the lakes in the Kambalda region, six were classified as intermittent. This is a reflection of the large fluctuations in water depth they exhibited associated with drying and filling cycles that occur due to the more temporally and spatially variable nature of rainfall in the region. The water regimes of two lakes in the Kambalda region were too modified by human intervention to be classified on this basis.

Canonical correspondence analysis showed that, of the physicochemical parameters investigated in this study, both salinity and pH interacted in determining algal community structure. Both of these attributes were correlated with water depth, which varied according to climatic conditions in a seasonal drying and filling cycle.

The general relationship between species richness and pH and salinity, and species diversity and pH and salinity was simple and linear; with increasing pH and salinity, species diversity and species richness decreased. What was less simple, and non-linear, was the nature of the relationship between species diversity and salinity, and species richness and salinity within more narrowly defined ranges of salinity. One possible basis for this non-linear relationship is that once a salt tolerant algal species is able to survive the initial physiological problem of osmoregulatory stress, it is able to occupy a wide salinity range; within this range factors such as their ability to survive desiccation, nutrient availability, temperature and light penetration, rather than salinity itself, seem more likely to determine whether it persists or not.

This study has provided information on the aquatic biodiversity values of seasonal and semi-permanent saline lakes in the Esperance region and intermittent saline lakes in the Kambalda region. The information presented is particularly important as lakes in the Esperance region are impacted by eutrophication as a result of agricultural practices in their catchments, and six of the eight lakes sampled in Kambalda are impacted by water extraction, diversion or dewatering activities associated with mining operations in the region. One of the first steps in the long term management of environments such as these is recognition of their biological values, and potential compromises of those values. This relies upon a clear statement of major features of the lakes, both biological and physicochemical. In addition, the data can act as a baseline against which future changes, be they anthropogenic or naturally induced, may be compared.

7.0 REFERENCES

Agriculture Western Australia, Department of Conservation and Land Management, Department of Environmental Protection and Water and Rivers Commission 1996, Salinity: a situation statement for Western Australia, Government of Western Australia.

Albertano, P. & Hernandez-Marine, M. 2001, 'Algae in habitats with reduced and extreme radiation', *Nova Hedwigia, Beiheft*, vol. 123, pp. 225-227.

American Public Health Association, American Water Works Association and Water Pollution Control Federation 1989, *Standard Methods for the Examination of Water and Wastewater,* 17th ed., APHA, AWW and WPCF, United States of America.

Asquith, J. & Messer, J. 1996, *Nature Conservation Council bush fire management program. Fire & Wetlands Bulletin,* Nature Conservation Council of NSW Inc., New South Wales.

Baker, P. & Fabbro, L. 2002, 'A guide to the identification of common blue-green (Cyanoprokaryotes) in Australian freshwaters. 2nd Edition (1st ed 1999)', *Cooperative Research Centre for Freshwater Ecology Identification Guide No. 25.*

Baltanas, A., Montes, C. & Martino, P. 1990, 'Distribution patterns of ostracods in Iberian saline lakes. Influence of ecological factors', *Hydrobiologia* vol. 197, pp. 207-220.

Bauld, J. 1986, 'Benthic microbial communities of Australian saline lakes', in P. DeDeckker & W.D. Williams (eds), *Limnology in Australia,* Dr W. Junk Publishers, Dordrecht, pp. 95-111.

Bayly, I.A.E. & Williams, W.D. 1966, 'Chemical and biological studies on some saline lakes of South-East Australia', *Australian Journal of Marine and Freshwater Research* vol. 17, pp. 177-228.

Bayly, I.A.E. & Williams, W.D. 1974, *Inland waters and their ecology.* Longman Australia, Hawthorn.

Beadle, L.C. 1974, *The inland waters of tropical Africa.* Longman, London.

Beard, J. S. 1973, *The vegetation of the Esperance and Malcolm areas, Western Australia. Map and explanatory memoir, 1:250 000 series,* Vegmap Publications, Perth.

Beard, J.S. 1990, *Plant life of Western Australia*, Kangaroo Press Pty Ltd. Kenthurst.

Beutel, M.W. 2001, 'Oxygen consumption and ammonia accumulation in the hypolimnion of Walker Lake, Nevada', *Hydrobiologia*, vol. 466, pp. 107-117.

Blinn, D.W. 1991, 'The diatom flora of Lake Eyre South: a large episodically filled salt lake in South Australia', *Hydrobiologia,* vol. 210, pp. 101-104.

Blinn, D.W. 1993, 'Diatom community structure along physicochemical gradients in saline lakes', *Ecology*, vol. 74, no. 4, pp. 1246-1263.

Blinn, D. 1995, 'Diatom community structure along salinity gradients in Australian saline lakes: biogeographic comparisons with other continents', in J.P. Kociolek & M.J. Sullivan (eds), *A Century of Diatom Research in North America: A Tribute to the Distinguished Careers of Charles W. Reimer and Ruth Patrick,* Koeltz Scientific Books, Illinois, pp. 163-174.

Blinn, D.W. & Bailey, P.C.E. 2001, 'Land-use influence on stream water quality and diatom communities in Victoria, Australia: a response to secondary salinization', *Hydrobiologia*, vol. 466, pp. 231-244.

Borowitzka, L.J. 1981, 'The microflora: adaptations to life in extremely saline lakes', *Hydrobiologia,* vol. 81, pp. 33-46.

Boulton, A.J. & Brock, M.A. 1999, *Australian freshwater ecology – processes and management*, Gleneagles Publishing, South Australia.

Bourrelly, P. 1970, *Les Algues D'Eau Douce; Initiation a la Systematique*, Editions N. Boubee & Cie, Paris.

Brennan, K.E.C. 1999, 'Terrestrial invertebrates', in J.M. Osborne & N.J. Dunlop (eds), *Baseline Ecological Study of Lake Lefroy: Long Term Reference and Monitoring Sites. Report to WMC Resources Ltd (St Ives Gold),* School of Environmental Biology, Curtin University of Technology, Bentley.

Brock, M.A. 1981, 'The ecology of halophytes in the south-east of South Australia', *Hydrobiologia,* vol. 81, pp. 23-32.

Brock, M.A. 1986, 'Adaptation to fluctuations rather than to extremes of environmental parameters', in P. De Deckker & W. Williams (eds), *Limnology in Australia,* CSIRO-Australia and Dr W. Junk Publishers, The Netherlands, pp. 131-140.

Brock, M.A. & Casanova, M.T. 1991, 'Plant survival in temporary waters: A comparison of charophytes and angiosperms', *Verh. Internat. Verein. Limnol.,* vol. 24, pp. 2668-2672.

Brock, M.A. & Lane, J.A.K. 1983, 'The aquatic macrophyte flora of saline wetlands in Western Australia in relation to salinity and permanence', *Hydrobiologia*, vol. 105, pp. 63-76.

Brock, M.A. & Shiel, R.J. 1983, 'The composition of aquatic communities in saline wetlands in Western Australia', *Hydrobiologia*, vol. 105, pp. 77-84.

Bunn, S.E., Boon, P.I., Brock, M.A. & Schofield, N.J. 1997, *National wetlands R&D program: scoping review. Land and Water Resources Research and Development Corporation Occasional Paper 01/97*, Land and Water Resources Research and Development Corporation, Canberra.

Burne, R.V., Bauld, J. & De Deckker, P. 1980, 'Saline lake charophytes and their geological significance', *Journal of Sedimentary Petrology*, vol. 50, no. 1, pp. 281-293.

Burne, R.V. & Moore, L.S. 1987, 'Microbialites: organosedimentary deposits of benthic microbial communities', *Palaios*, vol. 2, pp. 241-254.

Burton, H.R. 1981, 'Chemistry, physics and evolution of Antarctic saline lakes', *Hydrobiologia*, vol. 82, pp. 339-362.

Caljon, A.G. 1983, *Brackish-water phytoplankton of the Flemish lowland,* Dr W. Junk Publishers, The Hague.

Chaplin, S. 1999, 'Aquatic invertebrates', in J.M. Osborne & N.J. Dunlop (eds), *Baseline Ecological Study of Lake Lefroy: Long Term Reference and Monitoring Sites. Report to WMC Resources Ltd (St Ives Gold),* School of Environmental Biology, Curtin University of Technology, Bentley.

Chaplin, S. & John, J. 1999, *Biology and water chemistry of lakes in the semi-arid Lefroy-Cowan region of Western Australia, October,* School of Environmental Biology, Curtin University of Technology, Bentley.

Clarke, J.D.A. 1990, *The geology of Lake Lefroy. Western Mining Corporation technical paper*, Western Mining Corporation, Australia.

Clarke, J.D.A. 1991, *The hydrology, stratigraphy and history of Lake Lefroy. Western Mining Corporation technical paper*, Western Mining Corporation, Australia.

Clarke, J.D.A. 1994, 'Geomorphology of the Kambalda region, Western Australia', *Australian Journal of Earth Sciences*, vol. 41, pp. 229-239.

Clavero, V., Fernández, J.A. & Niell, F.X. 1990, 'Influence of salinity on the concentration and rate of interchange of dissolved phosphate between water and sediment in Fuente Piedra lagoon (S.Spain)', *Hydrobiologia,* vol. 197, pp. 91-97.

Cohen, Y., Krumbein, W.E., Golberg, M. & Shilo, M. 1977a, 'Solar Lake (Sinai). 1. Physical and chemical limnology', *Limnology and Oceanography*, vol. 22, no. 4, pp. 597-608.

Cohen, Y., Krumbein, W.E. & Shilo, M. 1977b, 'Solar Lake (Sinai). 2. Distribution of photosynthetic microrganisms and primary production', *Limnology and Oceanography*, vol. 22, no. 4, pp. 609-620.

Cohen, Y., Krumbein, W.E. & Shilo, M. 1977c, Solar Lake (Sinai). 3. Bacterial distribution and production', *Limnology and Oceanography*, vol. 22, no. 4, pp. 621-634.

Colburn, E.A. 1988, 'Factors influencing species diversity in saline waters of Death Valley, USA', *Hydrobiologia*, vol. 105, pp. 215-226.

Comin, E.A. & Alsono, M. 1988, 'Spanish salt lakes: their chemistry and biota', *Hydrobiologia*, vol. 158, pp. 237-245.

Dames & Moore Pty Ltd 1999, *Public environmental review - Gold mine developments on Lake Lefroy for WMC Resources Ltd (St Ives Gold). EPA Assessment Number 1250*, Dames and Moore, East Perth.

Davis, T.J. 1994, *The Ramsar Convention manual. A guide to the Convention of Wetlands of International Importance especially as waterfowl habitat*, Ramsar Convention Bureau, Gland.

De Deckker, P. 1983, 'Australian salt lakes: their history, chemistry, and biota - a review', *Hydrobiologia*, vol. 105, pp. 231-244.

De Deckker, P. 1988, 'Biological and sedimentary facies of Australian salt lakes', *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 62, pp. 237-270.

Department of Conservation and Environment (DCE) 1986, *The Pink Lake Hydrological Study Group report. Department of Conservation and Environment Bulletin 262.* Department of Conservation and Environment, Western Australia.

Department of Conservation and Land Management (CALM) 1990, *Nomination of Lake Warden system to the Ramsar Convention List of Wetlands of International Importance*, Department of Conservation and Land Management, Perth.

Department of Conservation and Land Management (CALM) 1997, *Esperance Lakes Nature Reserve. Draft management plan,* Department of Conservation and Land Management, Perth.

Desikachary, T.V. 1959, *Cyanophyta*, Academic Press, New York.

Dillard, G.E. 1989, *Freshwater algae of the Southeastern United States*, J. Cramer, Stuttgart.

Dillard, G.E. 1999, *Common freshwater algae of the United States. An illustrated key to the genera (excluding the diatoms)*, J.Cramer, Stuttgart.

Donohue, R. & Phillips, B. 1991, *Educating and managing for wetlands conservation. Proceedings of the Wetlands Conservation and Management Workshop,* Australian National Parks and Wildlife Service, Australia.

Drever, J.I. 1982, *The geochemistry of natural waters,* Prentice-Hall Inc., New York.

Egge, J.K. & Aksnes, D.L. 1992, 'Silicate as regulating nutrient in phytoplankton competition', *Marine Ecology Progress Series,* vol. 83, pp. 281-289.

Ehrlich, A. 1978, 'The diatoms of the hypersaline solar lake', *Israel Journal of Botany*, vol. 27, pp. 1-13.

Ehrlich, A. & Dor, I. 1985, 'Photosynthetic microorganisms of the Gavish Sabkha' in G.M. Friedman & W.E. Krumbein (eds), *Hypersaline Ecosystems, The Gavish Sabkha, Ecological Studies 53,* Springer-Verlag, New York, pp. 296-321.

Ehrlich, A. & Ortal, R. 1979, 'The influence of salinity on the benthic diatom communities of the lower Jordan River', *Nova Hedwigia,* vol. 64, pp. 325-339.

Entwisle, T.J., Sonnerman, J.A. & Lewis, S.H. 1997, *Freshwater algae in Australia: a guide to conspicuous genera*, Sainty and Associates, Potts Point.

Eugster, H.P. & Hardie, L.A. 1978, 'Saline lakes', in A. Lerman (ed), *Lakes: chemistry, geology physics,* Springer-Verlag, New York, pp. 237-298.

Evans, M.S. 1993, 'Paleolimnological studies of saline lakes', *Journal of Paleolimnology*, vol. 8, pp. 97-101.

Felix, E.A. & Rushforth, S.R. 1979, 'The algal flora of the Great Salt Lake, Utah, U.S.A.', *Nova Hedwigia*, vol. 31, pp. 163-195.

Foged, N. 1978, 'Diatoms in Eastern Australia', *Bibliotheca Phycologia,* vol. 41, pp. 1-243.

Geddes, M.C. 1981, 'The brine shrimps *Artemia* and *Parartemia*', *Hydrobiologia*, vol. 81, pp. 169-179.

Geddes, M.C., De Deckker, P., Williams, W.D., Morton, D.W. & Topping, M. 1981, 'On the chemistry and biota of some saline lakes in Western Australia', *Hydrobiologia,* vol. 82, pp. 210-222.

Geitler, L. 1932, *Cyanophyceae*, Koeltz Scientific Books, West 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*, vol. 45, pp. 389-423.

Gell, P.A. & Gasse, F. 1990, 'Relationships between salinity and diatom flora from some Australian saline lakes', in *Proceedings of the 11th Diatom Symposium*, Otto Koeltz Publishers, Koenigstein, pp. 631-647.

Gentilli, J. (ed), 1979, *Western Landscapes,* University of Western Australia Press, Perth.

Godfrey, N., Jennings, P. & Nichols, O. 1992, *A guide to wetland management on the Swan Coastal Plain,* Wetlands Conservation Society, Western Australia.

Grey, K., Moore, L.S., Burne, R.V., Pierson, B.K. & Bauld, J. 1990, 'Lake Thetis, Western Australia: an example of saline lake sedimentation dominated by benthic microbial processes', *Australian Journal of Marine and Freshwater Research*, vol. 41, pp. 275-300.

Hammer, U.T. 1981, 'Primary production in saline lakes. A review', *Hydrobiologia*, vol. 81, pp. 47-57.

Hammer, U.T., Shamess, J. & Haynes, R.C. 1983, 'The distribution and abundance of algae in saline lakes of Saskatchewan, Canada', *Hydrobiologia*, vol. 105, pp. 1-26.

Hammer, U.T., Sheard, J.S. & Kranabetter, J. 1990, 'Distribution and abundance of littoral benthic fauna in Canadian prairie saline lakes', *Hydrobiologia*, vol. 197, pp. 173-192.

Hart, B.T. & I.D. McKelvie 1986, 'Chemical Limnology in Australia', in P. De Deckker & W. Williams (eds), *Limnology in Australia*, CSIRO-Australia and Dr W. Junk Publishers, The Netherlands, pp. 3-32.

Helleren, S.K.R. 1993, *Diatoms as indicators of water quality in the wetlands of the Swan Coastal Plain, Western Australia*, Master of Science Thesis, School of Environmental Biology, Curtin University of Technology, Western Australia.

Henley, W.J. 2001, 'Algae and Cyanobacteria under desiccation and ionic stress', *Nova Hedwigia, Beiheft*, vol. 123, pp. 443-452.

Herbst, D.B., 2001, 'Gradients of salinity stress, environmental stability and water chemistry as a template for defining habitat types and physiological strategies in inland salt waters', *Hydrobiologia*, vol. 466, pp 209-219.

Hirsch, P. 1980, 'Distribution and pure culture studies of morphologically distinct solar lake microorganisms', in A. Nissenbaun (ed), *Hypersaline brines and evaporite environments; developments in sedimentology*, Elsevier, New York, pp. 41-60.

Hollis, G.E. & Finlayson, C.M. 1996, 'Ecological change in Mediterranean wetlands', in P. Tomas-Vines, C.M. Finlayson, B. Goldsmith, R. Rufino & P. Grillas (eds), *Methodological guide to monitoring Mediterranean wetlands,* MedWet, Slimbridge, UK, pp. 5-24.

Hudson, P. 1995, *Report on a Survey of the Terrestrial Invertebrate Fauna of Lake Lefroy, WA,* Unpublished report prepared for WMC Resources Limited.

Hutchinson, G.E. 1975, *A Treatise of Limnology, Volume III, Limnological Botany,* Wiley, New York.

Javor, B. 1989, *Hypersaline environments: microbiology and biogeochemistry,* Springer-Verlag, Berlin.

Jensen, A. 1993, *Assigning values to wetlands and natural resources in the south east of South Australia. A background paper prepared for the "Upper East Dryland Salinity and Flood Management Plan Environmental Impact Statement",* Department of Environment and Land Management, South Australia.

Jensen, A. 1996a, *Conservation-based management: From theory to practice in River Murray Valley wetlands,* Department of Environment and Natural Resources, South Australia.

Jensen, A. 1996b, *Ecotones research project sites in the Murray-Darling Basin, Australia,* Department of Environment and Natural Resources, South Australia.

Jensen, A. 1996c, *Identifying and redressing the ecological consequences of river regulation in the lower River Murray,* Department of Environment and Natural Resources, South Australia.

Jensen, A. 1996d, *Rehabilitation and integrated management of wetland systems of the River Murray floodplain,* Department of Environment and Natural Resources, South Australia.

Jensen, A. 1996e, *Rehabilitation of the River Murray: Identifying causes of degradation and options for bringing the environment into the management equation,* Department of Environment and Natural Resources, South Australia.

Jensen, A. & Mc Phail, B. 1996, *Environmental issues and multi-purpose use in the Murray-Darling Basin,* Department of Environment and Natural Resources, South Australia.

Jensen, A., Nicolson, C. & Carter, J. 1996a, *Preservation and management of natural wetlands in the South Australian Murray Valley,* Department of Environment and Natural Resources, South Australia.

Jensen, A., Nicolson, C. & Carter, J. 1996b, *Restoration techniques for wetland systems: A case study in the South Australian River Murray Valley,* Department of Environment and Natural Resources, South Australia.

Johansen, J.R., Rushforth, S.R. & Brotherson, J.D. 1981, 'Subaerial algae of Navajo National Monument, Arizona', *Great Basin Naturalist,* vol. 41, no. 4, pp. 434-441.

Johansen, J.R., Rushforth, S.R. & Brotherson, J.D. 1983, 'The algal flora of Navajo Monument, Arizona, U.S.A.', *Nova Hedwigia,* vol. 38, pp. 501-553.

John, J. 1983, 'The diatom flora of the Swan River Estuary, Western Australia', *Bibliotheca Phycologia,* vol. 64, pp. 1-360.

John, J. 1984, 'The algal flora of the hypersaline lakes in Rottnest Island', in *Proceedings of the Australasian Society for Phycology and Aquatic Botany December 1984*, Otto Koeltz Publishers, Koenigstein, pp 1-8.

John, J. 1986, 'Morphology and ecology of *Navicula elegans* W. Smith populations from Western Australia', in F.E. Round (ed), *Proceedings of the Ninth International Diatom Symposium,* Otto Koeltz Publishers, Koenigstein, pp. 417-425.

John, J. 1990, 'The diatom flora of the microbial communities associated with stromatolites at Shark Bay, Indian Ocean, West Coast of Australia', *Ouvrage dédié à H. Germain*, Koeltz Publishers, West Germany, pp. 97-

110.

John, J. 1994, 'Eutrophication of the Swan River Estuary, Western Australia and the management strategy', in M.J. Mitsch (ed), *Global Wetlands: Old World and New*, Elsevier, New York, pp. 749-757.

John, J. 1998, *Evaluation of attached diatoms as a tool for riverine bioassessment of water quality. Final Report to Land and Water Resources Research and Development Corporation*, Curtin University of Technology, Western Australia.

John, J. 1999, 'Aquatic Flora', in J.M. Osborne & N.J. Dunlop (eds), *Baseline Ecological Study of Lake Lefroy: Long Term Reference and Monitoring Sites. Report to WMC Resources Ltd (St Ives Gold)*, School of Environmental Biology, Curtin University of Technology, Bentley.

John, J. 2000, 'A guide to diatoms as indicators of urban stream health', *National River Health Program, Urban Subprogram*, Report No 7, *LWRRDC Occasional Paper* 14/99.

John, J. 2002, *Lake Raeside Report*, School of Environmental Biology, Curtin University of Technology, Bentley.

John, J., Dunlop, N., Goldberg, J., Lowe, E. & Osborne, J. 2000, *Baseline aquatic biology survey of Lake Miranda, September*, School of Environmental Biology, Curtin University of Technology, Western Australia.

John, J., Lowe, E., Butson, F. & Osborne, J. 2001, *Lake Miranda study: April 2001 quarterly report*, School of Environmental Biology, Curtin University of Technology, Western Australia.

Jorgensen, B.B., Kevsbech, N.P. & Cohen, Y. 1983, 'Photosynthesis and structure of benthic microbial mats: microelectrode and SEM studies of four cyanobacterial communities', *Limnology and Oceanography*, vol. 28, pp 1075-1093.

Juggins, S., Battarbee, R.W., Fritz, S.C. & Gasse, F. 1994, 'The CASPIA project: diatoms, salt lakes, and environmental change', *Journal of Paleolimnology*, vol. 12, pp. 191-196.

Kennedy, J.H., Cook, R.E. & Anderson, G.M. 1998, 'Diversity and temporal patterns of macroinvertebrates inhabiting Southern High Plains playas', in A.J. McComb & J.A. Davis (eds), *Wetlands for the Future*, Gleneagles Publishing, Adelaide, pp. 139-160.

Kingsford, R.T. & Halse, S.A. 1998, 'Waterbirds as the 'flagship' for the conservation of arid zone wetlands of Australia', in A.J. McComb & J.A.

Davis (eds), *Wetlands for the Future*, Gleneagles Publishing, Adelaide, pp. 139-160.

Kotwicki, V. & Isdale, P. 1991, 'Hydrology of Lake Eyre, Australia: El Nino link', *Palaeogeography, Palaeoclimatology, Palaeoecology,* vol. 84, pp. 87-98.

Krumbein, W.E., Cohen, Y. & Shilo, M. 1977, 'Solar Lake (Sinai) 4. Stomatolitic cyanobacterial mats', *Limnology and Oceanography*, vol. 22, pp 635-656.

Laybourn-Parry, J. & Marchant, H. 1992, 'The microbial plankton of freshwater lakes in the Vestfold Hills, Antarctica', *Polar Biology,* vol. 12, pp. 405-410.

Ling, H. & Tyler, P. 1986, *A limnological survey of the Alligator Rivers region. II Freshwater algae, exclusion of diatoms*, Commonwealth of Australia, Canberra.

Lothian, J.A. & Williams, W.D. 1988, 'Wetland conservation in South Australia', in A.J. McComb & P.S. Lake (eds), *The Conservation of Australian Wetlands*, Surrey Beatty and Sons Pty Ltd, New South Wales, pp. 147-166.

Lund, J.W.G., Kipling, C. & Le Cren, E.D. 1958, 'The inverted microscope method of estimating algal numbers and the statistical basis of estimations by counting', *Hydrobiologia,* vol. 11, pp. 143-170.

McComb, A.J. & Lake, P.S. 1990, *Australian Wetlands,* Angus and Robertson, Australia.

Masojidek, J. 2001, 'Physiological and molecular responses of algae to extreme conditions', *Nova Hedwigia, Beiheft*, vol. 123, pp. 499-500.

Melack, J.M. 1981, 'Photosynthetic activity of phytoplankton in tropical African soda lakes', *Hydrobiologia,* vol. 81, pp. 71-85.

Mianping, Z. 2001, 'On salinology', *Hydrobiologia*, vol. 466, pp. 339-347.

Moore, L. 1987, Water chemistry of the coastal saline lakes of the Clifton-Preston Lakeland system, South-Western Australia, and its influence on stromatolite formation, *Aust. J. Mar. Freshwat. Res.*, vol. 38, pp. 647-660.

Moore, L. 1991, 'Lake Clifton – an internationally significant wetland in need of management', *Land and Water News*, issue 8, pp. 37-41.

Moore, L. 1993, *The modern microbialites of Lake Clifton, South-Western Australia*, Doctor of Philosophy Thesis, Department of Microbiology, University of Western Australia, Western Australia.

Moore, L., Knott, B. & Stanley, N. 1983, 'Stromatolites of Lake Clifton, Western Australia', *Search*, vol. 14, no. 11-12, pp. 309-314.

Morgan, K.H. & Peers, R. 1973, *1:250 000 Geological Series - Explanatory Notes. Esperance - Mondrain Island Western Australia. Geological survey of Western Australia Sheet S1/51-6, 10 International Index*, Australian Government Publishing Service, Canberra.

Munks, S.A. 1996, *A Guide to riparian (river-bank) vegetation and its management*, Department of Primary Industry and Fisheries, Tasmania.

National Parks Service 1996, *Manual of Wetlands Management. Wetlands Conservation Report Series Number 4*, Department of Natural Resources and Environment, Victoria.

Newbey, K.R. 1984, 'The Biological Survey of the Eastern Goldfields of Western Australia', *Records of the Western Australian Museum*, Supplement Number 18.

Nishri, A. & Ben-Yaakov, S. 1990, 'Solubility of oxygen in the Dead Sea brine', *Hydrobiologia*, vol. 197, pp. 99 -104.

Oren, A. 2001, 'The bioenergetic basis for the decrease in metabolic diversity at increasing salt concentrations: implications for the functioning of salt lake ecosystems', *Hydrobiologia*, vol. 466, pp. 61-72.

Oren, A. 2002, *Halophilic microorganisms and their environments*, Kulwer Academic Publishers, The Netherlands.

Oren, A. & Seckback, J. 2001, 'Oxygenic photosynthetic microorganisms in extreme environments', in *Nova Hedwigia, Beiheft*, vol. 123, pp. 13-31.

Paijmans, K., Galloway, R.W., Faith, D.P., Fleming, P.M., Haantjens, H.A., Heyligers, P.C., Kalma, J.D. & Löffler, E. 1985, 'Aspects of Australian Wetlands', *Division of Water and Land Resources Technical Paper No. 44*, CSIRO, Australia.

Patrick, R. & Reimer, C.W. 1975, 'The diatoms of the United States Vol. 2', *Monographs of the Academy of Sciences of Philadelphia*, vol. 13, 688pp.

Pentecost, A. 1984, *Introduction to freshwater algae*, The Richmond Publishing Group, England.

Platt, J. 1996, *Esperance Region Catchment Planning Strategy. A Project of the Esperance Land Conservation District Committee supported by National Landcare Program and Agriculture Western Australia, Esperance. Miscellaneous Publication 10/96*, Agdex 527, Western Australia.

Playford, P.E. 1988, *Guidebook to Rottnest Island*, Excursion Guidebook No.2, Geological Society of Western Australia WA Division and Geological Survey of Western Australia.

Post, F.J. 1981, 'Microbiology of the Great Salt Lake north arm', *Hydrobiologia*, vol. 81, pp. 59-69.

Post, F.J., Borowitzka, L.J., Mackay, B. & Moulton, T. 1983, 'The protozoa of a Western Australian hypersaline lagoon', *Hydrobiologia*, vol. 105, pp. 95-113.

Prescott, G.W. 1978, *How to know the freshwater alga,* W.M.C. Brown Company Publishers, Iowa.

Quesada, A., Sanchez-Contreras, M. & Fernandez-Valiente, E. 2001, 'Tolerance of Antarctic cyanobacterial microbial mats to natural UV radiation', *Nova Hedwigia, Beiheft*, vol. 123, pp. 275-290.

Rader, R.B. & Richardson, C.J. 1992, 'The effects of nutrient enrichment on algae and macroinvertebrates in the Everglades: a review', *Wetlands*, vol. 12, no. 2, pp. 121-135.

Rayment, G.E. & Higginson F.R. 1992, *Australian laboratory handbook of soil and water chemical methods,* Inkata Press, Melbourne.

Roshier, D.A., Whetton, P.H., Allan, R.J. & Robertson, A.I. 2001, 'Distribution and persistence of temporary wetland habitats in arid Australia in relation to climate', *Austral Ecology*, vol. 26, pp. 371-384.

Round, F.E. 1981, *The ecology of algae,* Cambridge University Press, Cambridge.

Round, F.E., Crawford, R.M. & Mann, D.G. 1990, *The Diatoms,* Cambridge University Press, New York.

Royle, R.N. & King, R.J. 1992, 'The phytoplankton of Lake Liddell, New South Wales: chlorophyll *a* concentrations, species seasonal succession, and covariation with nutrients', *Hydrobiologia*, vol. 245, pp. 41-52.

Rushforth, S.R. & Johansen, J.R. 1986, 'The inland *Chaetoceros* (Bacillariophyceae) species of North America', *J. Phycol.*, vol. 22, pp. 441-448.

Ryding, S.O. & Rast, R.J. 1989, *The control of eutrophication of lakes and reservoirs*, United Nations Educational Scientific and Cultural Organisation (UNESCO) and The Parthenon Publishing Group, Paris and the United Kingdom respectively.

Seaman, M.T., Ashton, P.J. & Williams, W.D. 1991, 'Inland salt waters of southern Africa', *Hydrobiologia*, vol. 210, pp. 75-91.

Seamer, D.G. 1998, 'Freshwater algae of Tasmania. A new guide to the identification of Tasmanian's freshwater algae', Department of Primary Industry and Fisheries, Resource Management Division, *WRA Unit Report, 98/02*.

Seip, K.L., Sas, H. & Vermij, S. 1992, 'Changes in Secchi disk depth with eutrophication', *Arch. Hydrobiol.,* vol. 124, no. 2, pp. 149-165.

Semeniuk, C.A. & Semeniuk, V. 1993, 'The geomorphic classification of wetlands', in A. Hill, C. Semeniuk, V. Semeniuk & A. Del Marco (eds), *Wetlands of the Swan Coastal Plain – Volume 2a: Main Report*, Water and Rivers Commission, Western Australia, pp. 30-49.

Servant-Vildary, S. & Roux, M. 1990, 'Multivariate analysis of diatoms and water chemistry in Bolivian saline lakes', *Hydrobiologia,* vol. 197, pp. 267-290.

South, G.R. & Whittick, A. 1987, *Introduction to phycology*, Blackwell, Oxford, London.

Stephens, D.W. 1990, 'Changes in lakes levels, salinity and the biological community of Great Salt Lake (Utah, USA), 1847-1987', *Hydrobiologia,* vol. 197, pp. 139-146.

Ter Braak, C.J.F. 1987, *Canoco - a FORTRAN program for canonical community ordination*, TNO Institute of Applied Computer Science, The Netherlands.

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,* vol. 466, pp. 245-254.

Tudorancea, C. & Harrison, A.D. 1988, 'The benthic communities of the saline lakes Abijata and Shala (Ethiopia)', *Hydrobiologia,* vol. 158, pp. 117-123.

Vallentyne, J.R. 1972, 'Freshwater supplies and pollution: Effects of the demographic explosion on water and man', in N. Polonin (ed), *The Environmental Future,* Macmillan, London.

Vincent, W.F. & Howard-Williams, C. 2001, 'Algae in environments with extreme temperatures', *Nova Hedwgia, Beiheft*, vol. 123, pp. 33-36.

Vyvermam, W. 1991, *Diatoms from Papua New Guinea, Bibliotheca Diatomologica*, J.Cramer, Berlin.

Walker, K.F. 1973 'Studies on a saline ecosystem', *Australian Journal of Marine and Freshwater Research*, vol. 24, pp. 21-71.

Williams, W.D. 1978, 'Limnology of Victorian salt lakes, Australia', *Verh. International Verin. Limnol.*, vol. 20, pp. 1165-1174.

Williams, W.D. 1981, 'Inland salt lakes: An introduction', *Hydrobiologia,* vol. 81, pp. 1-14.

Williams, W.D. 1982, 'The limnology of saline lakes in Western Victoria', *Hydrobiologia*, vol. 82, pp. 233-259.

Williams, W.D. 1985, 'Biotic adaptations in temporary lentic waters, with special reference to those in semi-arid and arid regions', *Hydrobiologia*, vol. 125, pp. 85-110.

Williams, W.D. 1986a, 'Limnology, the study of inland waters: a comment on perceptions of studies of salt lakes, past and present', in P. De Deckker & W.D. Williams (eds), *Limnology in Australia,* Dr W. Junk Publishers, Dordrecht, pp. 471-484.

Williams, W.D. 1986b, 'Conductivity and salinity of Australian salt Lakes', *Australian Journal of Marine and Freshwater Research,* vol. 37, pp. 177-82.

Williams, W.D. 1993a, 'The importance of salt lakes in Australia', *Search,* vol. 24, no. 7, pp. 197-200.

Williams, W.D. 1993b, 'Conservation of salt lakes', *Hydrobiologia*, vol. 267, pp. 291-306.

Williams, W.D. 1993c, 'Australian inland waters: a limited resource', *Australian Biologist*, vol. 6, no. 1, pp. 2-10.

Williams, W.D. 1993d, 'The conservation of salt lakes: important aquatic habitats of semi-arid regions', *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 3, pp. 71-72.

Williams, W.D. 1998, 'Biodiversity in salt lakes', in A.J. McComb & J.A. Davis (eds), *Wetlands for the Future,* Gleneagles Publishing, Glen Osmond, South Australia, pp. 161-166.

Williams, W.D. 2001, 'Anthropogenic salinisation of inland waters', *Hydrobiologia,* vol. 466, pp 329-337.

Williams, W.D., Boulton, A.J. & Taaffe, R.G. 1990, 'Salinity as a determinant of salt lake fauna: a question of scale', *Hydrobiologia*, vol. 197, pp. 257-266.

Williams, W.D. & Buckney, R.T. 1976a, 'Stability of ionic proportions in five salt lakes in Victoria, Australia', *Australian Journal of Marine and Freshwater Research*, vol. 27, pp. 367-77.

Williams, W.D. & Buckney, R.T. 1976b, 'Chemical composition of some inland surface waters in South, Western and Northern Australia', *Australian Journal of Marine and Freshwater Research*, vol. 27, pp. 379-397.

Williams, W.D. & Kokkinn, M.J. 1988, 'The biogeographical affinities of the fauna in episodically filled salt lakes: A study of Lake Eyre South, Australia', *Hydrobiologia*, vol. 158, pp. 227-236.

Wood, R.B. & Talling, J.F. 1988, 'Chemical and algal relationships in a salinity series of Ethiopian inland waters', *Hydrobiologia*, vol. 158, pp. 29-67.

Wood, R.D. & Imahori, K. 1965, *Revision of the Characeae,* J.Cramer, Weinheim.

Wright, S.W. & Burton, H.R. 1981, 'The biology of Antarctic saline lakes', *Hydrobiologia,* vol. 82, pp. 319-338.

Zar, J.H. 1984, *Biostatistical Analysis, 2nd Edition,* Prentice-Hall Inc., New Jersey.

APPENDIX 1

OECD boundary values for open trophic classification system (annual mean values). A waterbody can be considered correctly classified if no more than one of the parameters deviates from its geometric mean value by ± 2 standard deviations (from Ryding and Rast, 1989).

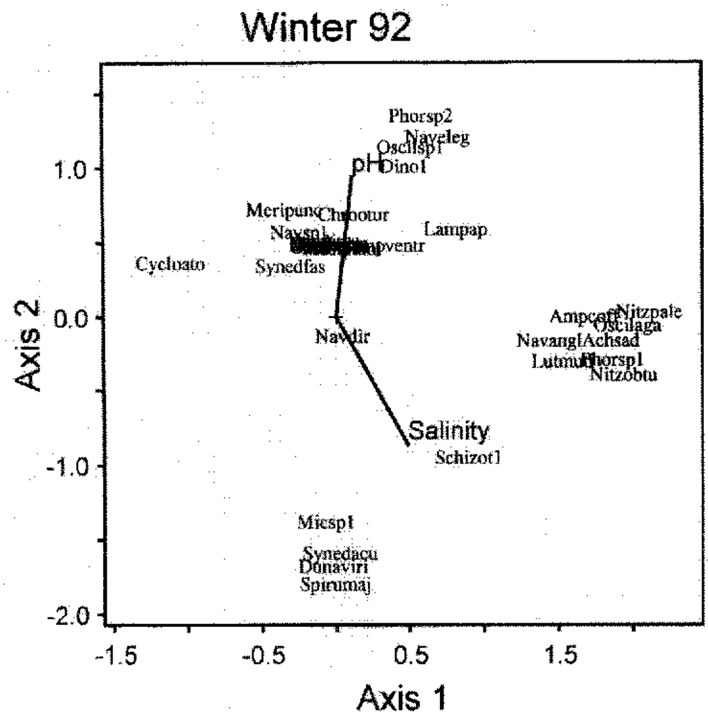
Parameter		Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
	mean	8.0	26.7	84.4	
Total	± 1 SD	4.85 - 13.3	14.5 - 49	48 - 189	
Phosphorus	± 2 SD	2.9 - 22.1	7.9 - 90.8	16.8 - 424	
(µg P/l)	Range	3.0 - 17.7	10.9 - 95.6	16.2 - 396	750 - 1200
	n	21	19 (21)	71 (72)	2
Total Nitrogen	mean	661	753	1875	
(µg N/l)	± 1 SD	371 - 1180	485 - 1170	861 - 4081	
	± 2 SD	208 - 2103	313 - 1816	395 - 8913	
	Range	307 - 1630	361 - 1387	393 - 6100	
	n	11	8	37 (38)	
Secchi	mean	9.9	4.2	2.45	
depth	± 1 SD	5.9 - 16.5	2.4 - 7.4	1.5 - 4.0	
(m)	± 2 SD	3.6 - 27.5	1.4 - 13	0.9 - 6.7	
	Range	5.4 - 28.3	1.5 - 8.1	0.8 - 7.0	0.4 - 0.5
	n	13	20	70 (72)	

Where:

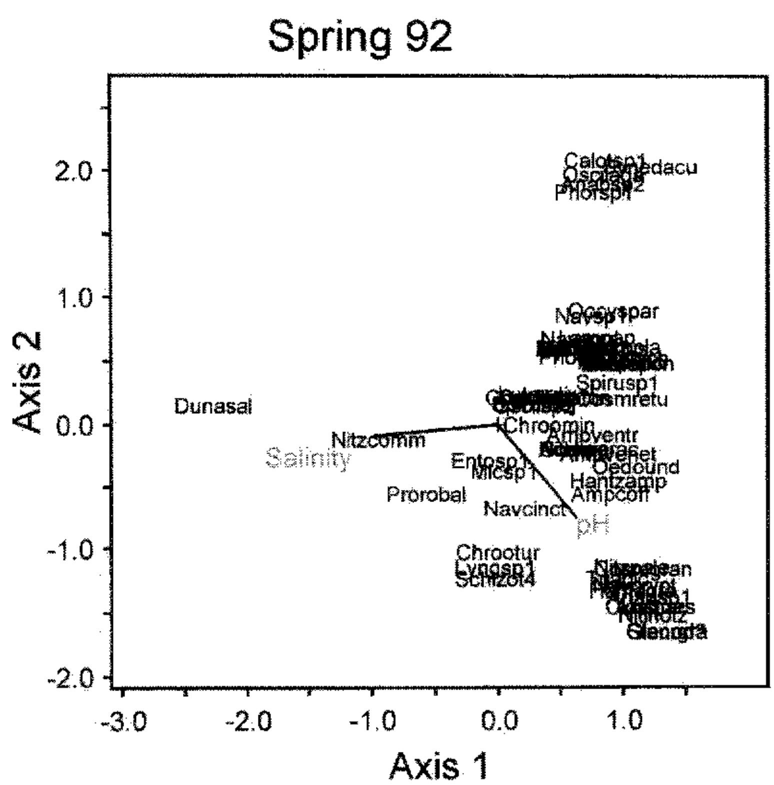
mean = geometric mean (calculated after removing values which were greater than, or less than, two times the standard deviation obtained [where applicable] in the first calculation).
SD = standard deviation.
( ) = the value in brackets refers to the number of variables (n) used in the first calculation.

APPENDIX 2

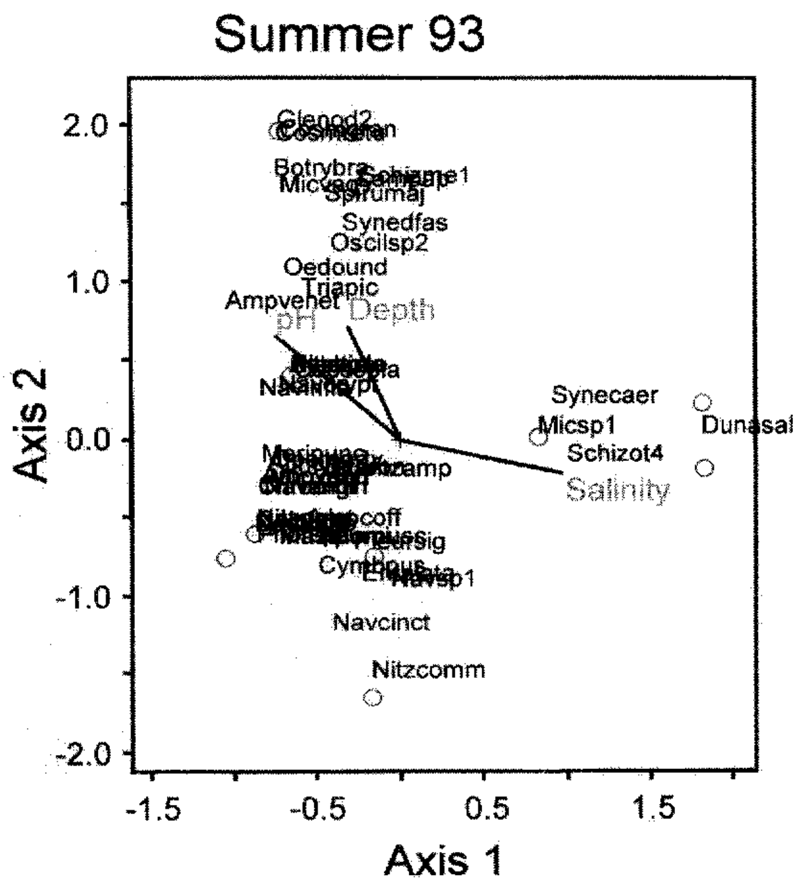
Components correspondence analysis of species data plotted in relation to environmental parameters. The scores from axes 1 and 2 are presented for winter 1992 (a), spring 1992 (b), summer 1993 (c), autumn 1993 (d), and winter 1993 (e). Dominant algal taxa have been plotted.



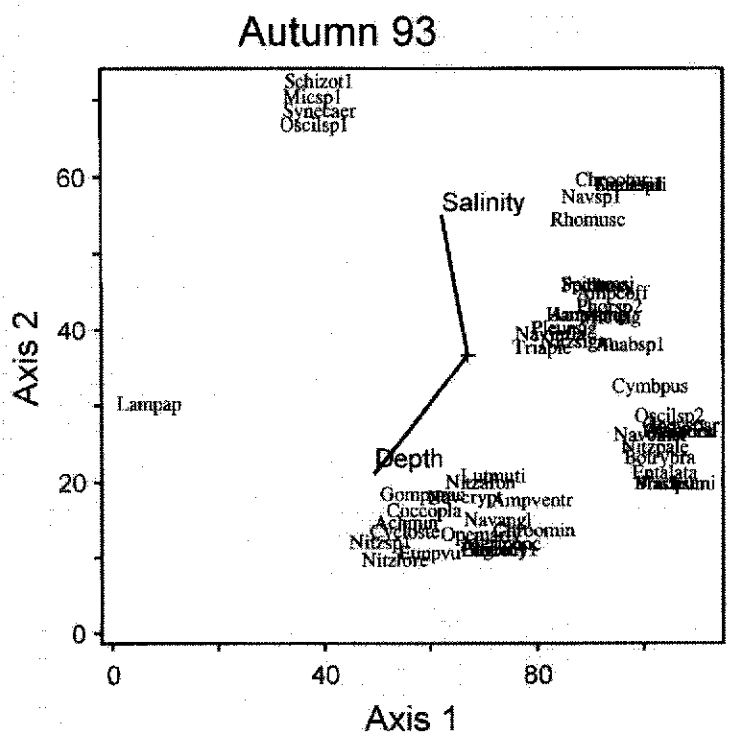
(a)



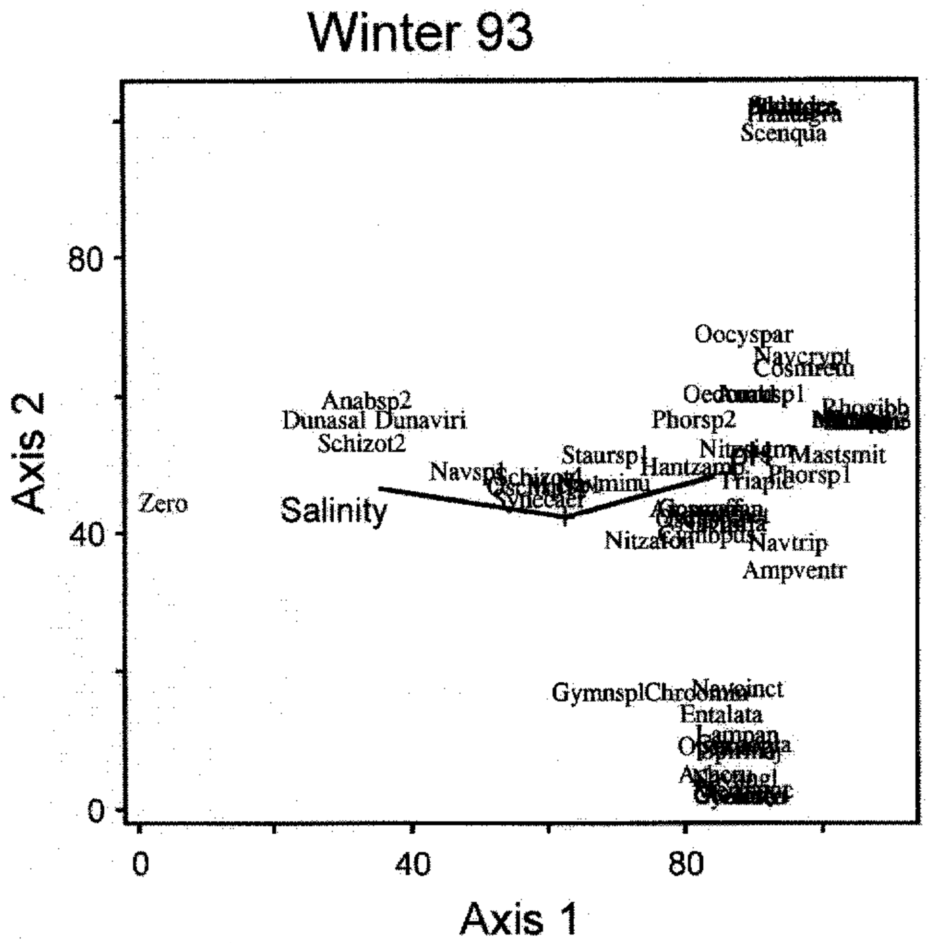
(b)


Summer 93
Axis 2
Axis 1
2.0
1.0
0.0
-1.0
-2.0
-1.5
-0.5
0.5
1.5
Botrybra
Synedfas
Oscilsp2
Oedound
Triapic
Ampvenet
pH
Depth
Synecaer
Micsp1
Schizot4
Dunasal
Salinity
Cymbpus
Navcinct
Nitzcomm

(c)


Autumn 93
Axis 2
Axis 1
60
40
20
0
0
40
80
Schizot1
Micsp1
Synecaer
Oscilsp1
Salinity
Navsp1
Rhomusc
Triapic
Lampap
Cymbpus
Oscilsp2
Botrybra
Depth
Coccopla
Nitzsp1
Nitzfore

(d)


Winter 93
Axis 2
Axis 1
0
40
80
Scenqua
Oocyspar
Anabsp2
Dunasal Dunaviri
Schizot2
Phorsp2
Staursp1
Hantzamp
Mastsmit
Zero
Salinity
Nitzafon
Navtrip
Ampventr
Entalata

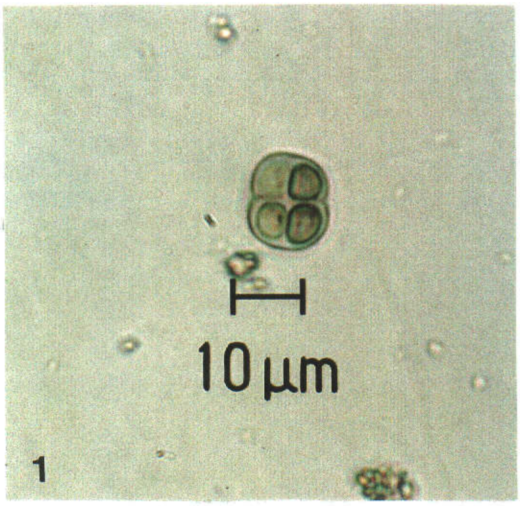
(e)

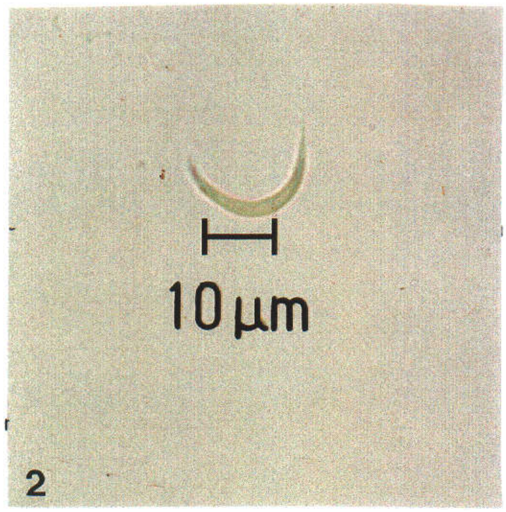
APPENDIX 3

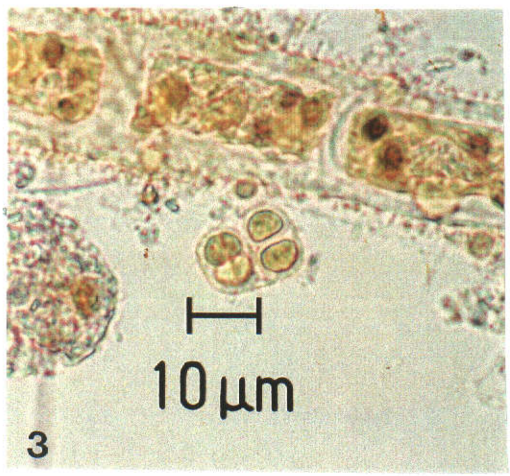
Plate 1

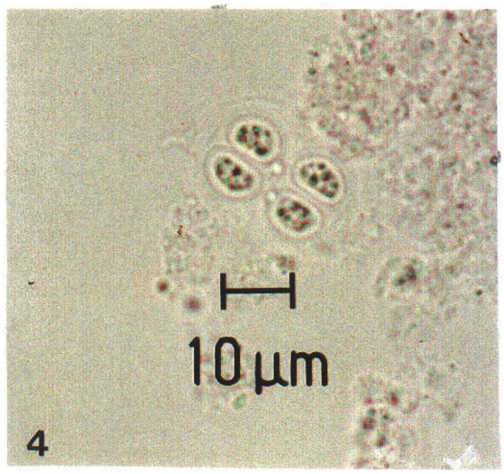
Fig	1	*Chroococcus minutus*
	2	*Dactylococcopsis rhaphiodiodes*
	3 - 4	*Gloeocapsa punctata*
	5	*Gomphosphaeria aponina*
	6	*Microcystis littoralis*

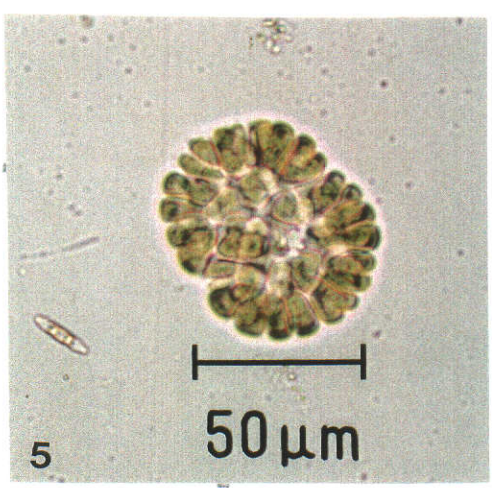
Plate 1











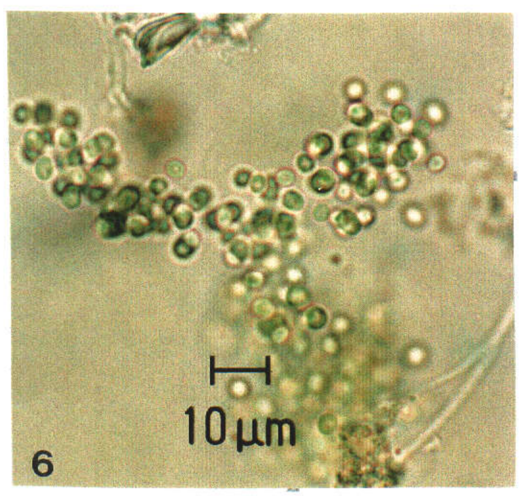
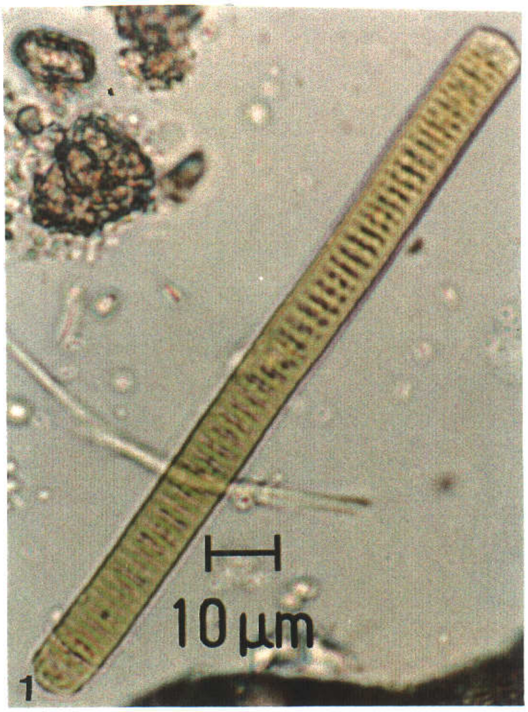
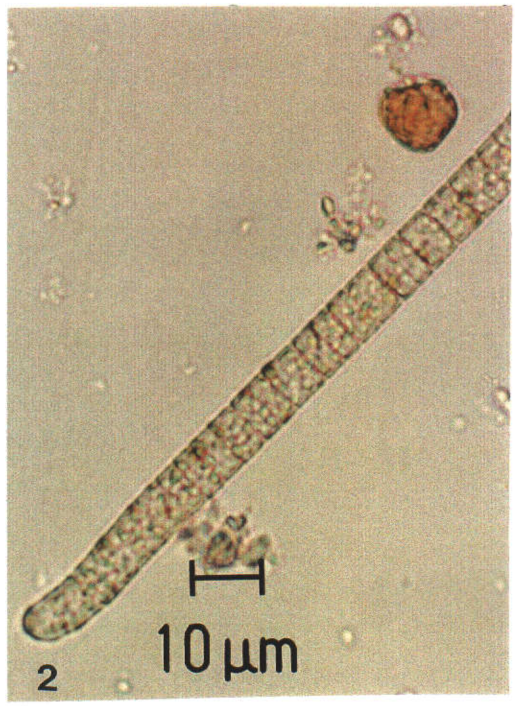


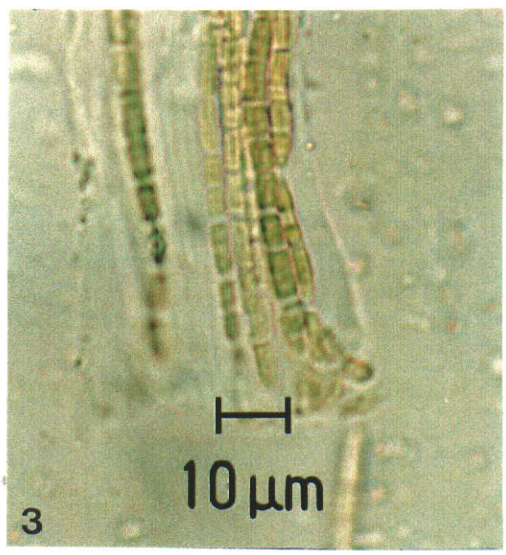
Plate 2

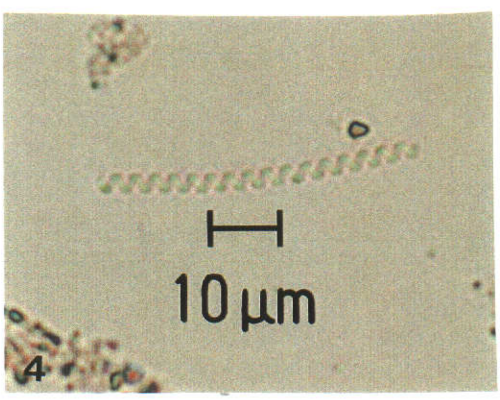
Fig	1	*Lyngbya* sp. 1
	2	*Microcoleus vaginatus*
	3	*Schizothrix* sp. 1
	4	*Spirulina major*
	5	*Spirulina subsalsa*

Plate 2









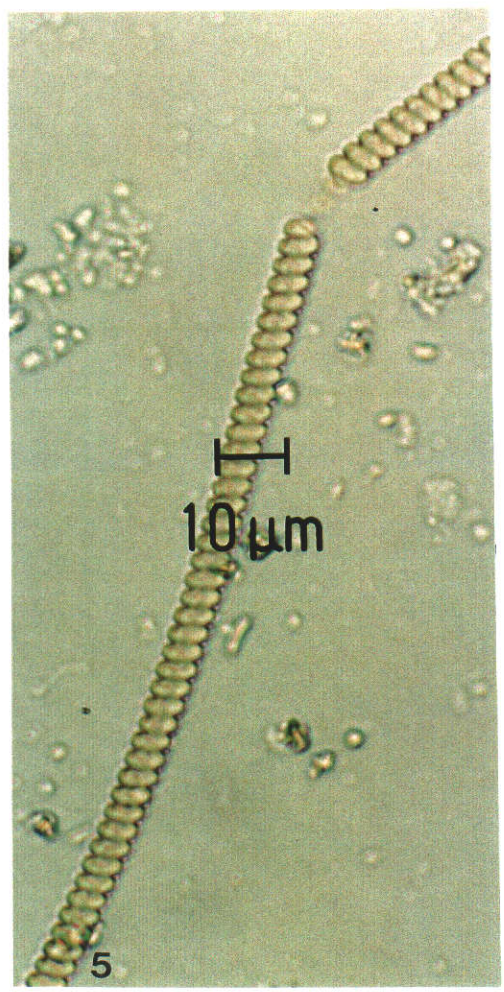
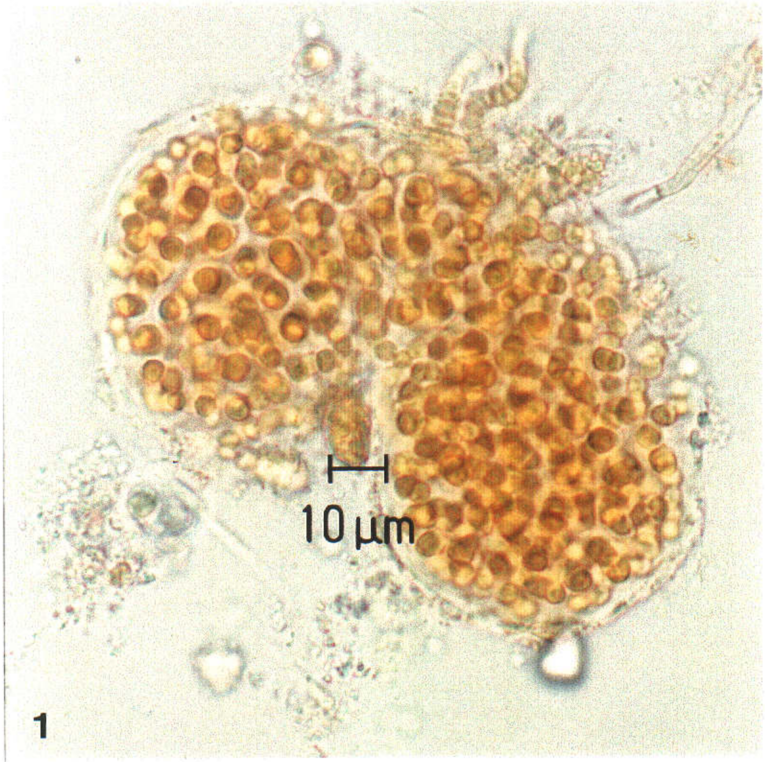
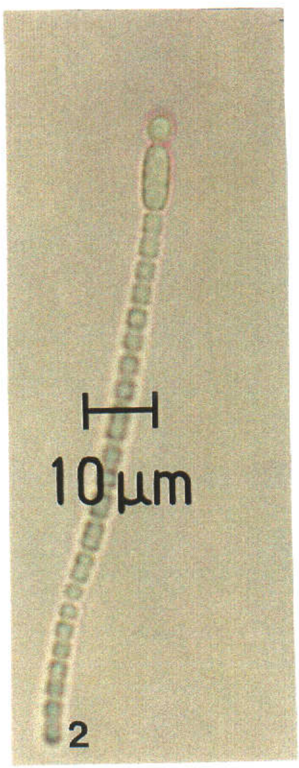


Plate 3

Fig	1	*Nostoc* sp.1
	2	*Anabaena* sp.1
	3	*Calothrix* sp. 1

Plate 3





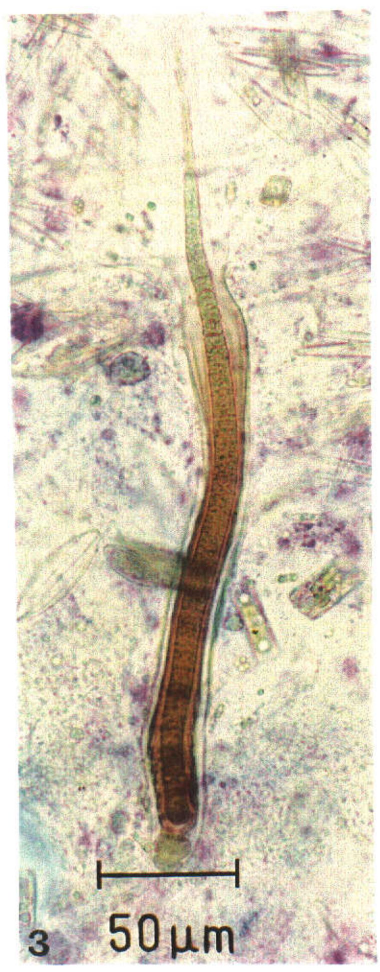


Plate 4

Fig	1	*Chlamydomonas* sp. 1
	2	*Chlamydomonas* sp. 1 (Palmella Stage)
	3 – 4	*Ankistrodesmus spiralis*
	5	*Botryococcus braunii*

Plate 4

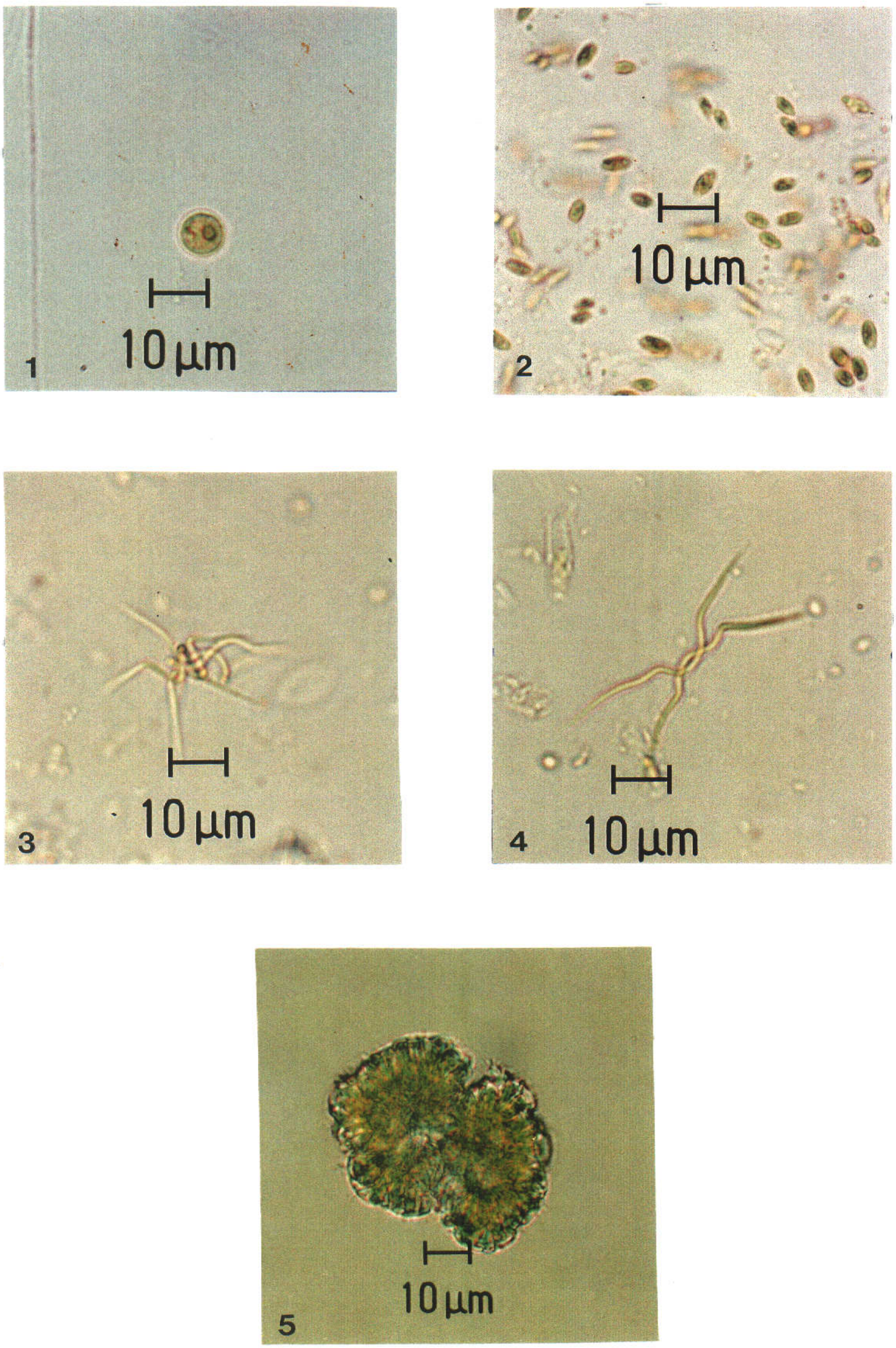
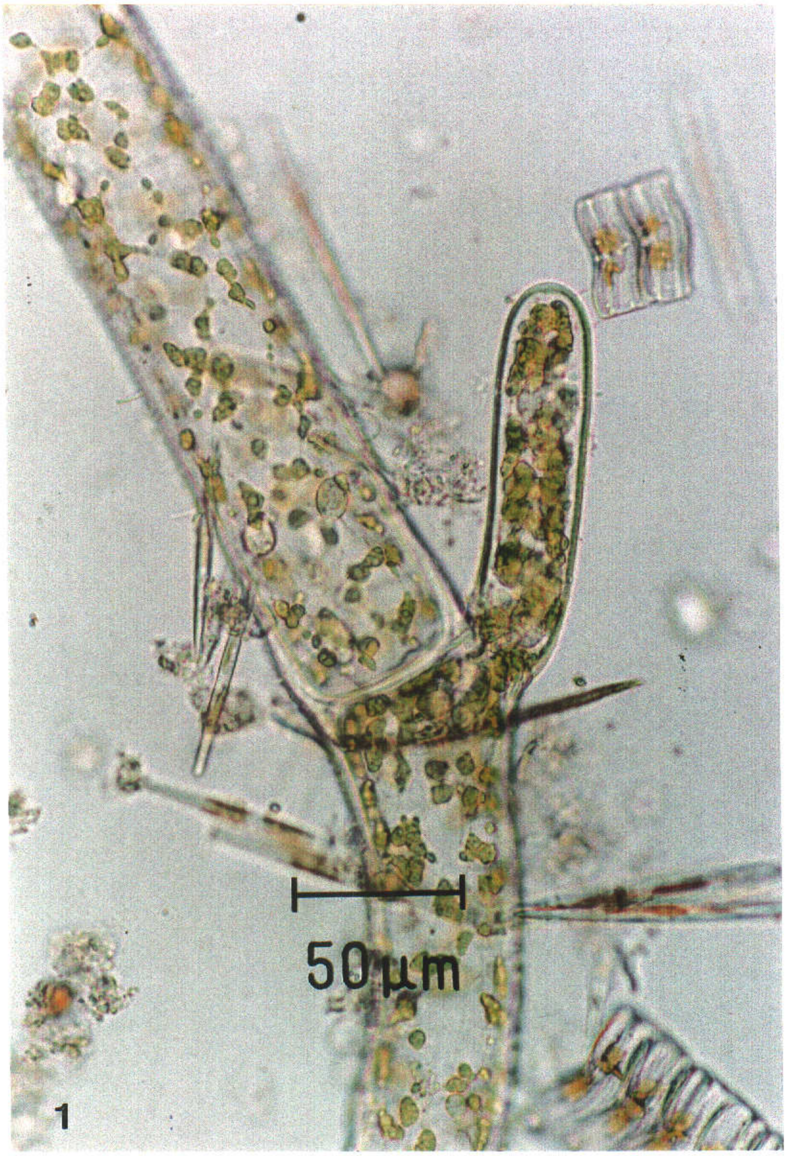
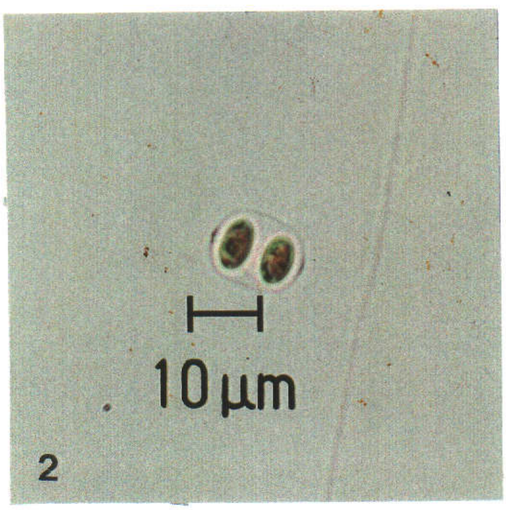


Plate 5

Fig	1	*Cladophora* sp. 1
	2	*Oocystis parva*
	3	*Pediastrum boryanum*

Plate 5





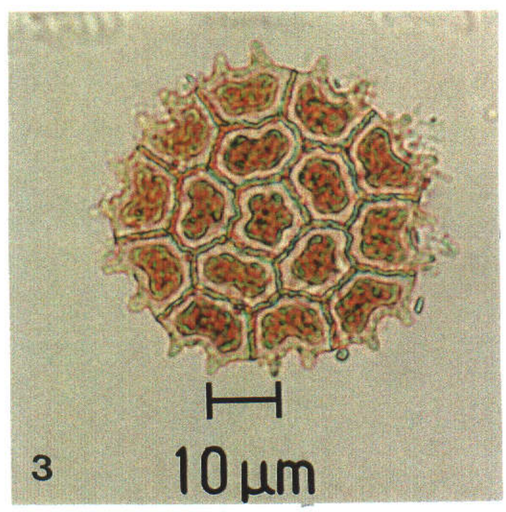


Plate 6

Fig	1 – 2	*Oedogonium undulatum*
	3	*Oedogonium* sp. 1
	4	*Microspora* sp. 1

Plate 6

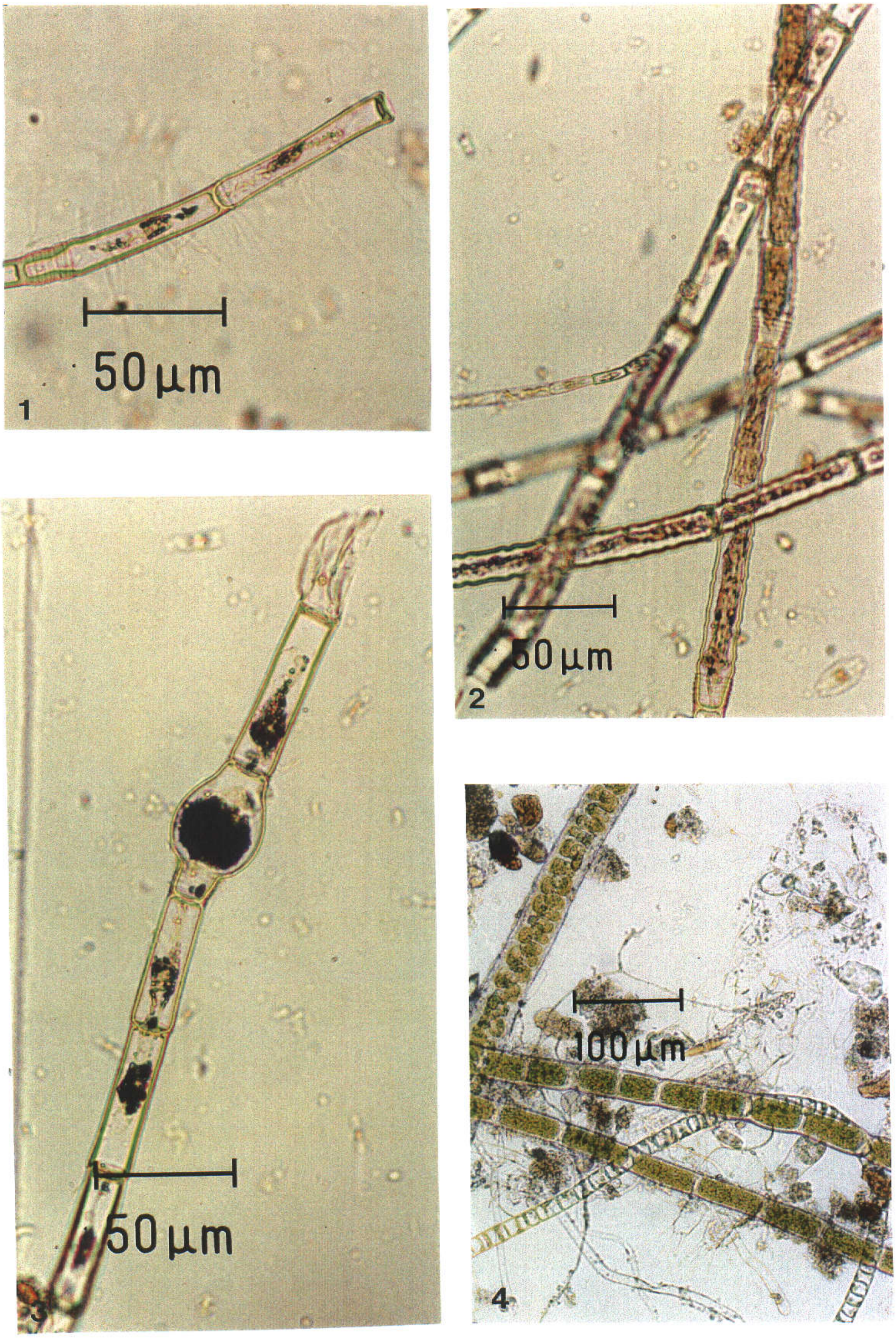


Plate 7

Fig	1 - 2	*Schizomeris* sp. 1
	3	*Closterium parvulum*
	4	*Cosmarium granatum*
	5 - 6	*Cosmarium quadrifarium*

Plate 7

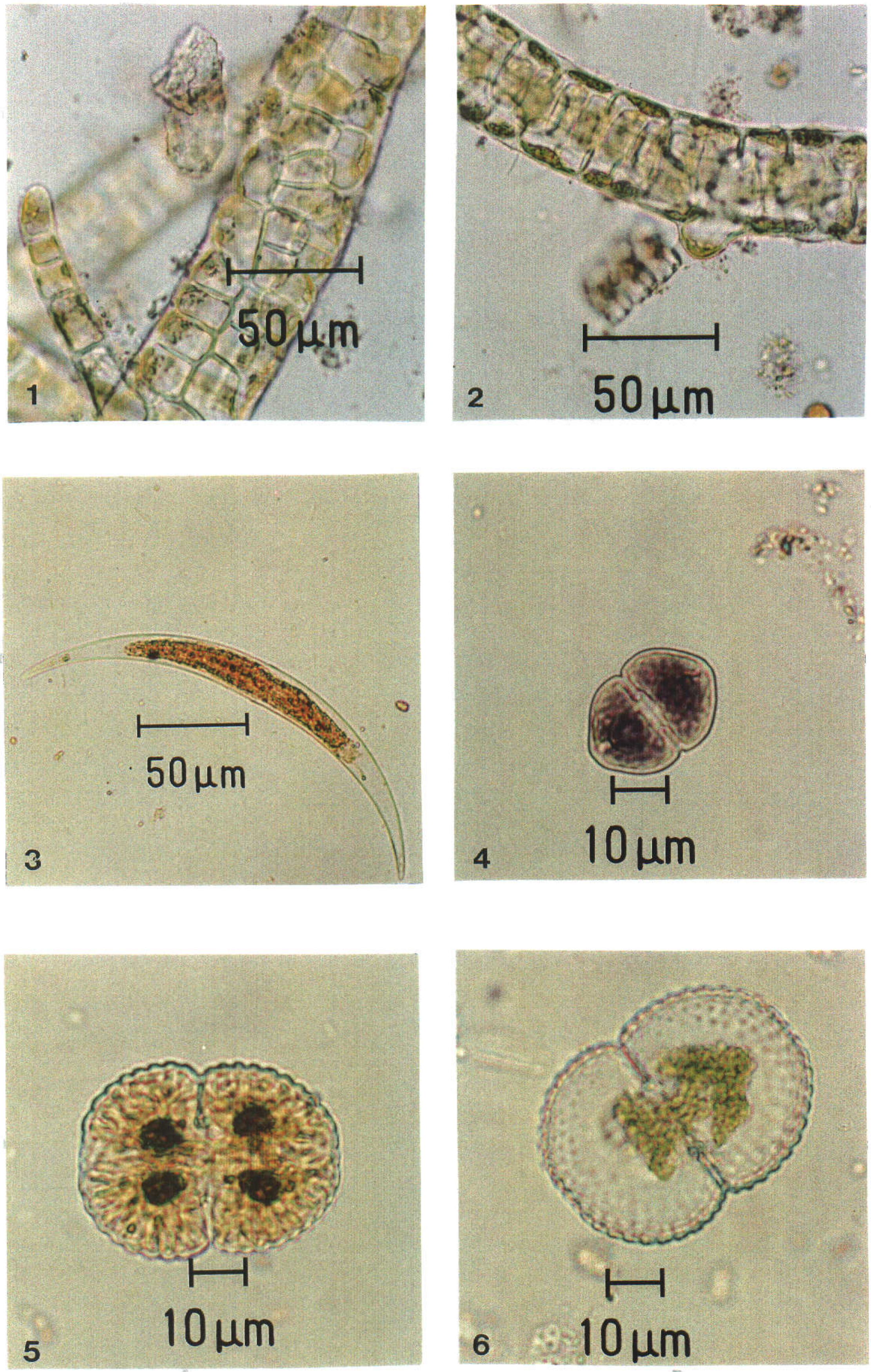


Plate 8

Fig	1	*Euastrum verrucosum*
	2	*Spirogyra* sp. 1
	3	Staustrum gracile
	4	*Zygnema* sp. 1

Plate 8

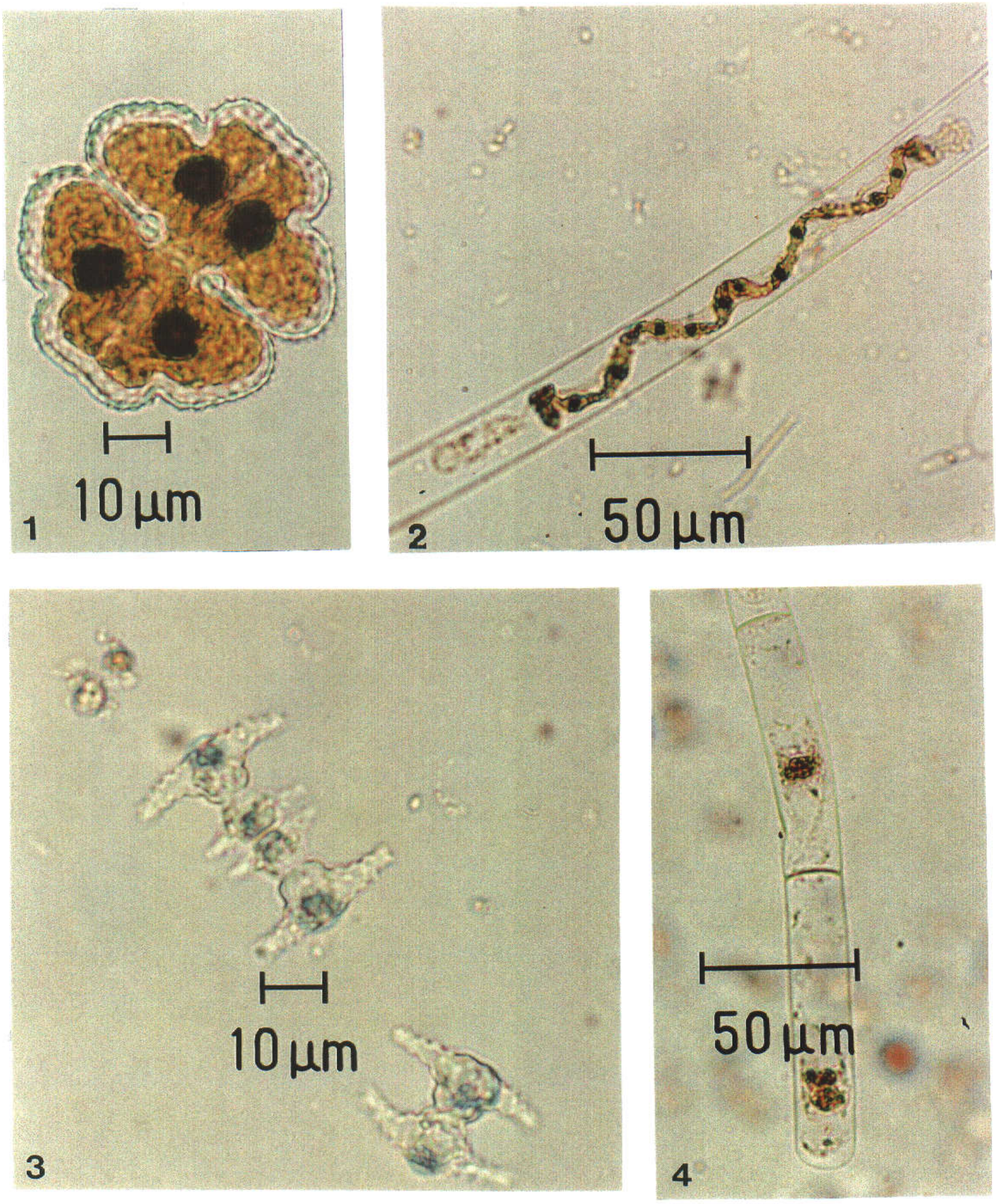


Plate 9

Fig	1 - 2	*Nitella lhotzkyi*
	3	*Gloeocystis* sp. 1
	4	*Euglena* sp. 1

Plate 9

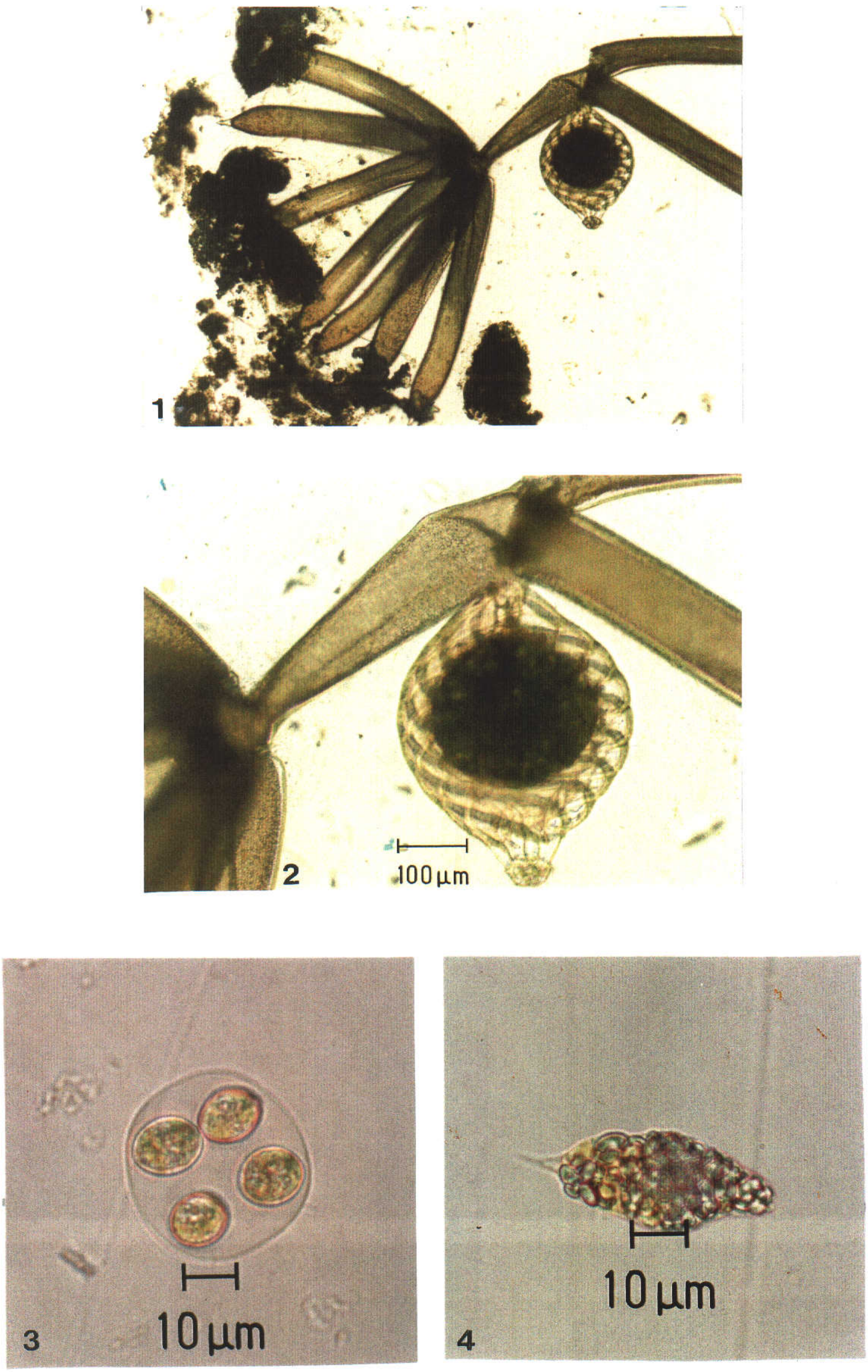


Plate 10

Fig	1 - 2	*Achnanthes brevipes*
	3	*Achnanthes coarctata*
	4 - 5	*Achnanthes lanceolata* var. *dubia*
	6 - 7	*Cocconeis placentula*
	8 - 9	*Eunotia pectinalis* var. *undulata*

Scale = 10 µm

Plate 10

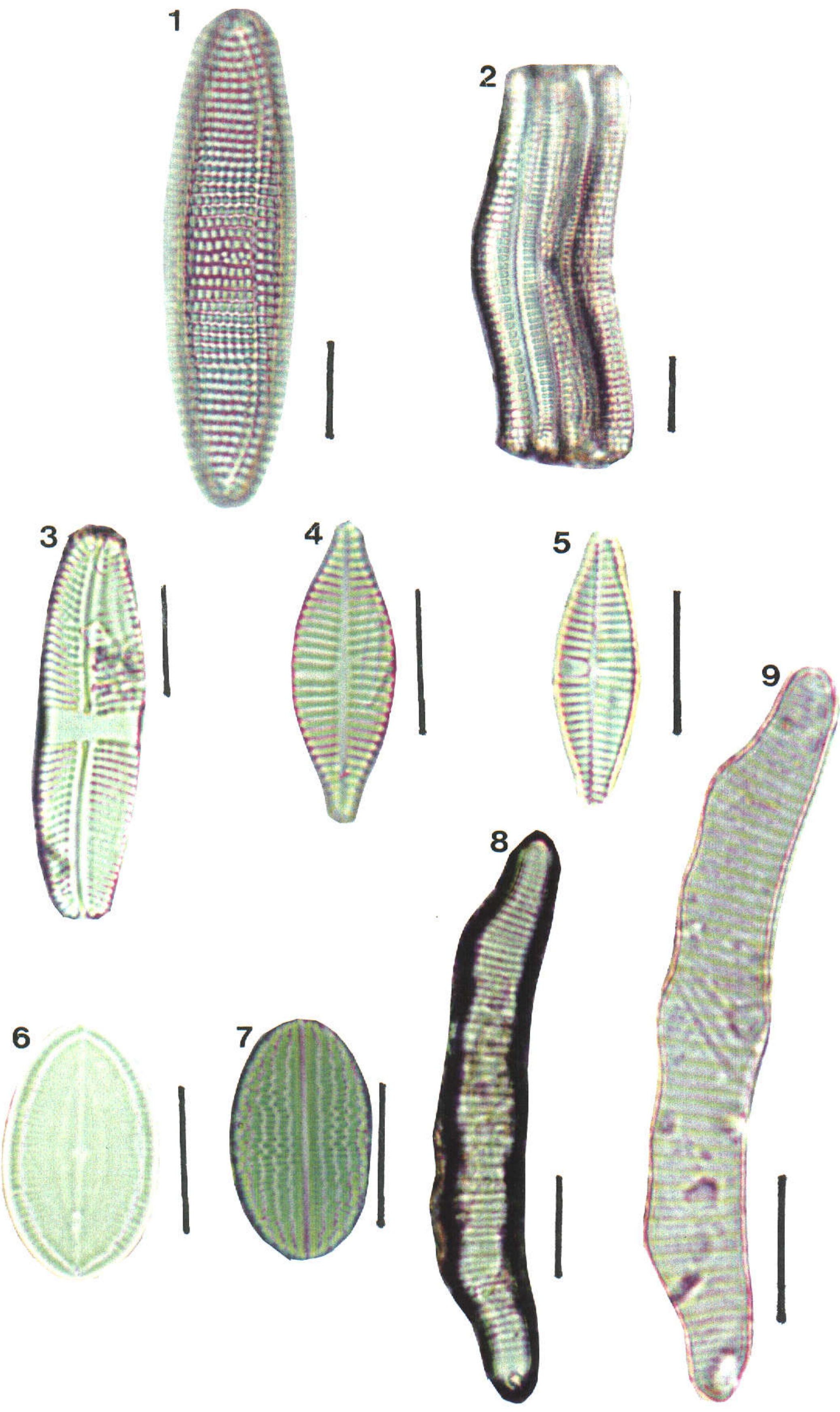


Plate 11

Fig	1	*Staurosira construens*
	2	*Martyana martyi*
	3	*Martyana martyi (whole view)*
	4 – 5	*Synedra acus*
	6	*Tabularia fasciculata*
	7	*Ctenophora pulchella* var. *lacerata*

Scale = 10 μm

Plate 11

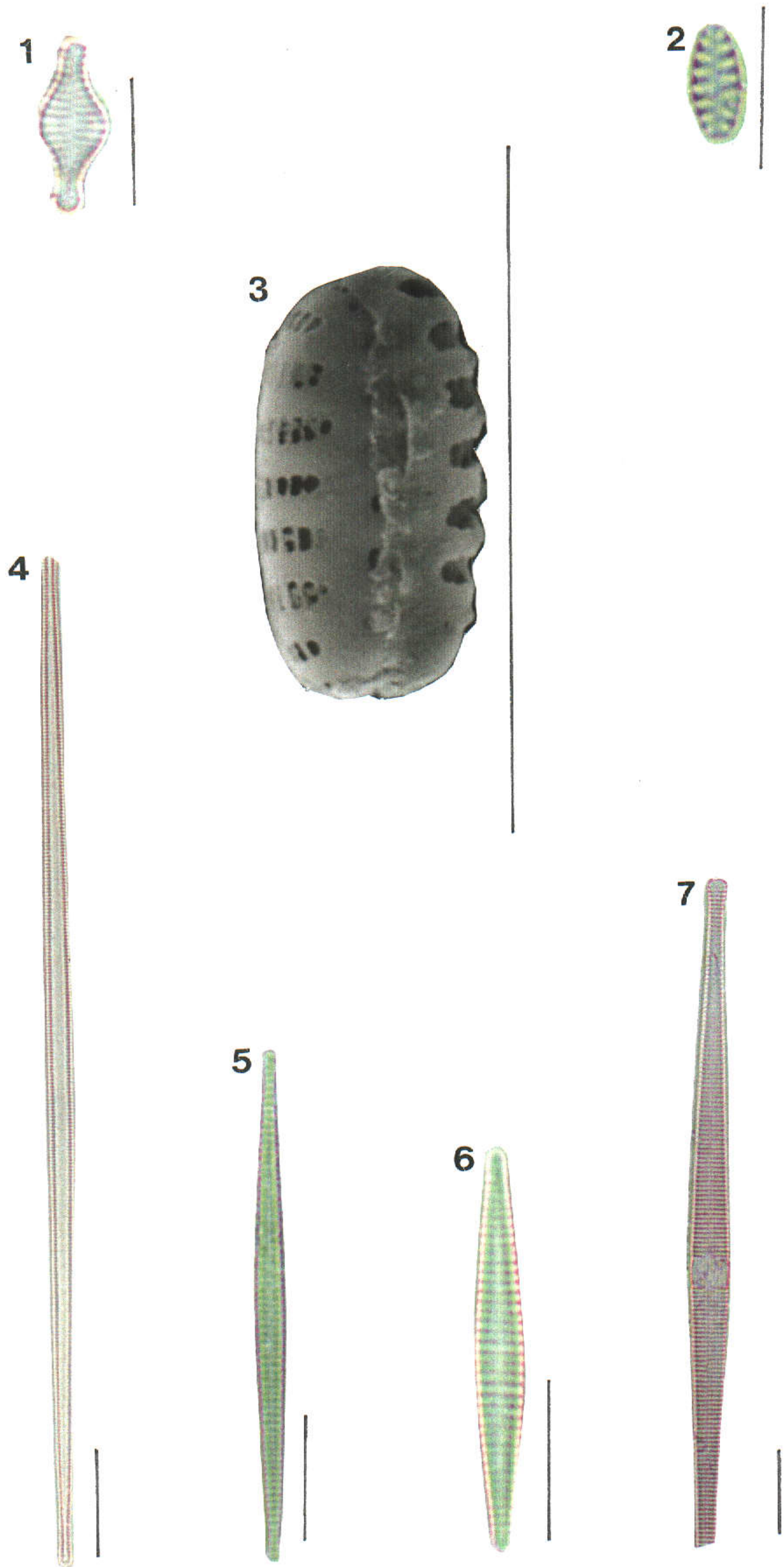


Plate 12

Fig	1 - 2	*Diploneis ovalis*
	3	*Luticola mutica*
	4 - 5	*Mastogloia elliptica*
	6 - 7	*Mastogloia reimeri*
	8	*Mastogloia pumila*
	9	*Mastogloia pusilla*
	10	*Mastogloia smithii*

Scale = 10 μm

Plate 12

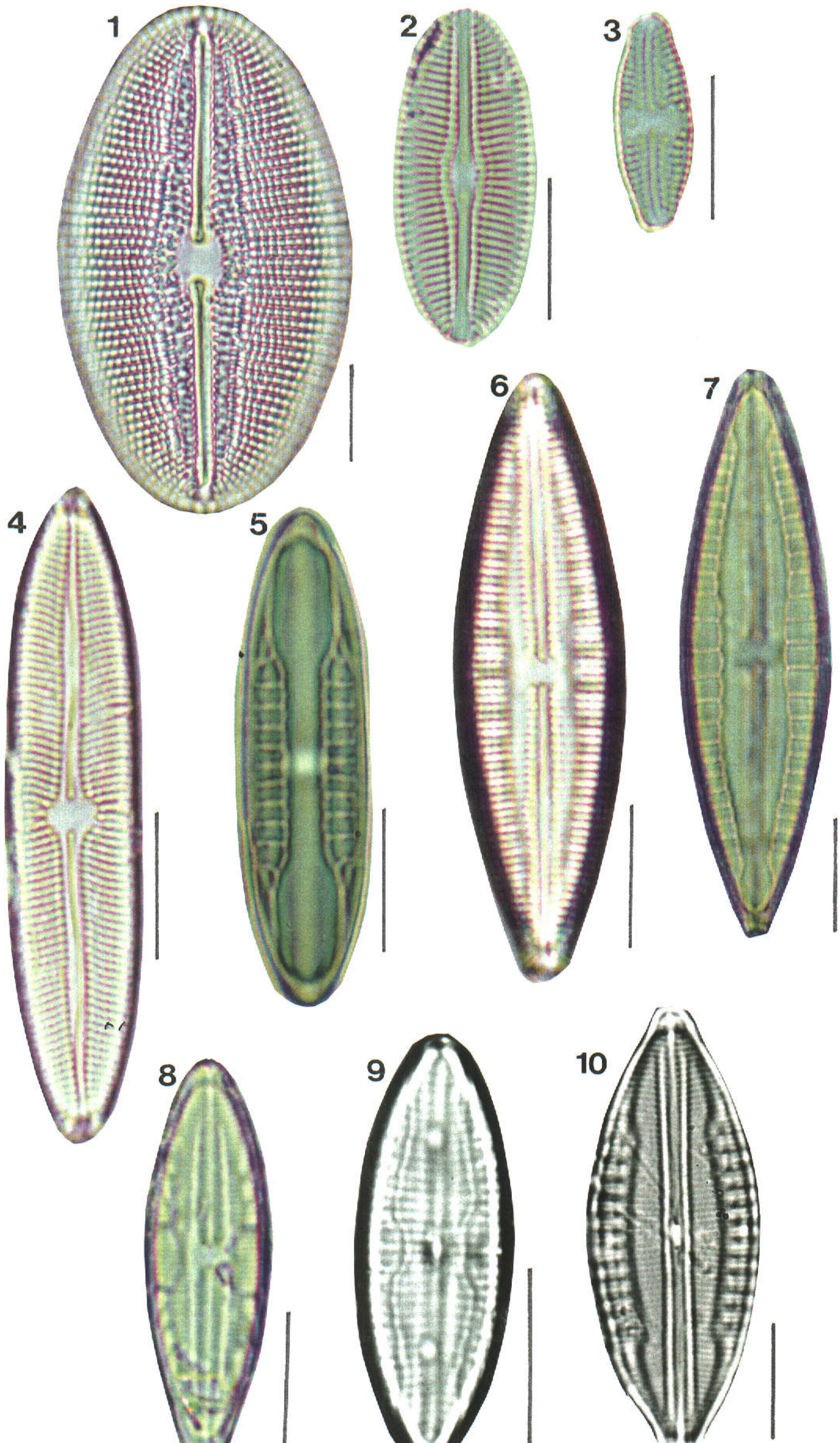


Plate 13

Fig	1 - 2	*Navicula cincta*
	3 - 4	*Craticula cuspidata*
	5	*Navicula subinflatoides*
	6	*Navicula* sp. 1
	7	*Pinnularia borealis*
	8	*Pinnularia obscura*
	9	*Stauroneis anceps*
	10	*Stauroneis pachycephala*

Scale = 10 µm

Plate 13

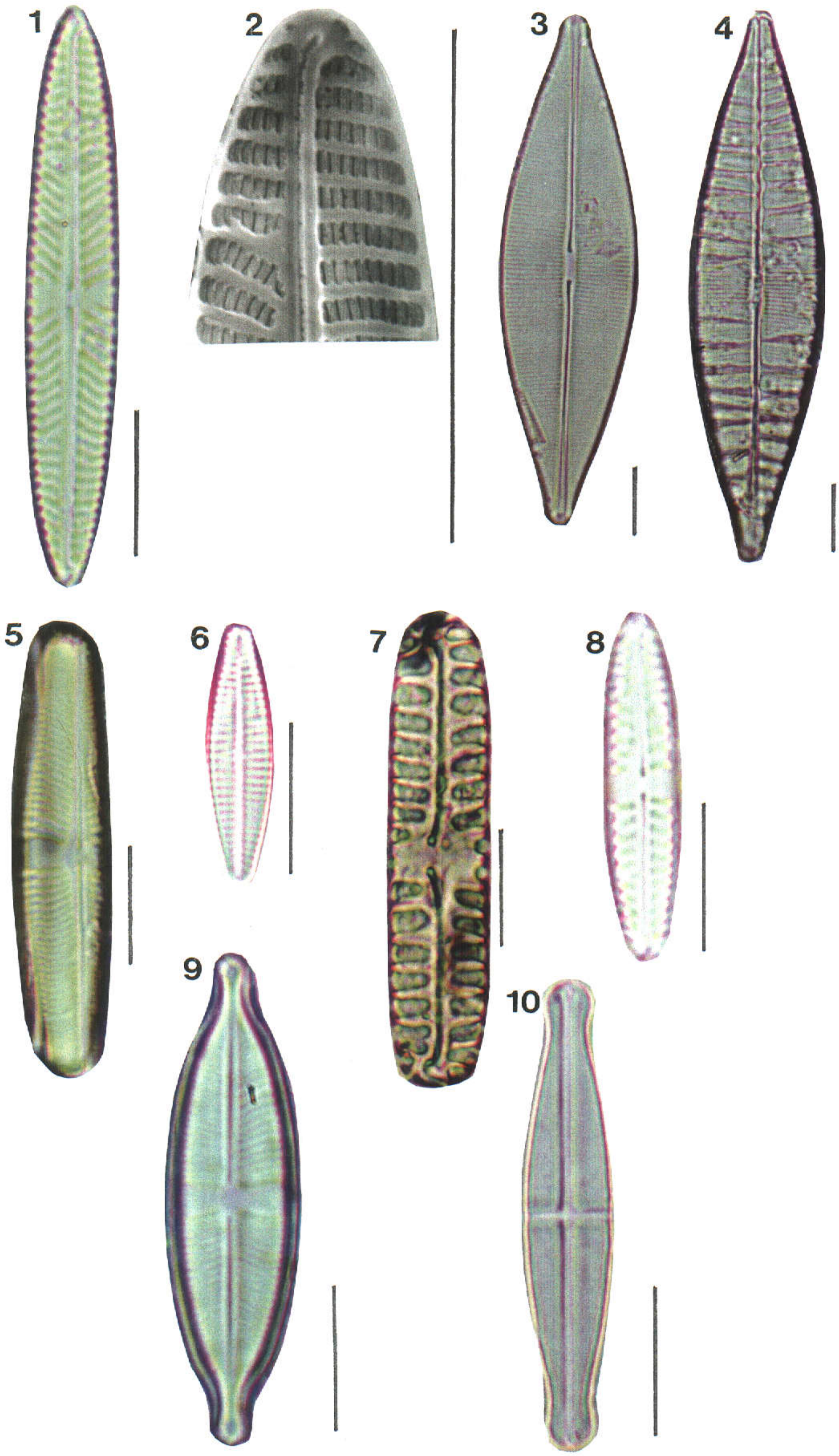


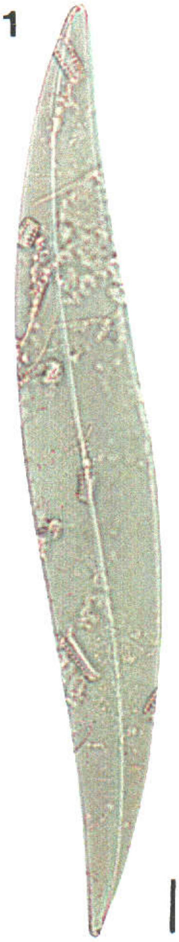
Plate 14

Fig	1 - 2	*Pleurosigma salinarum*
	3	*Gomphonema gracile*

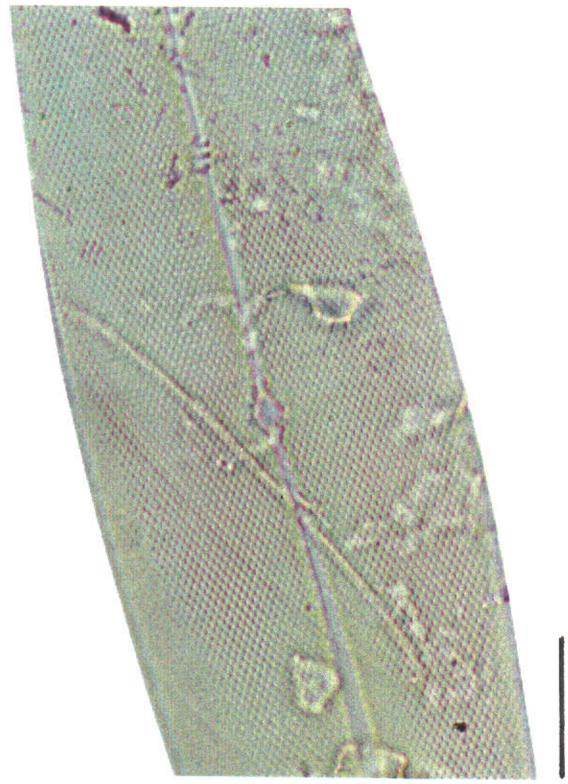
Scale = 10 µm

Plate 14

1



2



3

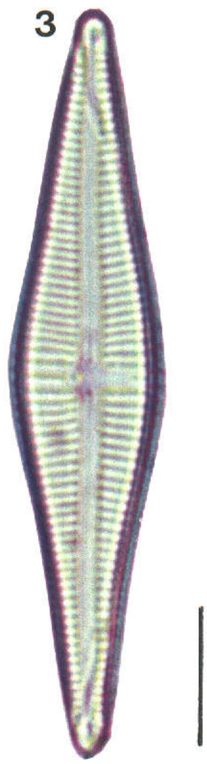


Plate 15

Fig 1 *Amphora veneta* (whole view)

2 *Amphora veneta* (bands)

3 *Amphora veneta* (central node)

4 *Amphora coffeaeformis* (valve view)

5 *Amphora coffeaeformis* (dorsal view)

6 *Navicella pusilla*

Scale = 10 µm

Plate 15

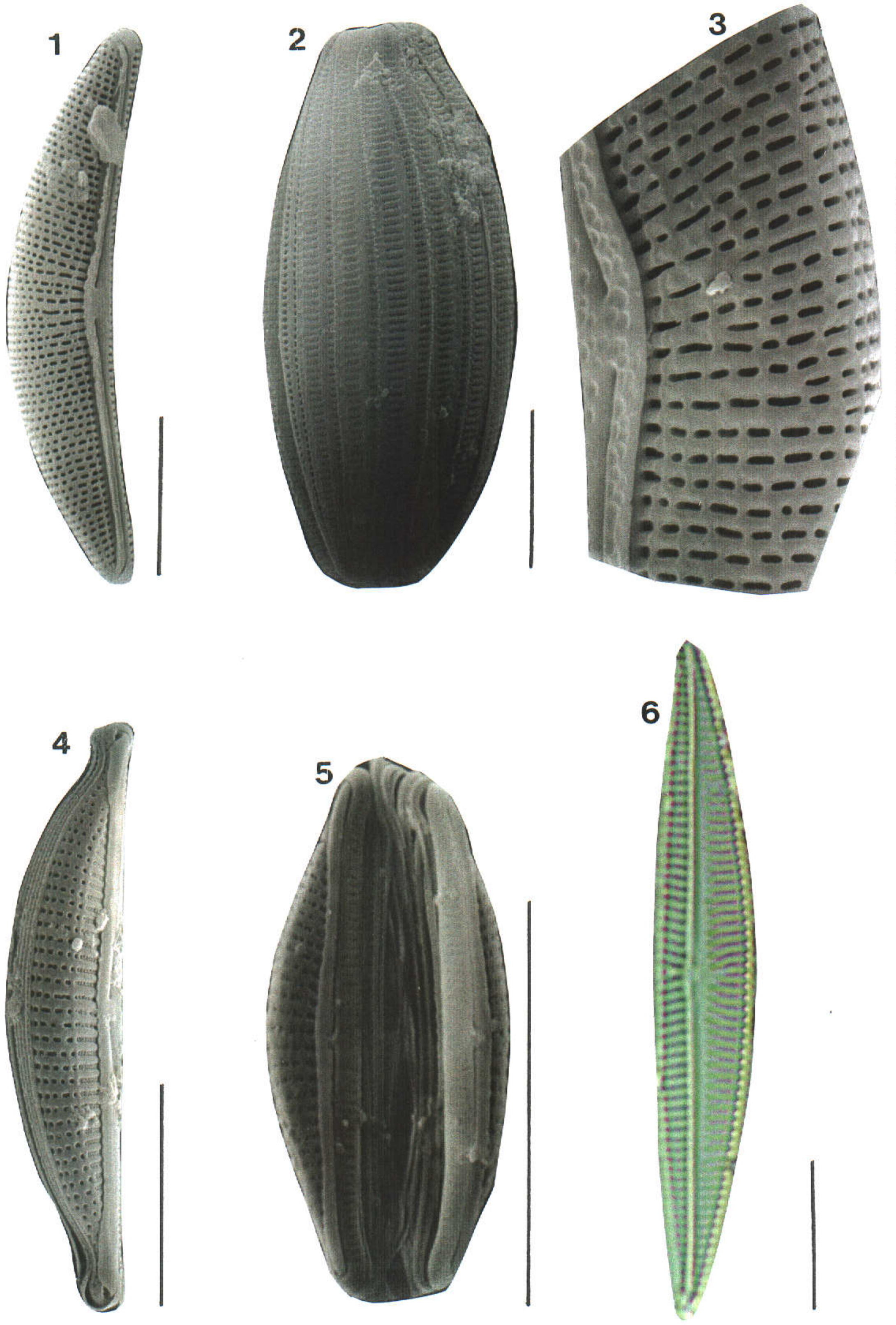


Plate 16

Fig	1	*Rhopalodia musculus*
	2	*Hantzschia amphioxys*
	3	*Hantzschia* aff. *amphioxys gracilis*
	4	*Nitzschia lorenziana*
	5	*Nitzschia obtusa*
	6	*Nitzschia communis* (valve view)
	7	*Nitzschia communis* (valve end)

Scale = 10 µm

Plate 16

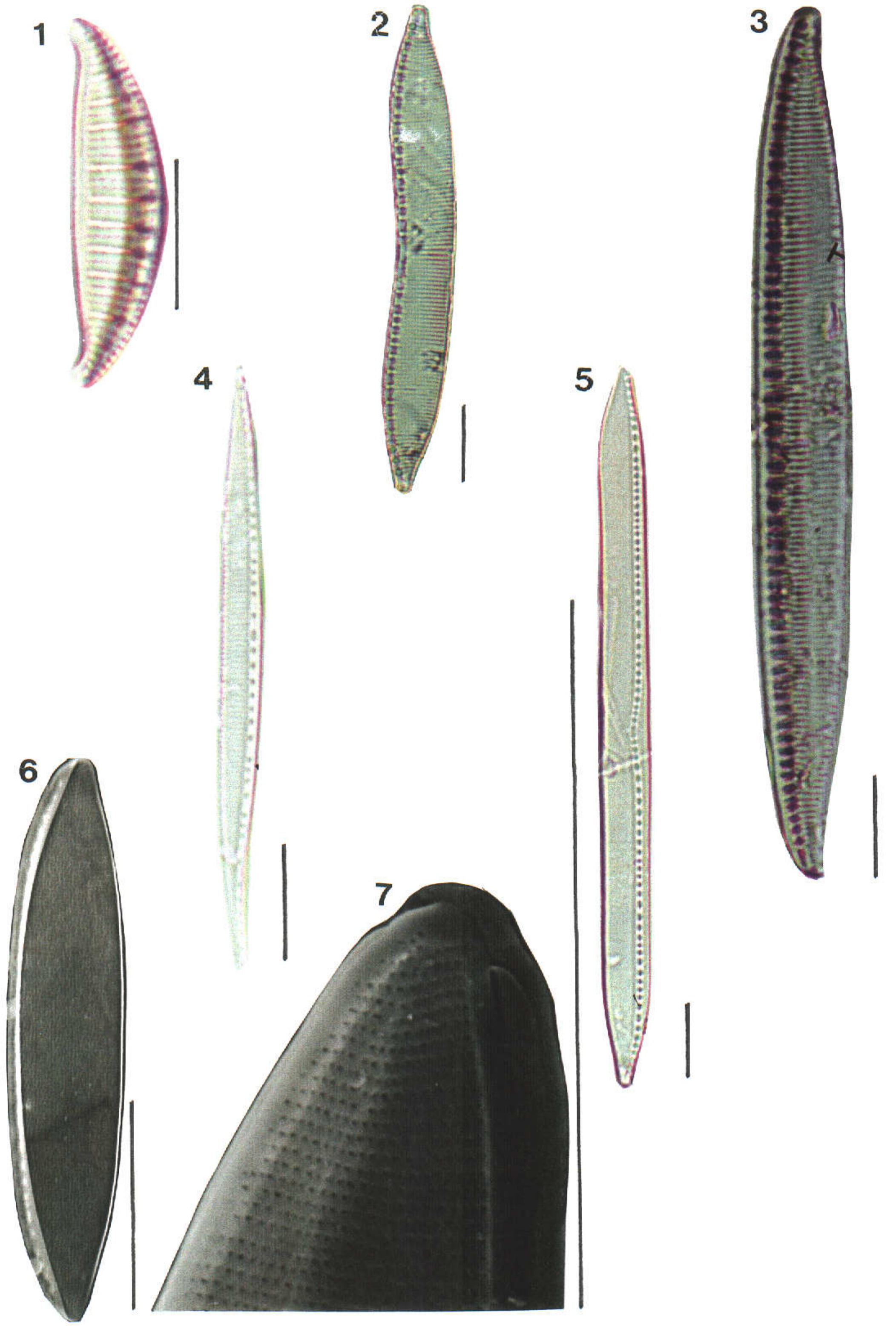


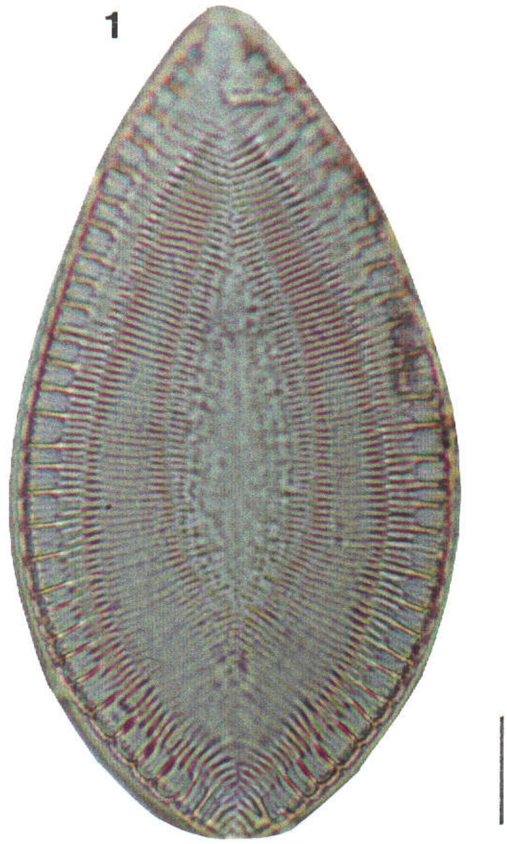
Plate 17

Fig	1	*Surirella ovalis*
	2	*Campylodiscus clypeus*
	3	*Campylodiscus clypeus*

Scale = 10 µm

Plate 17

1



2

3

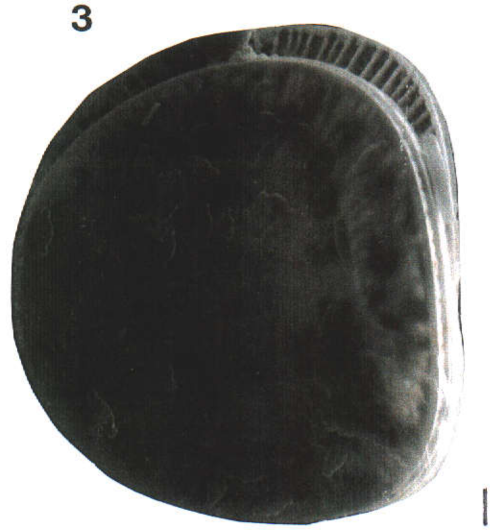


Plate 18

Fig	1	*Cyclotella meneghiniana*
	2	*Cyclotella stelligera*
	3	*Cyclotella striata*
	4	*Thalassiosira weissflogii*

Scale = 10 µm

Plate 18