



Dampier Salt Limited

Lake MacLeod

Aquatic Assessment of Lake MacLeod, 2011

December 2011

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RioTinto

FINAL REPORT

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Aquatic Assessment of Lake MacLeod, 2011

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Executive Summary

Dampier Salt Limited (DSL) currently harvests salt from an operation on Lake MacLeod, 50 km north-west of Carnarvon, in Western Australia. With plans to expand the project, a number of environmental studies have been undertaken, one of which involved an aquatic assessment by Outback Ecology in May 2011, following substantial flooding of the lake.

The assessment was designed to investigate the aquatic biological communities in the southern part of the lake, previously highlighted as an area where information is limited. Specific objectives were to:

- analyse water and sediment quality, and determine differences between sites;
- compare phytoplankton, diatoms, invertebrates and macrophytes(where present) from the southern part of the lake; and
- provide a regional comparison of aquatic biota inhabiting the lake's surface waters.

A total of 10 sites were sampled north and south of DSL operations. A range of abiotic and biotic components were collected for analyses including water and sediment samples, phytoplankton (free-floating algae), periphyton (diatoms) and aquatic invertebrates. There were no submerged macrophytes found during the assessment.

Water in the lake was classified as mesosaline to hypersaline (with significantly higher salinity concentrations at sites north of DSL operations). As water levels recede it is expected that the concentration of salts will increase. The majority of metals were low in comparison to the ANZECC guidelines, with the exception of copper, which was slightly above the recommended value (although not considered a risk to biota). Concentrations of copper were also comparatively high in a number of the sediment samples, a trend previously noted at Lake MacLeod, which appears to be associated with natural mineralisation in the catchment. Nutrient concentrations, particularly total nitrogen, were comparatively high in the surface waters, and low in the sediments, reflecting mobilisation and runoff after the flood event.

Biological communities in the lake system were comprised of common, salt-tolerant taxa indicative of inland saline waters, and marine coastal environments. There were also few differences between sites located north and south of DSL operations, with similar biological assemblages, reflecting the relatively uniform habitat of the lake during flood. The microalgal component was dominated by diatoms (mainly *Nitzschia* representatives), with blue-green and green algae found to a lesser extent. Aquatic invertebrates were characterised by crustaceans, in particular copepods, with ostracods also abundant. A small number of fish larvae (likely to be marine taxa) were also identified from the lake.

There were no rare or restricted species identified from Lake MacLeod during the May 2011 aquatic assessment. Most of the biota found was considered to be widespread, occurring in Western Australian waters and in many cases distributed in salt-affected and coastal environments overseas.

Based on these results there appears to be no apparent risk to aquatic biota from the proposed expansion by DSL. As long as some parts of the southern basin remain undisturbed, and surface flow is maintained, this will allow for the completion of reproductive cycles by organisms during future wet events.

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1. INTRODUCTION

1.1 Project Background

Dampier Salt Limited (DSL) currently harvests salt from its operation on Lake MacLeod (Study area), 50 km north-west of Carnarvon, in Western Australia **(Figure 1)**. The operation comprises 1,650 ha of evaporators, with a production capacity of 4.2 million tonnes of salt per year. Plans to expand the operation are currently in pre-feasibility stage, and DSL therefore have a vested interest in maintaining the ecological integrity of the lake. As part of these plans, DSL have commissioned a number of environmental studies on the lake, with Outback Ecology conducting an aquatic assessment of Lake MacLeod in May 2011, following a substantial flood event.

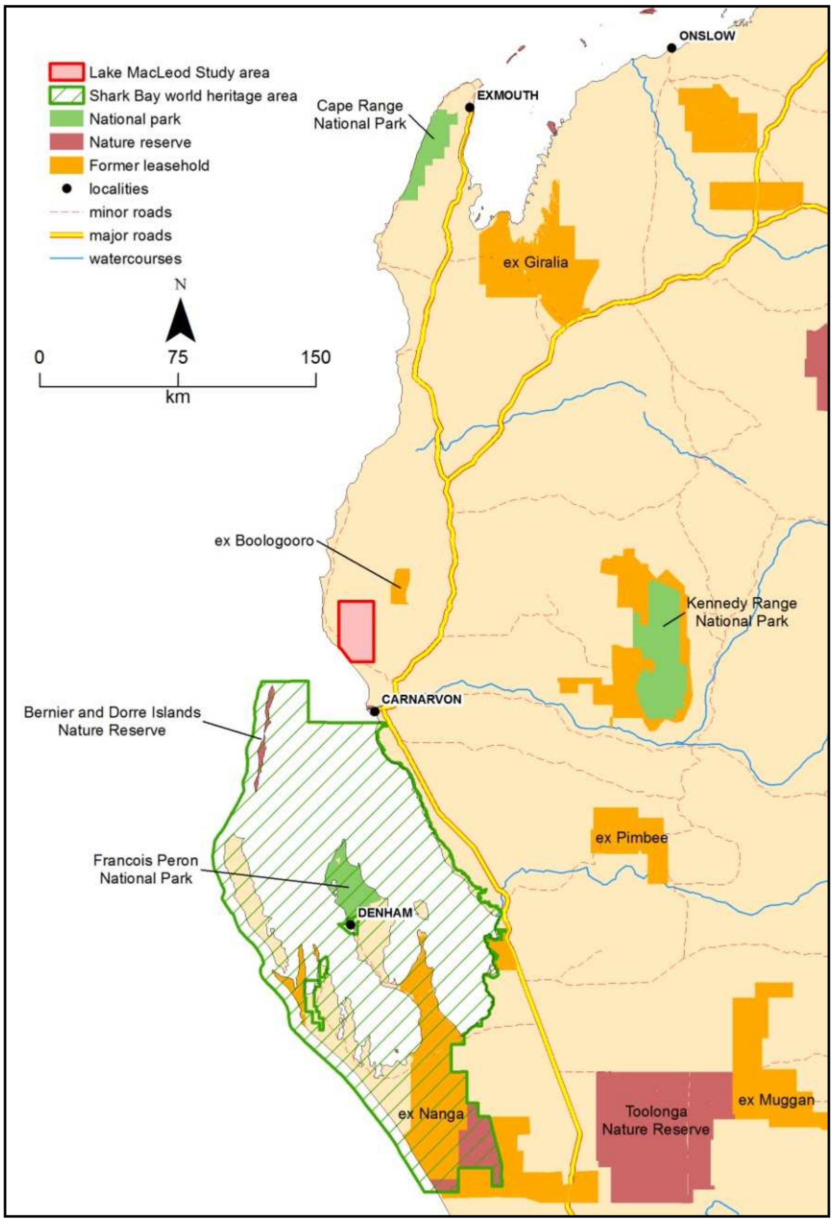

Figure 1: Regional location of the study area, north of Carnarvon, Western Australia.

Lake MacLeod is a large (220,000 ha) coastal salt lake connected to the Indian Ocean via subterranean seepage, and has a range of widely recognised ecosystem values. The northern end (commonly known as the Northern Ponds) supports a large stand of inland mangroves (Ellison and Simmonds 2003) and provides an important refuge for migratory birds (Halse *et al.* 2000). The lake is also currently listed in the Directory of Important Wetlands in Australia (Environment Australia 2001) and is a proposed Ramsar site (Department of Environment and Conservation 2009). The Northern Ponds comprise permanent saline waters (maintained by groundwater seepage), covering around 2.5 % of the lake. In contrast, the southern part of the lake tends to remain dry, and there is little information available on the significance of this area as aquatic habitat (Outback Ecology 2009).

1.2 Scope and Objectives

A previous desktop review was undertaken on the aquatic ecology of Lake MacLeod by Outback Ecology in 2009 (Outback Ecology 2009). This was followed by a dry sampling event that focussed on the southern area in September 2010 (Outback Ecology 2011). In 2011, heavy rainfall provided a unique opportunity to conduct an aquatic assessment of the lake during flood. This data contributes to the understanding of the lake's diversity and productivity following inundation, considered vital for the maintenance of ecological integrity. Specific objectives of the assessment were to:

- analyse water and sediment quality, and determine differences between sites;
- compare phytoplankton, diatoms, invertebrates and macrophytes from the southern part of the lake; and
- provide a regional comparison of aquatic biota inhabiting surface waters.

1.3 Biogeographic Region

The Interim Biogeographic Regionalisation for Australia (IBRA) is a bioregional framework that divides Australia into 85 bioregions and 403 subregions on the basis of climate, geology, landforms, vegetation and fauna. Lake MacLeod is located within the Wooramel subregion of the Carnarvon bioregion (**Figure 2**).

The Wooramel subregion covers an area of 6,667,540 ha, and is characterised by alluvial plains associated with downstream sections and deltas of the Gascoyne, Minilya and Wooramel Rivers. Landforms of the Wooramel subregion include aeolian red sand dunes, Permian sediments, and red sand plains overlying limestone plateaux. Landforms within and surrounding Lake MacLeod are typified by sand dune systems and saline alluvial plains (Kendrick and McKenzie 2001). Vegetation on these substrates are typically *Acacia*, samphire (*Tecticornia*) and saltbush (Chenopodiaceae) shrublands (Desmond and Chant 2001).

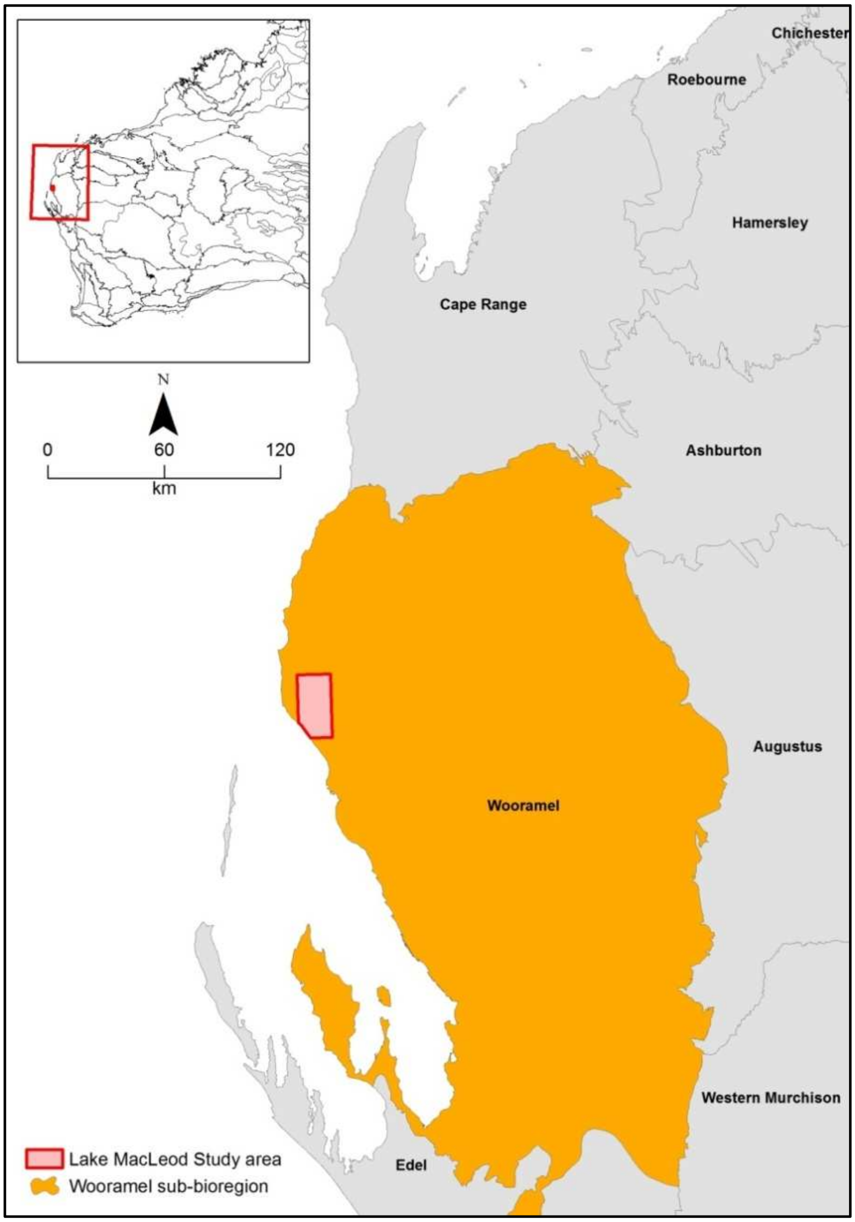

Figure 2: The location of the Study area with respect to IBRA subregions.

The Study area traverses the Quobba and Boolathanna pastoral leases and unallocated crown land, which cover Lake MacLeod. Land use is mostly grazing of native pastures (approximately 90 %), conservation (reserves and national parks), salt production (by DSL) and tourism (Desmond and Chant 2001). An algal production facility also exists in the southern part of Lake MacLeod, to the south of DSL's existing operations The primary cause of land degradation in the region is over-grazing, with associated damage by feral rabbits and goats (Kendrick and McKenzie 2001).

1.4 Climate

Lake MacLeod is situated in a transitional climatic zone, influenced by winter rainfall patterns from southern Australia, and monsoonal summer rain from northern Australia (Wyrwoll *et al.* 2000). As a consequence, its seasonally arid climate tends towards a bimodal rainfall distribution (Desmond and Chant 2001). The majority of rainfall usually occurs between May and July, with a smaller peak between February and March (**Figure 3**). Tropical cyclones, decaying cyclones or tropical cloud bands can produce unusually heavy falls between January and July. In contrast, conditions are typically dry from September to December (Bureau of Meteorology 2010).

In the 12 months prior to the aquatic assessment of Lake MacLeod, rainfall was well-above average (close to 230 mm), with more than 580 mm received (Bureau of Meteorology 2010). This can be attributed to heavy falls recorded in December 2010 (255 mm), January and February 2011 (62 and 89 mm respectively). Rainfall was attributed to an early monsoon onset in the north of Western Australia, which caused substantial flooding in the Gascoyne (Bureau of Meteorology 2010), and resulted in the complete inundation of Lake MacLeod, with water persisting into the latter part of 2011.

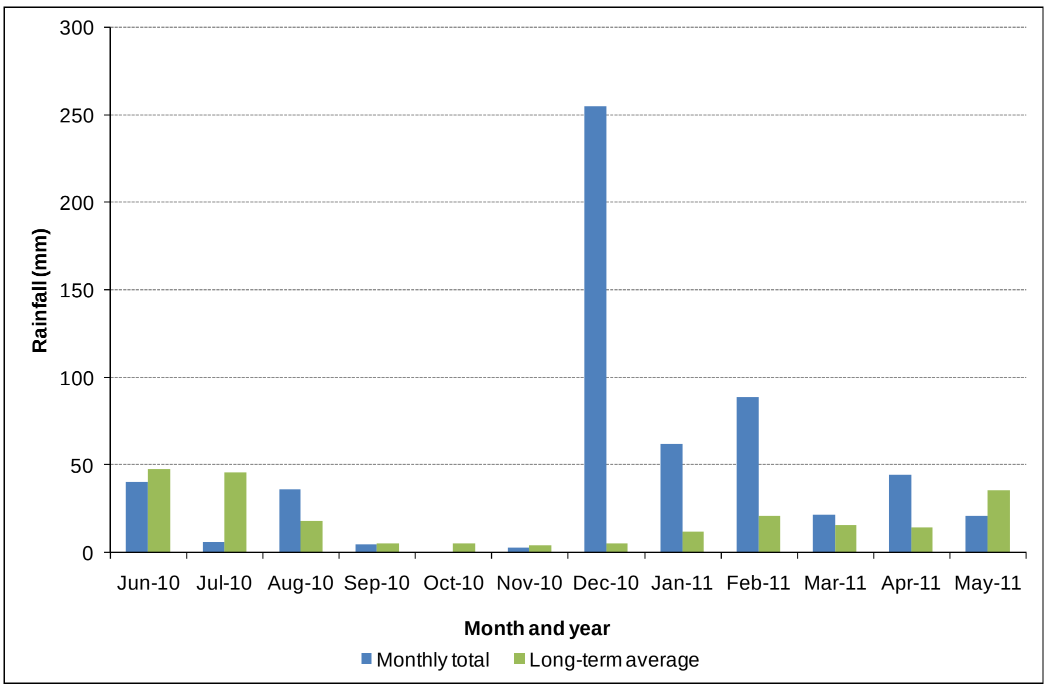

Figure 3: Rainfall recorded in the 12 months prior to the Lake MacLeod aquatic assessment, compared to long-term monthly averages (1945 to 2010) for the Carnarvon Airport Weather Station (Bureau of Meteorology 2010).

1.5 Hydrology

Lake MacLeod is a former ocean embayment that was separated by a combination of sand dune formation (at its southern end) and decreasing sea levels (Ellison and Simmonds 2003). As the lake bed is situated below sea level, a hydraulic head drives sea water through the underlying carbonate rocks and into the lake via sinkholes or vents (Ellison and Simmonds 2003). This has resulted in the formation of permanent, saline pools, present at the northern end of the lake. In contrast, the southern part of the lake is predominantly dry, with inundation dependent on factors such as rainfall and prevailing winds (Ellison and Simmonds 2003).

During the typically dry conditions, seawater input into the Northern Ponds is released in the form of brine sheets that flow across the lake. These surface flows generally follow a southerly direction along the western margin of the lake, and are heavily influenced by the prevailing winds (MWH 2007). Major topographical low points are located in the north-east and southern parts of Lake MacLeod, known as the Ralph and Texada Sinks respectively (**Figure 4**). Evaporite flats (referred to as majanna) encompass most of the Study area, and feature a suppressed brine table below the surface that fluctuates daily and seasonally (Babel 2004).

Freshwater enters the lake infrequently from the Lyndon, Minilya and Gascoyne Rivers (**Figure 5**), following substantial rainfall. Flooding from the Gascoyne River in particular can lead to extensive inundation of Lake MacLeod, which on average occurs every ten years (Ellison and Simmonds 2003). Past filling events (or partial events) attributed to inflows from the Gascoyne River occurred in 1980, 1989 and 2000 (Ellison and Simmonds 2003), with the most recent occurring in 2011.

Figure 4: Satellite image of Lake MacLeod (1981) showing the location of the Ralph and Texada Sinks (Logan 1987).

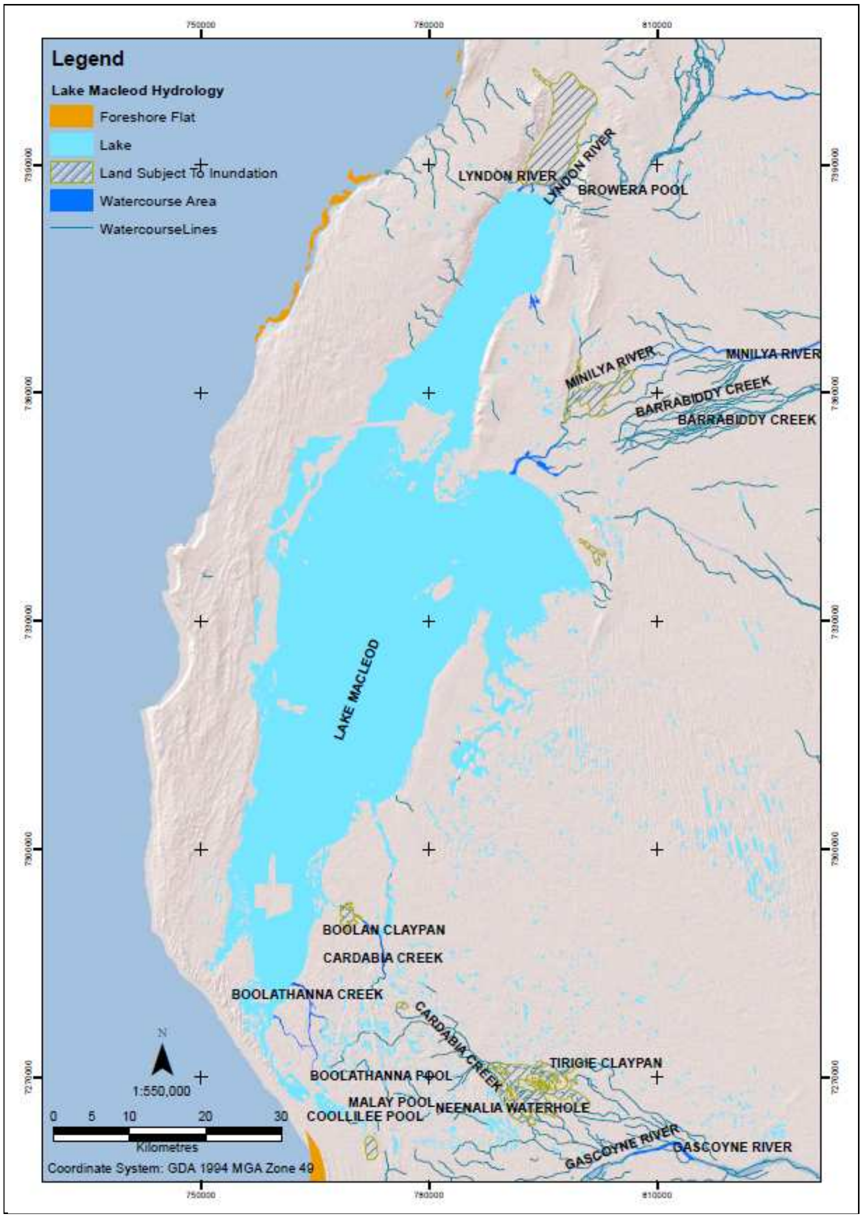

Figure 5: Regional surface hydrology, showing the location of the Lyndon, Minilya and Gascoyne Rivers, which provide inflows to Lake MacLeod following substantial rainfall.

1.6 Ecological Significance

The permanent salt water intrusion and episodic fresh water inundation of Lake MacLeod has resulted in the development of unique biological assemblages (Royal Australasian Ornithologists Union 2001). The Northern Ponds is an important migration stop-over and drought refuge for shorebirds (Jaensch and Lane 1993), with over 70 species of waterbird recorded to date. If the Ramsar listing for this area is achieved, the lake will become a wetland of international significance, obtaining further protection under the Environment Protection and Biodiversity Act 1999 (*EPBC Act*) (Department of Environment and Conservation 2009).

The Northern Ponds supports the largest stand of inland mangroves in the world (Ellison and Simmonds 2003), and provide a nursery grounds for fish (Rangelands NRM WA 2011), with two native species identified from the lake. Lake MacLeod and the broader Carnarvon Basin are also known to support a rich diversity of aquatic invertebrates (Australian Natural Resources Atlas 2009).

As a result of its geographic and biological significance, Lake MacLeod is listed as a High Conservation Value Aquatic Ecosystem (Rangelands NRM WA 2011). It hosts a range of wetland types, including sink holes, channels, lakes and marshes (Department of Environment and Conservation 2009). However the lake is also considered an at risk, with key threats identified including the introduction of feral animals, grazing, agricultural practices and salt production activities (Kendrick and McKenzie 2001).

The majority of the ecological information available on the lake is based on the Northern Ponds (Outback Ecology 2009), due to the permanence of water in this area. In contrast relatively little is known about the southern end of the lake (particularly during flood), with the 2011 aquatic assessment commissioned by DSL to address this knowledge gap.

2. METHODS

2.1 Survey Design and Sampling

During the May 2011 aquatic assessment, ten sites were established in the southern area of Lake MacLeod (**Figure 6**), including areas to the north and south of the current DSL operations (**Table 1**). Sites comprised a range of habitats including playa, embayments, islands and inlets (**Plate 1**, **Plate 2**), typically inundated to a depth of between 40 and 60 cm (**Appendix A**). Field work was undertaken by an Outback Ecology staff member, Richard de Lange, and a DSL appointed representative, David Bauer. Prior to sampling a fauna collection permit (Fauna Licence No. SF008035) was obtained from the Department of Environment and Conservation (DEC). The following abiotic and biotic components were collected as part of the assessment:

- water and sediments (for analyses);
- phytoplankton (free-floating algae);
- periphyton (diatoms); and
- aquatic invertebrates (including zooplankton and macroinvertebrates).

Table 1: Site characteristics and GPS coordinates for Lake MacLeod, May 2011.

Site	GPS Coordinates	Classification	Habitat	Depth	Description
DSLM1W	764442 7310722	North	Island	62 cm	Northern-most site, located adjacent to a small island in the centre of Lake MacLeod. Sandy clay sediment, with no salt crust present. High organic material with algal mats, vegetation and debris along shore. Small fish observed amongst indundated vegetation. Nesting site for seagulls.
DSLM2W	773495 7306161	North	Playa	20 cm	Playa site located on the eastern shoreline just south of DSLM1W. Sandy clay sediment, carbonate observed along beach zone (no salt crust). Some organics represented by patches of algal material along shore.
DSLM3W	757178 7308198	North	Playa	30 cm	North of site office, on the western side of the lake. Small inlet enters the lake nearby. Sediment comprised sandy clay material with anoxic layer beneath surface. Algae observed growing on debris in the water. Shells in high abundance along shore. Small fish present amongst inundated vegetation and seagulls and a heron observed in the area.
DSLM4W	768667 7301629	North	Playa	25 cm	Site located on the eastern side of the lake, north-east of the boat ramp. Sandy clay sediment (no salt crust). High algal concentration in water column and in the benthos. Seagulls utilising the environment, small fish present in shallow water.
DSLM5W	0755348 7302179	North	Embayment	43 cm	Situated within an embayment on the western shoreline, just north of DSL site office. Elongated embankment nearby. Fine sandy clay sediments, with no salt crust present. Some algal mats observed growing on lake sediments. Seagulls observed in the area.
DSLM6W	764883 7290864	South	Playa	51 cm	Adjacent to the DSL operations on the eastern shore. Just north a large inlet opens onto the lake. Fine silty sediment (sand/clay), without the presence of a salt crust. High abundance of algal matter including filamentous mats in the shallows. Avian fauna observed in surrounding terrestrial environment.
DSLM7W	756731 7287683	South	Playa	41 cm	Playa site located on the west side of the lake, just south of current DSL operations. Nearby, a small inlet enters, and the water is turbid. Sandy/clay sediments (no salt crust). High algal concentration in the water column and along the shoreline. Small fish observed amongst inundated vegetation. Riparian plants in poor health.
DSLM8W	758184 7282368	South	Playa	55 cm	Situated on the south-western side of the lake, adjacent to a peninsula (comprising exposed rock). Playa site just north of the *Beta Nutrition Algal Production Facility.* A number of small embankments present in the area. Sediments sandy, clay material (sandy beach zone), with no salt crust. Algae growing on inundated vegetation and small fish observed in the shallows. Seagulls present in surrounding area.
DSLM9W	762757 7282055	South	Inlet	30 cm	Site located on the south-eastern side of the lake within a large inlet that enters from the south. Sediment fine silty clay material (no salt crust), with some sand along the shore. Pooling along the shoreline area supporting a high density of algae. Seagulls and heron observed utilising the environment. Small fish present in shallows.
DSLM10W	759870 7279394	South	Playa	10 cm	Southern-most site, on the south-eastern side of the lake, adjacent to the *Beta Nutrition Algal Production Facility*. This part of the lake begins to narrow to a large embayment, with a number of inlets nearby. Shallower part of the lake. No salt crust present, sediments comprise sand and clay. Algal mats present along parts of the lake bed, and high numbers of small fish observed. Seagulls present.

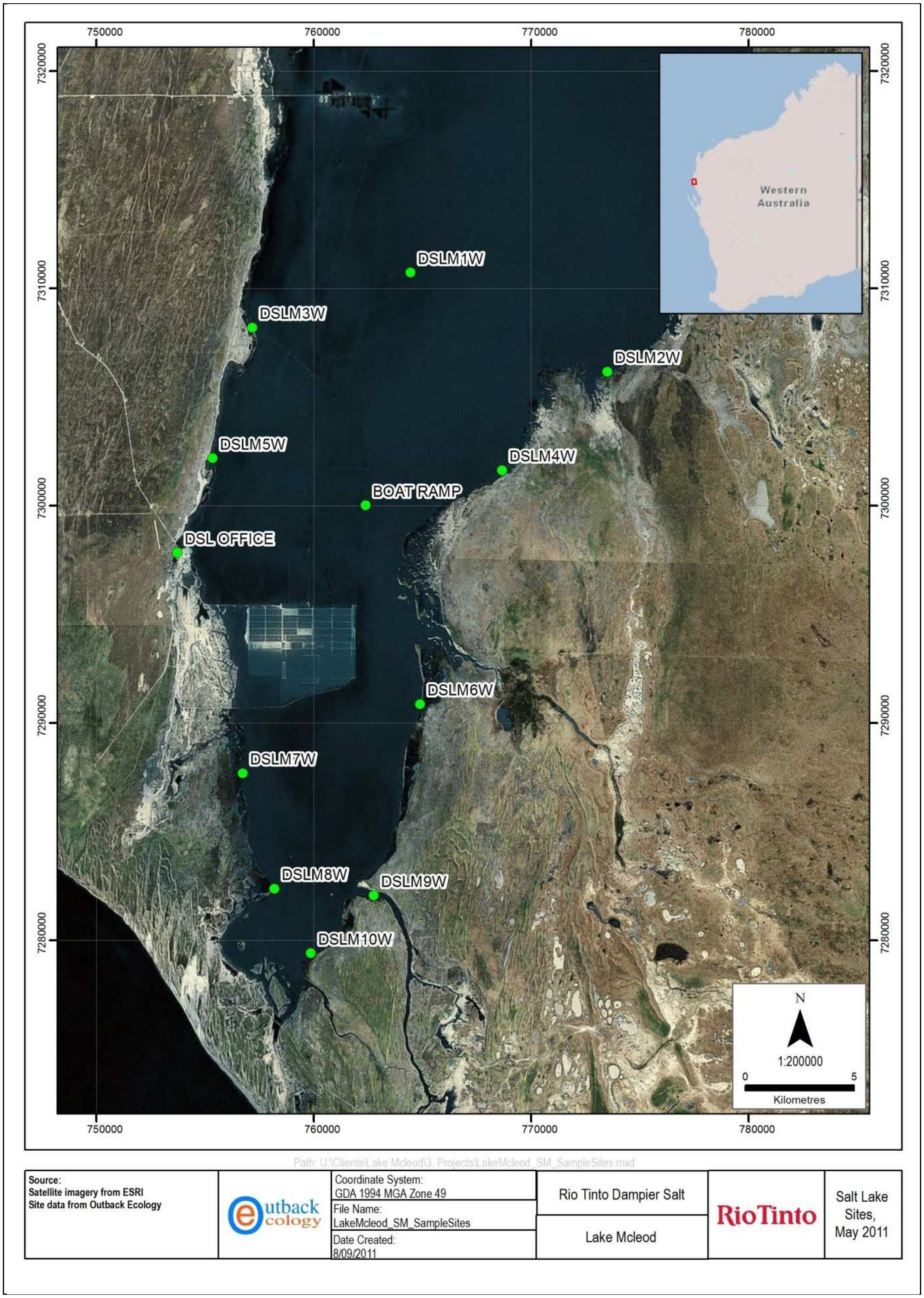

Figure 6: Location of Lake MacLeod sites, May 2011 (note the boat launch ramp and DSL site office are also indicated).

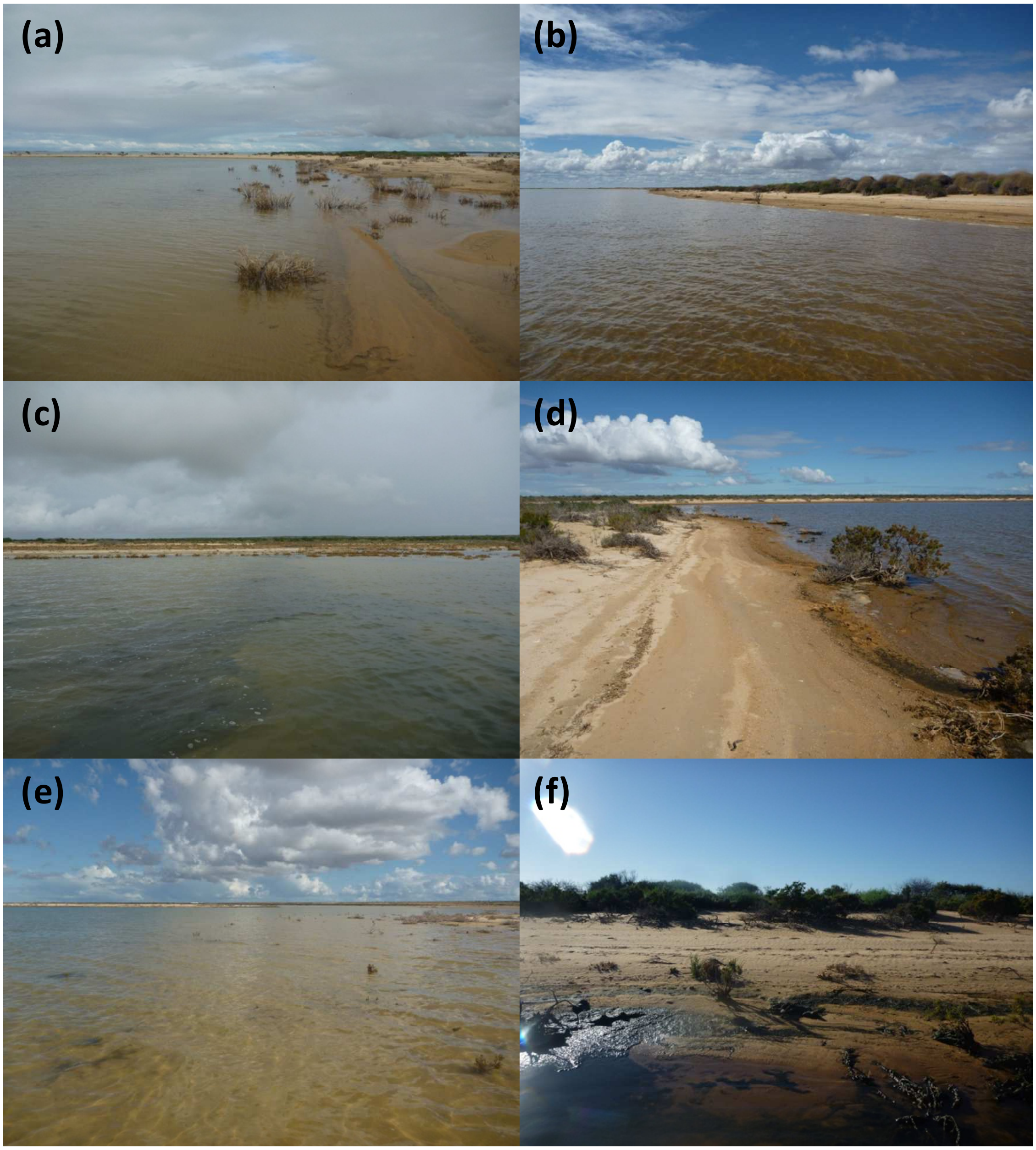

Plate 1: Representative site photographs of (a) DSLM1W, (b) DSLM2W, (c) DSLM3W, (d) DSLM4W, (e) DSLM5W and (f) DSLM6W.

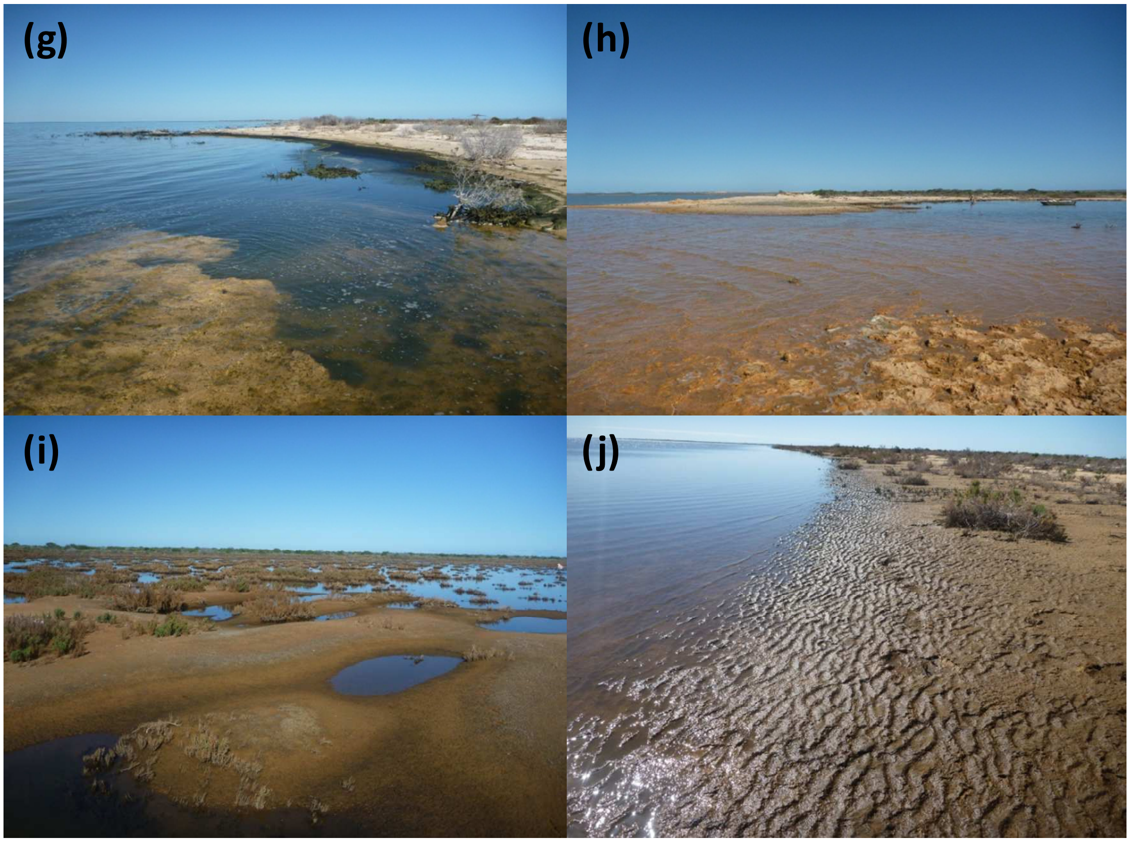

Plate 2: Representative site photographs of (g) DSLM7W, (h) DSLM8W, (i) DSLM9W and (j) DSLM10W.

2.2 Water Quality

Water samples were collected from all ten sites using sterilised bottles provided by the NATA-accredited Australian Laboratory Group (ALS), containing preservative where required. Bottles were completely filled with water and sealed, excluding air from the samples (following instructions provided by ALS). Samples collected for the analysis of dissolved metals were field filtered through 45 µm cellulose acetate membrane filter paper using a Millipore portable filtering device. Samples were then couriered to ALS (located in the Perth metropolitan suburb of Malaga) for analysis (**Table 2**). Holding times for analyses were generally met except for pH (all sites) and Chl *a* (site DSLM5W), and these results should be considered indicative only. Basic water quality parameters were also measured *in situ* with a TPS hand-held meter (**Appendix A**).

In the absence of any site-specific data, the water quality data for Lake MacLeod was compared to the Australian and New Zealand Conservation Council (ANZECC) guideline trigger values for the protection of 80 % of marine species (representative of highly disturbed ecosystems) (ANZECC 2000). These values were applied in the absence of site-specific data, and should be considered reference values only (and may not necessarily be applicable to hypersaline waters).

Table 2: Water quality analyte suite from Lake MacLeod, May 2011.

Basic and Nutrients	Anions and Cations	Metals and Trace Elements	
pH	Chloride (Cl)	Arsenic (As)	Mercury (Hg)
Electrical Conductivity (EC)	Sulphate (SO_4)	Barium (Ba)	Nickel (Ni)
Total Dissolved Solids (TDS)	Sodium (Na)	Beryllium (Be)	Silicon (Si)
Nitrite (NO_2)	Magnesium (Mg)	Cadmium (Cd)	Vanadium (V)
Nitrate (NO_3)	Calcium (Ca)	Chromium (Cr)	Zinc (Zn)
Nitrite/Nitrate (NO_2/NO_3)	Potassium (K)	Cobalt (Co)	
Total Nitrogen (TN)	Bicarbonate (HCO_3)	Copper (Cu)	
Total Kjeldahl Nitrogen (TKN)	Carbonate (CO_3)	Iron (Fe)	
Total Phosphorous (TP)		Lead (Pb)	
Chlorophyll *a* (Chl. *a*)		Manganese (Mn)	

2.3 Sediment Quality

At each site, the top two to three centimetres of lake sediments were scraped into a sterilised glass container (excluding voids), which was then sealed and sent to ALS for analysis. Samples were collected and stored using ALS provided containers and following ALS instructions. Holding times were generally met, except for pH, SO_4 and Cl at sites DSLM1W to DSLM5W. Subsequently, the results for these parameters should be considered indicative only.

Sediment quality data was compared to the ANZECC interim sediment quality guidelines (ISQG-Low values) (Simpson *et al.* 2005). However, it is acknowledged that developing site-specific trigger values provides a more accurate indication of local conditions, instead of applying broad-scale guidelines (ANZECC 2000).

Table 3: Sediment quality analyte suite from Lake MacLeod, May 2011.

Basic and Nutrients	Anions and Cations	Metals and Trace Elements	
pH	Chloride (Cl)	Arsenic (As)	Mercury (Hg)
Total soluble salts (TSS)	Sulphate (SO_4)	Barium (Ba)	Nickel (Ni)
Total Nitrogen (TN)	Sodium (Na)	Beryllium (Be)	Silicon (Si)
Total Kjeldahl Nitrogen (TKN)	Magnesium (Mg)	Cadmium (Cd)	Vanadium (V)
Nitrite (NO_2)	Calcium (Ca)	Chromium (Cr)	Zinc (Zn)
Nitrate (NO_3)	Potassium (K)	Cobalt (Co)	
Nitrite/Nitrate (NO_2/NO_3)		Copper (Cu)	
Total Phosphorous (TP)		Iron (Fe)	
Total organic carbon (TOC)		Lead (Pb)	
Moisture content (MC)		Manganese (Mn)	

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2.4 Phytoplankton

Phytoplankton was collected at all sites using a 25 µm mesh net. The net was towed in an L-shaped transect (25 x 25 m) approximately 10 to 20 m from the shore. Samples were transferred to 70 mL vials and preserved using two to three drops of Lugol's (potassium iodide) solution. On return to the laboratory, three slides were prepared from each sample for examination under a compound microscope. Slides were examined at 40X magnification and the abundance and diversity of phytoplankton was recorded. Taxa were identified to genera, with appropriate algal literature.

2.5 Periphyton (Diatoms)

Periphyton was sampled at each site and included the collection of twigs, sediment and rocks in shallow waters on the margin of the lake. This material was placed into 70 mL vials and kept cool (no preservative was added). On return to the laboratory, the material was treated in 70 % nitric acid (to remove organic material) and permanent slides were prepared according to (John 1983). Three replicate slides were made for each sample and enumeration was carried out at 1000X magnification under a compound microscope. A maximum of 200 diatoms were counted at each site to provide a representation of community structure, and the abundance and diversity of taxa were recorded. Taxa were identified to species level, with relevant taxonomic guides.

2.6 Aquatic Invertebrates

Zooplankton and macroinvertebrates were collected from each site using nets with different sized mesh. Zooplankton samples were collected with a 150 µm mesh net, towed through the water column in an L-shaped transect (50 x 50 m), approximately 10 to 20 m from the shoreline. Macroinvertebrate samples were collected with a 250 µm mesh invertebrate D-frame sweep net targeting the benthic environment, following the same method. Zooplankton and macroinvertebrate samples were transferred into separate 250 mL vials, preserved with 100 % undenatured ethanol and returned to the laboratory.

In the laboratory, all samples were examined under a stereo microscope and sorted into broad taxonomic groups. The abundance and diversity of taxa was recorded. Specimens were then identified to the lowest possible taxonomic rank by Dr Conor Wilson, Dr Erin Thomas and Dr Jason Coughran. Further specialist identification was provided by Bennelongia Environmental for the Copepoda and Ostracoda groups (microcrustaceans).

2.7 Macrophytes

It was intended that macrophytes would be collected from the lake environment where present; however no submerged aquatic plants were identified during the aquatic assessment of the lake. The main vegetation present during the assessment of Lake MacLeod consisted of flooded riparian species, typically *Tecticornia* spp., observed in a state of decomposition, due to the extended period of inundation.

2.8 Statistical Analyses

2.8.1 Univariate Statistics - Minitab

Univariate analysis is a statistical technique that is used for analysing a single parameter at a time, and was performed on water and sediment data in MINITAB (Version 14) (Minitab Incorporated 2003). Where values were below detection (the analytical reporting limit), a value equal to half the limit of reporting was substituted. This only applied to parameters where less than half of the values were below detection; otherwise these parameters were removed from any further analysis.

One-way analysis of variance (ANOVA) was used to compare the statistical means of water and parameters between sites, according to their location north and south of the current DSL operations. A confidence level of 95 % (p value of <0.05) was considered statistically significant (**Appendix B**).

2.8.2 Multivariate Statistics - Primer

Multivariate analysis involves the statistical analyses of more than one parameter at a time. The multivariate procedure principal components analysis (PCA) was used to assess abiotic parameters and hierarchical classification (which produces dendrograms) was applied to biotic communities from Lake MacLeod. These techniques were performed in the statistical package PRIMER, Version 6.0.

PCA is an explanatory tool and was applied to water and sediment data. Where values were recorded as below detection, a value equal to half the limit of reporting was substituted (analytes that recorded values mostly below detection were removed). Select parameters were transformed to reduce skewness (ensuring the data was normally distributed) and collinear variables (those that have a linear relationship) were removed during pre-treatment of the data. The results of the PCA are shown in the form of a plot, on which sites with similar characteristics are located close together, and those that are different are located further apart. Vectors are also displayed, which radiate from the centre of the plot and represent the influence of a particular parameter. The concentration of the parameter follows the direction of the vector, with higher concentrations tending to occur at sites situated near the end point of the vector. The percentage variance is a value used to explain the strength of the PCA; presented over the first two axes of the plot. A value which exceeds 60 % is considered a useful interpretation of the results (Clarke and Warwick 2001).

Hierarchical classification was performed on the phytoplankton, periphyton (diatoms) and aquatic invertebrate data. This procedure calculates the similarity between sites using the Bray-Curtis coefficient (Bray and Curtis 1957), suitable for use on biotic data. Classification was based on the group-average linking algorithm, a process that generates a dendrogram (link-tree), showing the similarity percentage between sites based on community structure. A higher percentage of similarity is recorded for sites that have the most similar species composition.

3. RESULTS AND DISCUSSION

3.1 Water Quality

Temporary saline wetlands are common throughout the inland region of Western Australia and often exhibit substantial fluctuations in water quality throughout the filling phase (Boulton and Brock 1999). Substantial changes in water quality can affect the aquatic biota, with adverse conditions (such as increases in salinity) often leading to a reduction in species diversity (Ghetti and Ravera 1994). Through consistent monitoring, contaminants that enter surface waters can be readily detected, by determining fluctuations outside the typical range, which may pose a risk to organisms inhabiting wetland environments (ANZECC 2000, Meybeck *et al.* 1992).

During the May 2011 aquatic assessment of Lake MacLeod, the pH of surface water ranged from 7.95 to 8.31 (**Table 4**), which is close to the typical pH of sea water (8.2) and similar to the pH range considered suitable for aquatic biota in marine habitats (8.0 to 8.4) (ANZECC 2000). While sudden changes in pH can affect aquatic biota, alkalinity measurements appear sufficiently high to buffer against fluctuations (ANZECC 2000). Dissolved oxygen levels (**Appendix A**) were also well within the acceptable limits for aquatic biota (>5.0 ppm) (Chapman and Kimstach 1996).

The southern area of Lake MacLeod was classified as mesosaline (30,000 to 70,000 µS/cm) to hypersaline (>70,000 µS/cm) *sensu* Hammer (1986), with a mean salinity of 64,910 µS/cm (**Table 4**). Salinity concentrations were variable (**Figure 7**), and ANOVA testing indicated sites north of the DSL operations (DSLM1W to DSLM5W) had significantly higher values than those sites located in the south (DSLM6W to DSLM10W) (**Appendix B**). These results are attributed to differences in surface and groundwater hydrology, as well as potential marine water influence (Department of Environment and Conservation 2009). In the 1980 Lake MacLeod flood, Logan (1987) also found that while surface waters were relatively homogenous, local variations occurred, particularly near inflows.

The major constituents of the ionic balance were Na and Cl (**Table 4**) in May 2011, however compared to sea water there was a proportionally greater contribution of Ca and SO_4 (Morcos 1970). This is likely due to the dissolution of gypsum ($CaSO_4$) during flooding, a dominant mineral present in the Lake MacLeod basin (Logan 1987). The concentrations of these ions were also higher in sites north of DSL operations, reflecting the increased salinity levels in this area. The overall cation dominance mostly followed Na>Ca>Mg>K (**Figure 8**), and the anion dominance was $Cl>SO_4>HCO_3$ (**Figure 9**) at all sites, common trends in Western Australian salt lakes (Gregory 2007).

Table 4: Basic water quality parameters, major ions and nutrients for Lake MacLeod, May 2011. All values presented in mg/L unless specified otherwise.

Analyte	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W	min	max	mean
pH (unit)	8.03	8.09	7.95	8.00	7.99	8.07	8.04	8.27	8.17	8.31	7.95	8.31	8.09
EC (µS/cm)	72,500	75,600	75,300	71,500	65,400	58,700	57,000	56,900	58,900	57,300	56,900	75,600	64,910
TDS	60,500	66,500	62,800	58,100	47,400	48,000	50,600	48,800	52,000	51,800	47,400	66,500	54,650
Na	13,600	15,500	15,600	14,200	13,000	10,700	10,400	10,100	10,500	10,700	10,100	15,600	12,430
Mg	1,550	1,740	1,640	1,540	1,400	1,170	1,140	1,140	1,180	1,170	1,140	1,740	1,367
Ca	1,540	1,680	1,560	1,610	1,650	1,430	1,430	1,430	1,400	1,430	1,400	1,680	1,516
K	624	708	655	605	570	474	453	451	455	465	451	708	546
Cl	24,900	31,200	32,300	29,400	26,300	23,900	22,800	23,000	23,700	23,900	22,800	32,300	26,140
SO_4	5,620	5,770	6,000	6500	5,530	4,900	4,700	4,860	4,840	5,060	4,700	6,500	5,378
Alkalinity	92	90	81	84	71	78	72	70	78	78	70	92	79
HCO_3	92	90	81	84	71	78	72	70	78	76	70	92	79
CO_3	BD	BD	BD	BD	BD	BD	BD	BD	BD	2.0	2.0	2.0	2.0
NO_2	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a
NO_3	BD	BD	BD	BD	BD	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02
NO_2/NO_3	BD	BD	BD	BD	BD	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02
TKN	1.50	2.50	2.40	1.40	1.30	2.10	1.80	1.90	2.10	1.80	1.30	2.50	1.88
TN	1.50	2.50	2.40	1.40	1.30	2.10	1.80	1.90	2.10	1.80	1.30	2.50	1.88
TP	0.11	BD	BD	BD	BD	BD	BD	BD	BD	BD	0.11	0.11	0.11
Chl. *a* (mg/m^3)	1	4	1	3	3	5	5	4	7	4	1	7	4

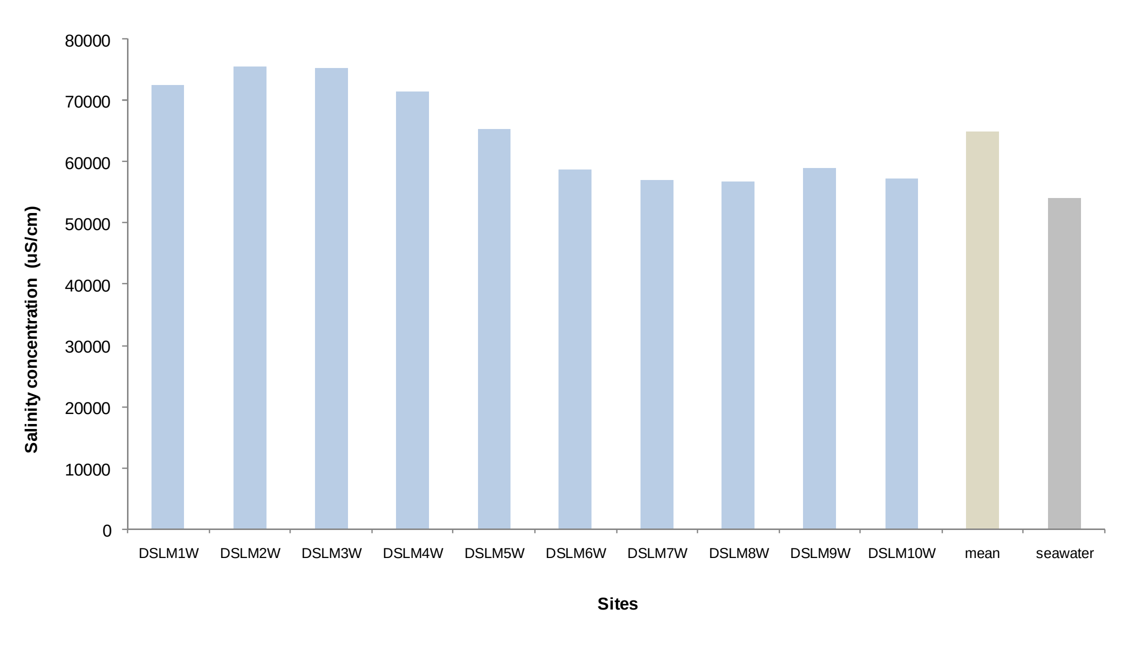


Figure 7: Salinity (electrical conductivity) of the Lake MacLeod surface waters, May 2011.

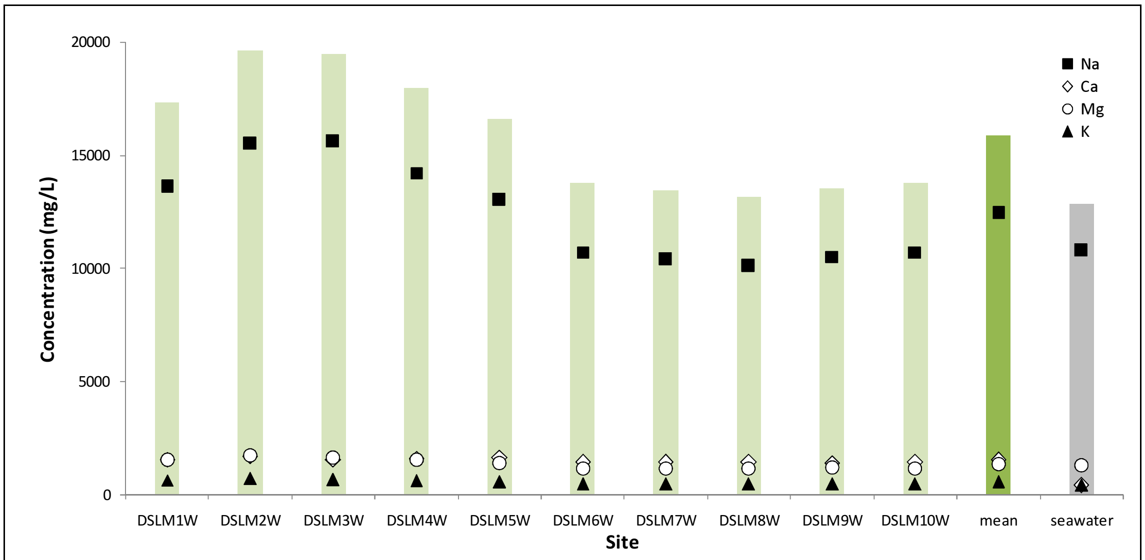


Figure 8: Cation dominance (bars represent the sum of cations) of the Lake MacLeod surface waters, May 2011.

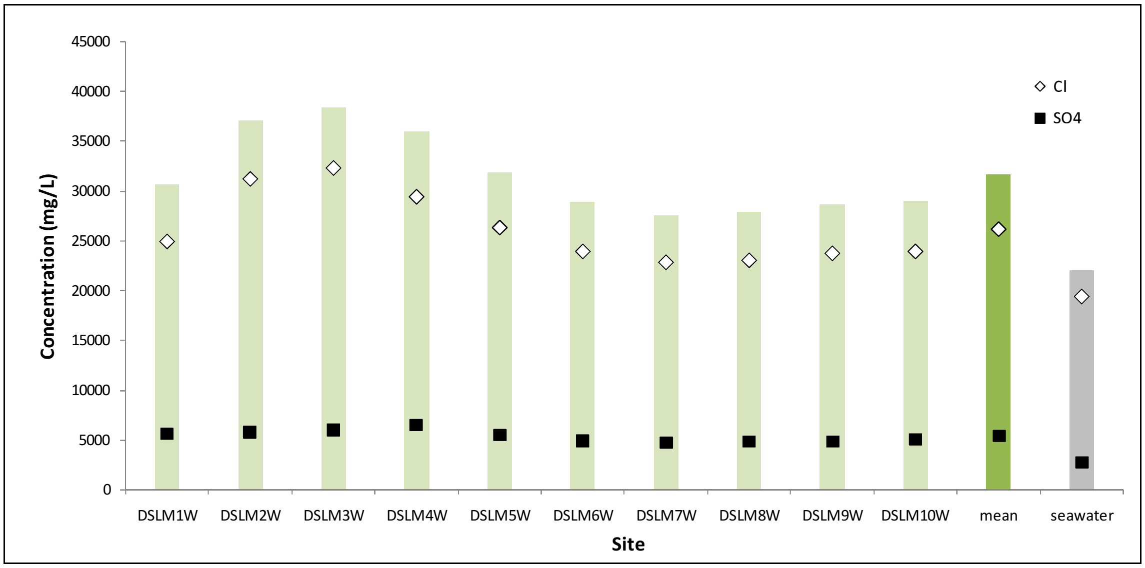


Figure 9: Anion dominance (bars represent the sum of anions) of the Lake MacLeod surface waters, May 2011.

Although the concentration of TP was below the level of analytical detection at most sites, higher concentrations of TN were found (**Table 4**). The TN concentrations, with values up to 2.5 mg/L recorded at DSLM2W, can be attributed to nutrient release from the recently re-wetted sediments, coupled with the inputs from the surrounding catchment via run-off. The combination of these two factors will often cause a spike in nitrogen levels during the initial stages of inundation (Boulton and Brock 1999, McComb and Qui 1998).

The concentrations of metals and trace elements were mostly below detection in the Lake MacLeod surface waters (**Table 5**). Only Ba, Cu, Mn and Ni were detected, and of these only Ba and Cu were detected in all sites. Although there are no trigger values applicable to Lake MacLeod, the ANZECC trigger values for the protection of 80 % of species in marine waters provide a useful comparative reference (ANZECC 2000). The concentrations of Cu were the only metal to slightly exceed the ANZECC guideline value, at all 10 sites. At DSLM1W, DSLM2W and DSLM4W Cu levels were 2.5 times greater (0.02 mg/L) than the ANZECC guideline value (0.008 mg/L). This trend has also been observed in previous studies of Lake MacLeod (GHD 2008), and may be a reflection of natural mineralisation within the catchment.

Table 5: Surface water concentrations of metals and trace elements for Lake MacLeod, May 2011. All values presented in mg/L. Values exceeding ANZECC guidelines (protection of 80% of species in marine water) are highlighted in red.

Analyte	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W	min	max	mean	*ANZECC*
As	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	n/a
Ba	0.15	0.14	0.06	0.14	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.15	0.09	n/a
Be	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	n/a
Cd	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.036*
Co	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.150*
Cr	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.085*
Cu	**0.02**	**0.02**	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	BD	0.02	0.01	*0.008*
Fe	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	n/a
Hg	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.0014*
Mn	0.01	0.01	0.01	BD	BD	0.01	0.02	0.01	0.06	0.05	BD	0.06	0.02	n/a
Ni	BD	0.01	BD	0.01	BD	BD	BD	BD	BD	BD	BD	0.01	0.01	*0.560*
Pb	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.012*
Si	BD	BD	BD	BD	BD	BD	BD	BD	BD	0.50	BD	BD	n/a	
V	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.280*
Zn	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.043*

PCA of water quality data showed a clear separation of sites north and south of DSL operations (**Figure 10**). This reflects the heterogeneity of the lake's surface waters, common in large salt lakes throughout Western Australia (John 2001). ANOVA testing also found significant differences ($p<0.05$) between northern and southern sites with higher salinity and related ions (SO_4 and Ca) at sites north of the DSL operations (**Appendix B**).

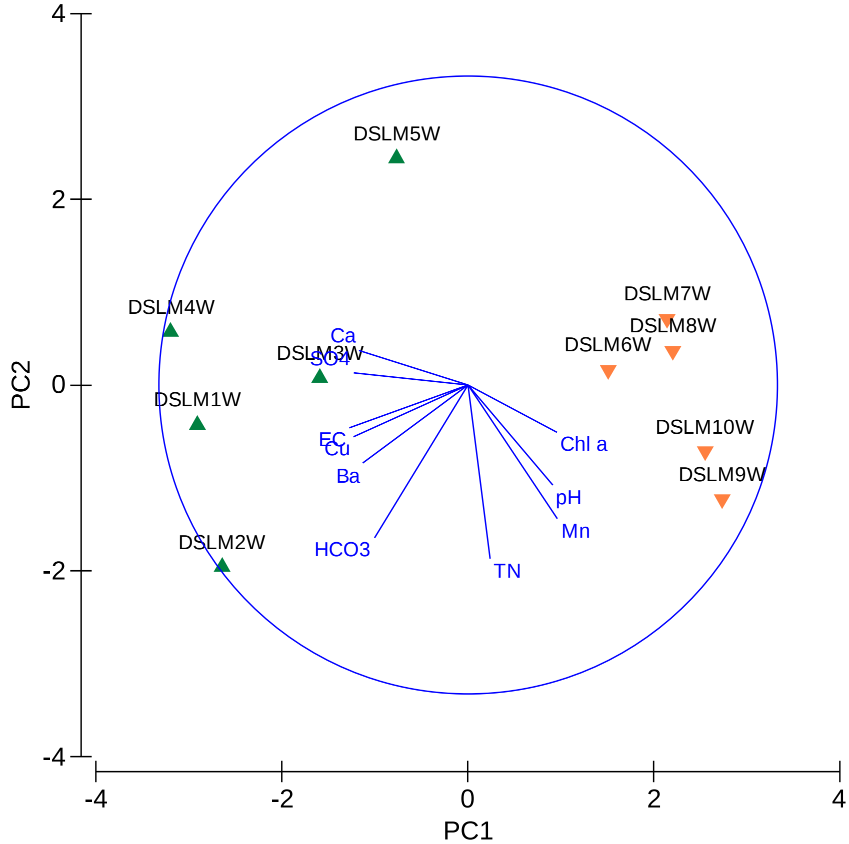


Figure 10: PCA of water quality from Lake MacLeod, May 2011 (▲= north and ▼ = south of DSL operation). Note that 75.1 % variation is explained by the first two axes.

3.2 Sediment Quality

Lake sediments are an important component of aquatic ecosystems and support a wide range of organisms (McKenzie *et al.* 2004, Pulford and Flowers 2006). They also serve as a sink for any contaminants entering a water body (Simpson *et al.* 2005). For this reason, understanding and interpreting sediment data is vital (Hazelton and Murphy 2007), and chemical analyses are a common tool used in conjunction with biological monitoring (Connell 2005). Lake sediments in the arid and semi-arid regions of Western Australia typically display high spatial heterogeneity (Simpson *et al.* 2005), with properties varying both horizontally and vertically (McKenzie *et al.* 2004).

Apart from the circumneutral pH of sediments at site DSLMW1 (pH 7.10), the Lake MacLeod sediments were moderately alkaline in May 2011, ranging from 7.70 to 8.50 (**Table 6**). These results were consistent with pH values recorded from the lake during dry conditions in September 2010 (Outback Ecology 2011), with alkaline sediments typical of salt lakes in the arid and semi-arid zones (Gregory 2007).

Sediment salinity (TSS) was considered low, with an average of close to 12,000 mg/kg (**Table 6**). This compares to concentrations of more than 65,000 mg/kg recorded during the dry sampling event (Outback Ecology 2011), and is to be expected, with salts mobilised into surface waters during the initial stages of flooding, leading to a decrease in sediment salinity (Boulton and Brock 1999, Gregory 2007, Logan 1987, Smith *et al.* 2004). As water levels recede over time and the lake eventually dries, evapoconcentration will lead to an increase in salinity throughout the southern area (Department of Environment and Conservation 2009). The dominant ions were Na and Cl, following the ionic sequence found in surface waters.

Nutrients levels in sediments were also comparatively low, and similar to the range recorded during September 2010 (Outback Ecology 2011). TN concentrations were typically <500 mg/L, although at DSLMW5 the concentration was nearly three times this amount (**Table 6**). The source of nitrogen at this site may be related to a number of factors, including the presence of algal mats and nutrient inputs from nearby stock (Connell 2005), with a large aggregation of sheep noted in this area. In contrast to TN, TP concentrations were generally <200 mg/L, although at site DSLMW6 the TP was notably higher (368 mg/L). The trend of elevated TN in relation to TP is consistent with most salt lakes situated in the inland region of Western Australia (John 2001).

The concentrations of metals and trace elements were low in the sediments of all sites, with Be, Cd and Hg below detection. The concentrations of all parameters were also well below the ANZECC guidelines recommended ISQG-Low trigger values (**Table 7**). This was also the case for Cu, which was elevated in surface waters. In sediments, Cu was only present in detectable quantities at sites DSLMW2, DSLMW4, DSLMW6 and DSLMW10, all of which are along the eastern margin of the lake near inflows. These findings suggest a natural enrichment of Cu in the south-eastern region of the Lake MacLeod catchment.

Table 6: Basic sediment quality parameters, major ions and nutrients for Lake MacLeod, May 2011. All values presented in mg/kg unless specified otherwise.

Analyte	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W	min	max	mean
pH (unit)	7.10	8.00	7.80	8.10	7.90	8.30	8.20	8.50	7.80	7.70	7.10	8.50	7.94
Alkalinity	2	12	5	5	22	14	7	23	6	8	2	23	11
TSS	9,620	16,200	11,200	12,000	12,400	10,400	12,200	11,200	12,000	13,200	9,620	16,200	12,042
MC (%)	31.4	31.7	32.5	27.9	42	38.9	37.7	23.1	23.7	40.7	23.1	42.0	33.0
SO_4	13,300	16,600	14,000	13,900	17,400	16,000	16,100	11,300	2,280	17,400	2,280	17,400	13,828
Cl	6,500	17,700	9,720	10,100	14,200	9,170	12,100	5,360	6,200	15,300	5,360	17,700	10,635
Ca	5,270	6,150	5,590	5,200	6,460	5,950	6,170	4,430	720	6,370	720	6,460	5,231
Mg	400	1,360	610	760	1,000	720	850	440	340	1,150	340	1,360	763
Na	3,830	10,700	5,830	6,510	8,550	6,110	7,510	3,250	3,670	9,480	3,250	10,700	6,544
K	300	680	320	390	570	520	420	300	340	720	300	720	456
NO_2	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a
NO_3	0.3	BD	0.8	0.1	BD	0.2	0.2	BD	0.2	0.2	0.1	0.8	0.3
NO_2/NO_3	0.3	BD	0.8	0.1	BD	0.2	0.2	BD	0.2	0.2	0.1	0.8	0.3
TKN	130	360	170	200	1,450	370	120	240	480	530	120	1,450	405
TN	130	360	170	200	1,450	370	120	240	480	530	120	1,450	405
TP	36	151	28	154	176	368	69	200	191	198	28	368	157
TOC (%)	0.16	0.19	0.25	0.17	0.39	0.23	0.09	0.18	0.1	0.34	0.09	0.39	0.21

Table 7: Concentrations of metals and trace elements in Lake MacLeod sediments, May 2011. All values presented in mg/kg. ANZECC ISQG-Low values are provided for comparison where applicable.

Analyte	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W	min	max	mean	*ANZECC*
As	BD	6	BD	BD	BD	5	5	BD	BD	BD	5	6	5	*20*
Ba	BD	20	BD	40	20	20	BD	10	20	20	10	40	21	n/a
Be	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	n/a
Cd	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*1.5*
Cr	4	11	BD	11	8	23	4	9	9	18	4	23	11	*80*
Co	BD	2	BD	BD	BD	6	BD	BD	BD	4	2	6	4	n/a
Cu	BD	7	BD	6	BD	15	BD	BD	BD	11	6	15	10	*65*
Fe	2,960	9,010	730	7,250	3,880	17,200	2,470	4,260	5,340	11,400	730	17,200	6,450	n/a
Pb	BD	BD	BD	BD	BD	6	BD	BD	BD	BD	6	6	6	*50*
Mn	17	107	8	60	48	257	22	82	98	132	8	257	83	n/a
Ni	BD	5	BD	4	3	10	BD	3	3	7	3	10	5	*21*
Si	6	9	BD	11	9	9	10	12	BD	20	6	20	11	n/a
V	7	20	BD	18	12	41	6	13	15	30	6	41	18	n/a
Zn	BD	9	BD	8	BD	19	BD	BD	6	14	6	19	11	*200*
Hg	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	n/a	*0.15*

Analysis of sediment quality data using PCA showed a high degree of overlap between the northern and southern sites (**Figure 11**). Unlike the differences found in the statistical analysis of water quality parameters, there were no significant differences in sites north and south of DSL operations in relation to sediment quality, suggests a relatively homogenous benthic environment in this part of the lake.

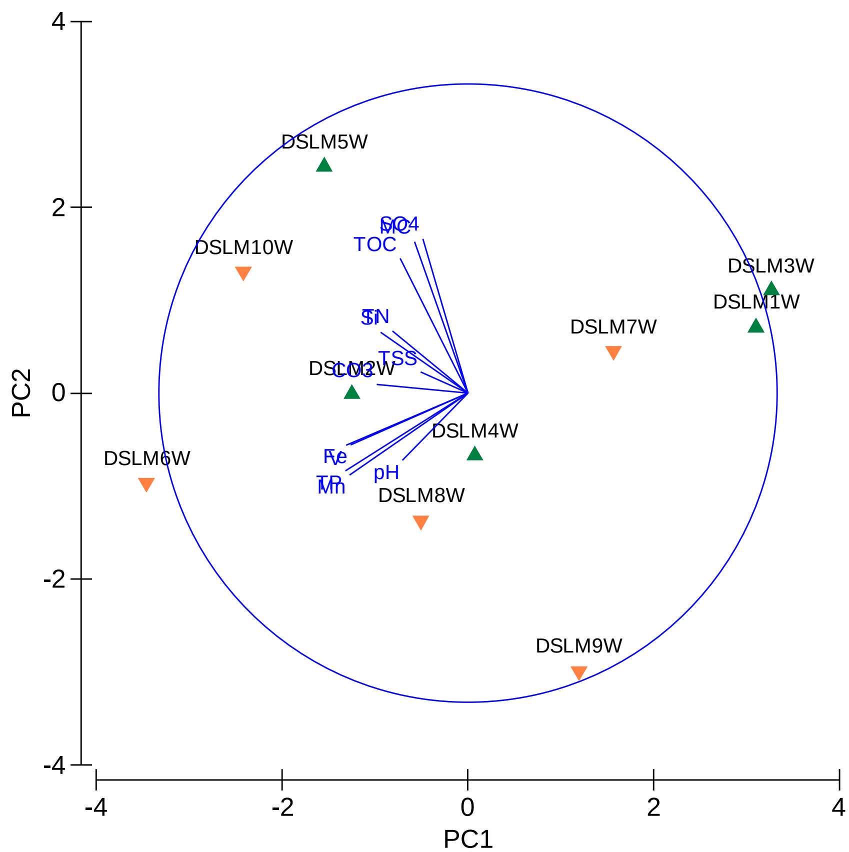


Figure 11: PCA of sediment quality from Lake MacLeod, May 2011 (▲= north and ▼ = south of DSL operation). Note that 63 % variation is explained by the first two axes.

3.3 Phytoplankton

Phytoplankton are an important component of aquatic systems, and are often the main primary producers (Hammer 1981). The species composition and structure of phytoplankton communities are affected by a range of abiotic parameters, with salinity considered to be a key determinant (Pilkaitytë *et al.* 2004). In elevated salinities, true phytoplankton are limited to one or two specialists that can withstand the extreme conditions (Borowitzka 1981). However in low salinity and freshwaters, phytoplankton communities are diverse, occurring in substantial numbers (Hammer 1986).

Thirteen taxa were recorded in the phytoplankton samples from Lake MacLeod in May 2011 (**Table 8**), representing three phyla including Bacillariophyta (diatoms), Cyanophyta (blue green algae) and Chlorophyta (green algae). Bacillariophyta and Cyanophyta were the dominant groups (with six and five taxa respectively), while Chlorophyta representatives were limited (two taxa) (**Figure 12a**). Species diversity was comparable to that recorded for other salt lakes in Western Australia (Gregory 2007, Handley 2003a), with all of the taxa considered cosmopolitan and able to withstand elevated salinities (Entwisle *et al.* 1997, Taukulis 2007).

Species diversity ranged from five to nine taxa throughout the lake. The most abundant taxon (recorded from all sites) was the diatom *Nitzschia closterium* (**Figure 12b**). This species has been recorded in bloom proportions from estuarine environments in Western Australia (John 1983), and is widespread throughout many coastal regions around the world (Witkowski *et al.* 2000). Diatoms including *Gyrosigma* and *Navicula* were also common in most of the Lake MacLeod sites. These ubiquitous genera have been documented from inland saline waters as well as marine environments, and comprise a number of salt tolerant taxa (Ehrlich 1995, John 1998, Witkowski *et al.* 2000).

The blue-green alga *Oscillatoria* was recorded in high numbers from the majority of sites (**Table 8**). This genus is known to withstand salinities in excess of 125,000 µS/cm, with blooms reported from a number of inland salt lakes in Western Australia (Coleman 2003, Handley 2003b, Smith *et al.* 2004). Of the remaining cyanobacteria found, *Anabaena* and *Nodularia* are known to contain toxins that are potentially harmful to humans or livestock (Entwisle *et al.* 1997), however as their numbers were limited, this was not considered cause for concern.

The algae found in the Lake MacLeod phytoplankton samples comprised mainly of periphytic taxa (those that live attached to substrates), with filamentous forms and a colonial species occurring to a lesser extent (**Table 8**). This is typical of hypersaline waters, which support few planktonic algal taxa (John 2001). *Dunaliella salina* for example is one of the most common free-floating green algae found in surface waters or benthic communities in salt lake ecosystems. While not recorded from the May 2011 assessment, it has been identified from the sediments of Lake MacLeod during sediment re-hydration trials (Outback Ecology 2011). Only two Chlorophyta representatives occurred in the phytoplankton samples, contributing to the least numerical abundance of all groups.

The periphyton dominant algal community was reflected in the hierarchical classification, with at least 40 % similarity in species composition across the lake, and no clear differences between sites located north and south of DSL operations (**Figure 13**). Algal groups consisted of a range of taxa associated with coastal environments and inland saline waters, a finding consistent with previous work conducted in the south-west region of Western Australia (Handley 2003). As salinities in surface waters increase due to evapoconcentration, periphytic and benthic taxa will continue to dominate, and will likely be the main primary producers within the system (Borowitzka 1981).

Table 8: Distribution (abundance and diversity) of phytoplankton taxa recorded from Lake MacLeod, May 2011 (P=periphytic form, growing attached to substrates, F=filamentous form, C=colonial form).

Taxon	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W
Bacillariophyta										
Amphora sp. P	1		330	8	418	9	12	24	36	125
Entomoneis sp. P						1		5	17	
Gyrosigma sp. P	80	26	9	43	81	40	49	49	78	4
Hantzschia sp. P	4		2	2	5	1			2	3
Navicula sp. P	5	23	34	17		12	13	39	2	
Nitzschia closterium P	148	230	19	154	49	323	305	144	249	363
Cyanophyta										
Anabaena sp. F		1						4		
Nodularia sp. F	2	24		1						
Oscillatoria sp. F	6	17		122	3	192	380	70	282	17
Pseudanabaena sp. F	1	3		31						
Spirulina sp. F		1		1					1	
Chlorophyta										
Oocystis sp. C		1			2				1	
Rhizoclonium sp. F	8									
Abundance of cells	**255**	**326**	**394**	**379**	**558**	**578**	**759**	**335**	**668**	**512**
Species diversity	**9**	**9**	**5**	**9**	**6**	**7**	**5**	**7**	**9**	**5**

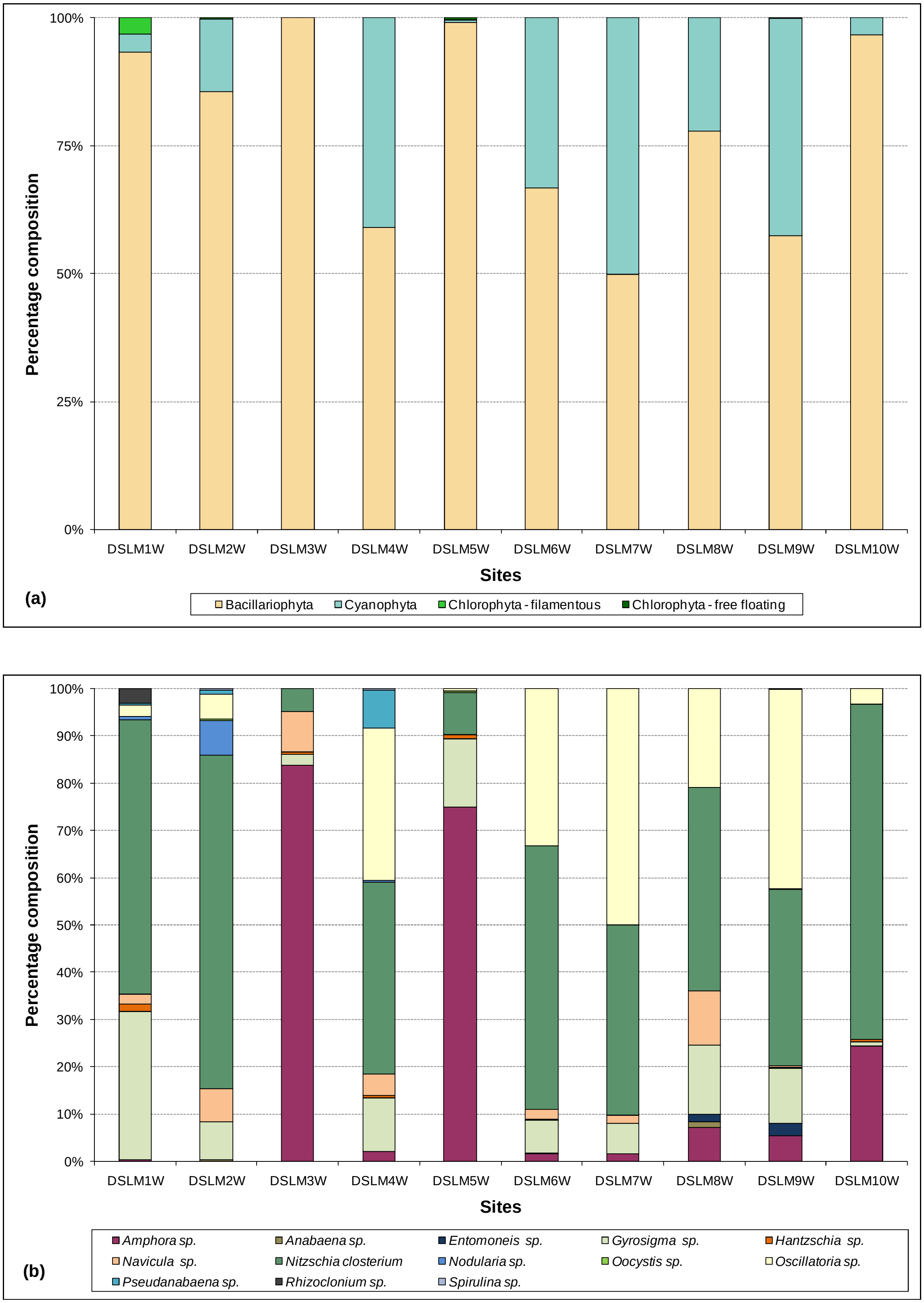


Figure 12: Percentage composition of phytoplankton from Lake MacLeod in May 2011, represented by (a) major groups and (b) taxa.

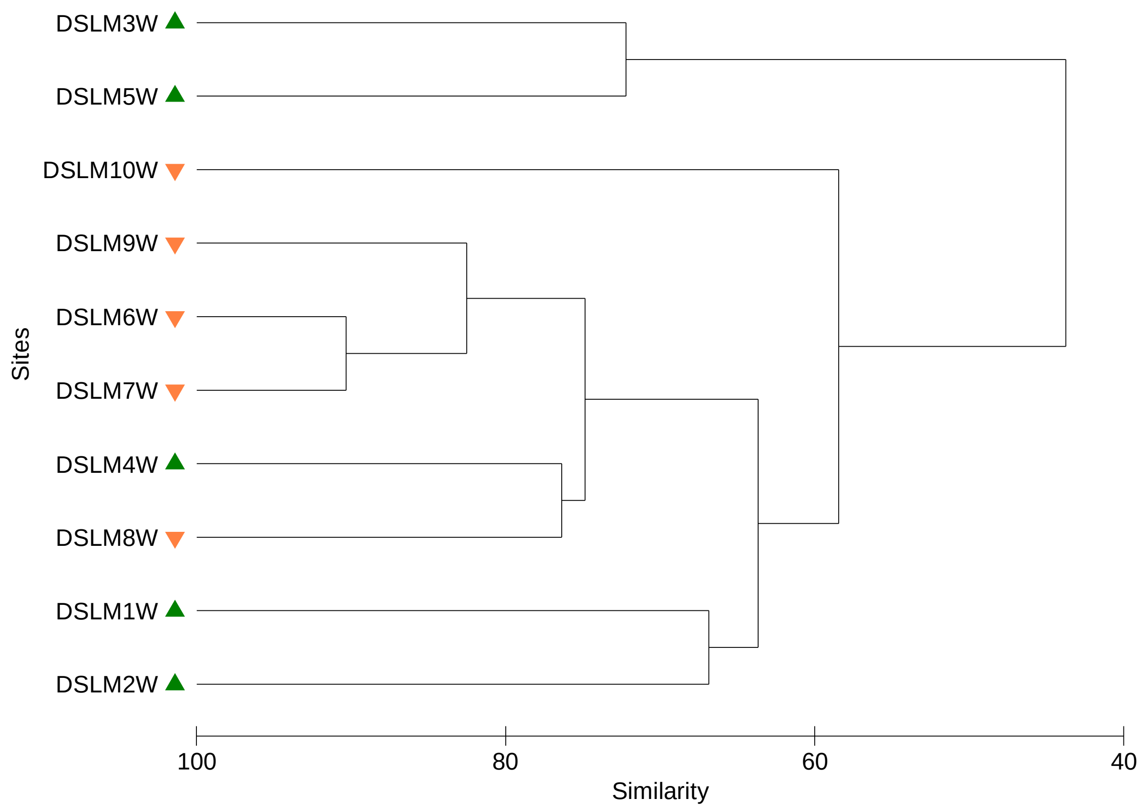


Figure 13: Dendrogram showing site classification (▲= north and ▼ = south of DSL operation) according to phytoplankton communities at Lake MacLeod, May 2011.

3.4 Periphyton (Diatoms)

Diatoms are eukaryotic, unicellular microalgae that belong to the phylum Bacillariophyta (Sze 1986), and have a cosmopolitan distribution in almost all aquatic habitats (Round *et al.* 1990). In shallow, temporary waters, diatoms form an important component of the BMCs and are often one of the dominant primary producers (Bauld 1981, 1986, Boggs *et al.* 2007). Their morphology is characterised by a cell wall composed of silica (termed a frustule), which in adverse conditions can thicken considerably to form a resting spore, allowing for survival during extended dry periods (McQuoid and Hobson 1996). The sensitivity of diatoms to their surrounding environment means they are ideal indicators of changing conditions, whereby shifts in community structure can reflect anthropogenic impacts, including those related to mining operations (John 1998, 2000).

Twenty-three diatom taxa were recorded in the periphyton samples from Lake MacLeod (**Table 9**). The most dominant genera included *Nitzschia*, *Amphora* and *Navicula* with at least four species each (**Figure 14a**), all common to inland salt lakes and marine environments throughout the world (Ehrlich 1995, Gasse 1986, Taukulis and John 2009, Witkowski *et al.* 2000). A number of taxa from these groups dominated sites throughout the lake in May 2011, while the remaining species occurred in much lower numbers.

Species diversity at each site ranged from five (DSLM7W) to 13 (DSLM9W) taxa, with most sites recording between seven and ten species (**Table 9**). While the diversity of the less abundant taxa varied amongst the sites, the dominant species remained consistent and included *Amphora coffeaeformis*, *Mastogloia pumila*, *Navicella pusilla*, *Navicula recens*, *Nitzschia punctata* and *Pleurosigma salinarum* (**Figure 14b**). These species have all been documented from inland lakes and streams throughout Western Australia (Taukulis 2007), with *Amphora coffeaeformis* for example, considered one of the most widespread saline diatoms in Australia (Gell and Gasse 1994, John 1998).

A number of the diatoms recorded from the periphyton samples of Lake MacLeod also commonly occur in coastal environments, reflecting the strong marine influence on the lake's hydrology. For example *Mastogloia pumila* and *Mastogloia halophila* have both been identified from the coast of Western Australia as well as the Mediterranean and Baltic coasts (Baltic Marine Biologists Working Group 27 1993, John 1994, Witkowski *et al.* 2000). *Navicula recens* is frequently encountered in marine waters, particularly off the Mediterranean and European coast lines (Miho and Witkowski 2005, Witkowski *et al.* 2000). Additionally the *Proschkinia* genus (represented by *Proschkinia* sp. 1) is almost solely associated with marine waters (Witkowski *et al.* 2000).

The species composition of diatoms was dominated by euryhaline taxa capable of surviving a broad spectrum of salinities. Previous studies have found that diatoms occurring in mesosaline waters (30,000 to 70,000 µS/cm) will often persist in hypersaline conditions (>70,000 µS/cm) (Taukulis 2007). The taxa identified from Lake MacLeod generally have a cosmopolitan distribution, and there was a minimum of 20 % similarity in species composition between all sites (according to hierarchical classification) (**Figure 15**). Sites located in close proximity other had the most comparable diatom assemblages, with more than 60 % similarity. This is likely a reflection of local microtopography and diatom colonisation (Krejci and Lowe 1986), with some species known to have substrate specific preferences (Townsend and Gell 2005).

The phytoplankton and diatom studies undertaken at the lake in May 2011 as part of the aquatic assessment will substantially increase knowledge on the algal flora of the region, which is currently limited (Department of Environment and Conservation 2009, Outback Ecology 2009). In particular, this assessment represents the first documented literature on microalgae inhabiting the southern part of Lake MacLeod, having shown that while species composition is typical of some of the larger inland salt lakes in Western Australia, the assemblages also reflect the strong marine connection.

Table 9: Distribution (abundance and diversity) of diatom taxa identified from Lake MacLeod, May 2011.

Taxon	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W
Bacillariophyta										
Amphora coffeaeformis	17	113	25			33	9	123	88	2
Amphora holsatica									13	
Amphora hybrida						9		4		
Amphora subturgida	2	5				4			2	
Amphora veneta	1						2			
Entomoneis sp. aff. *punctulata*				1					9	1
Gyrosigma spencerii						2			2	
Mastogloia halophila			13		34					
Mastogloia pumila	8	15	42	10	57			1		
Navicella pusilla			95		101	5				
Navicula cryptocephala	2		4	2		7			4	1
Navicula incertata	4	35	10			6	5		7	
Navicula recens				152	3			40	47	198
Navicula salinicola		1		5	3	10				
Nitzschia lorenziana									8	
Nitzschia punctata	48	26		32		77	6	25	11	
Nitzschia sigma									1	2
Nitzschia sp. aff. *archibaldii*	27	2		1						
Nitzschia sp. aff. *communis*			3			11		2		2
Pleurosigma elongatum									1	
Pleurosigma salinarum	12	8		8		45	5	11	22	1
Proschkinia sp. 1	80	1								
Synedra radians			17		3	2				
Abundance of frustules	**201**	**206**	**209**	**211**	**201**	**211**	**27**	**206**	**215**	**207**
Species diversity	**10**	**9**	**8**	**8**	**6**	**12**	**5**	**7**	**13**	**7**

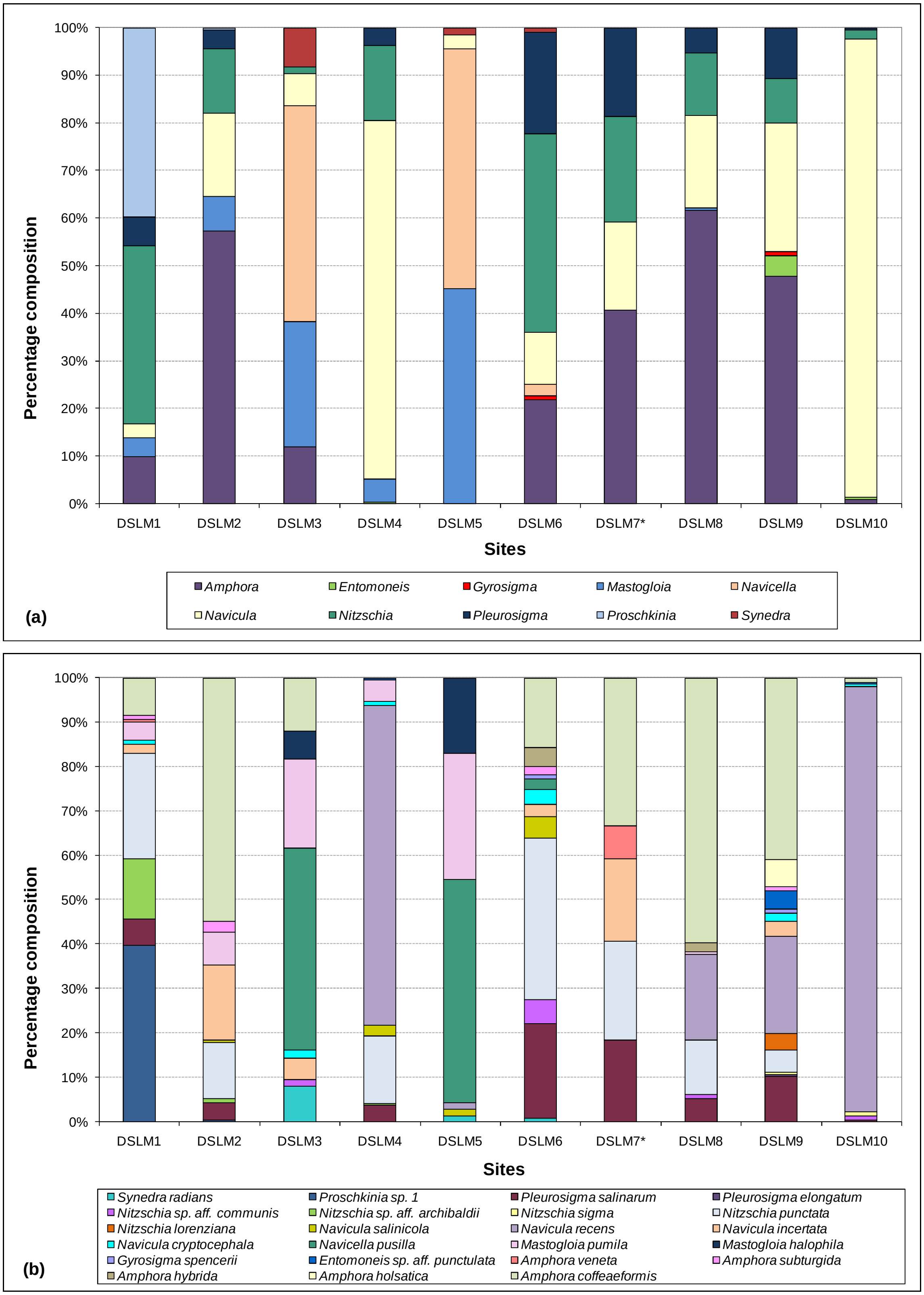


Figure 14: Percentage composition of diatoms from Lake MacLeod in May 2011, represented by (a) genera and (b) species.

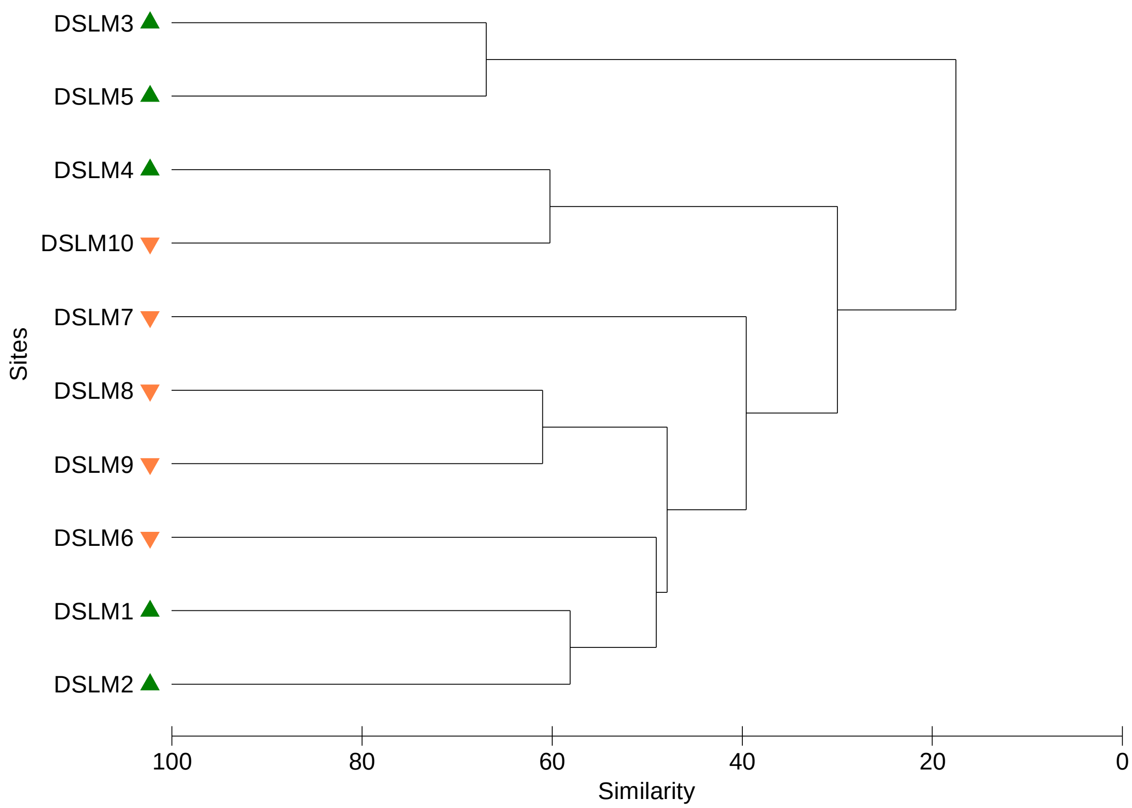


Figure 15: Dendrogram showing site classification (▲= north and ▼ = south of DSL operation) according to diatom communities at Lake MacLeod, May 2011.

3.5 Aquatic Invertebrates

Aquatic invertebrates inhabit a range of environments from freshwater streams to inland salt lakes. They belong to a number of trophic groups, including consumers and decomposers, and play an integral role in ecosystem function (Gooderham and Tsyrlin 2002). They are a diverse group of biota, sensitive to changes in water quality and can therefore be used as biological monitors to detect changes in physical and chemical parameters such as salinity (Cairns Jnr. and Pratt 1993, Dills and Rogers 1974, Hellawell 1986).

Fifteen aquatic invertebrate taxa were recorded from Lake MacLeod in May 2011 (**Table 10**), consistent with previous studies from the Northern Ponds (Department of Environment and Conservation 2009). Most sites recorded between five to eight taxa, with fewer recorded from DSLM7W and DSLMW9 (four and three taxa respectively).

Crustaceans were the most dominant group (11 taxa), and in particular copepods, represented by the orders Calanoida, Cyclopoida and Harpacticoida, which were well distributed across the lake (**Figure 16a**). Two taxa, *Acartia* sp. B1 and *Onychocamptus bengalensis*, were also relatively abundant and have been recorded from the Northern Ponds and broader Carnarvon Basin previously (Department of Environment and Conservation 2009).

Other crustaceans included a single specimen of Mysid shrimp (**Appendix C**, **Plate 3**) and a widespread and abundant ostracod, *Reticypris* aff. *kurdimurka* (**Table 10**), that is also known from Lake Annean and Lake Eyre located in the Goldfields and central region of Western Australia (Williams and Kokkinn 1988). It is likely the ostracods eggs identified from the sediments of Lake MacLeod in September 2010 during the dry sampling event belonged to *Reticypris* aff. *kurdimurka* (Outback Ecology 2011).

The remaining invertebrates included the almost cosmopolitan rotifer, *Branchionus rotundiformis* (Segers 2007, Vhargese and Krishnan 2010), and chironomid midges (**Appendix C**, **Plate 4**) such as *Tanytarsus barbitarsus* (**Table 10**), which is commonly found in Western Australian salt lakes in salinities between 5,000 and 200,000 µS/cm (Pinder *et al.* 2002). Fish larvae were also collected in the invertebrate samples, and larger fish were observed at most sites during the field sampling. Although they could not be identified to species level, the larval specimens collected may represent up to three different taxa, potentially of the common estuarine and marine families Atherinidae (Hardyheads), Sparidae (Cods), Terapontidae (Grunters) and Gobiidae (Gobies). Of these, Terapontidae (*Amniataba* sp.) have previously been recorded in the lake (Logan 1987).

Resting stages of the widespread branchiopod *Parartemia laticaudata* were previously identified from the Lake MacLeod sediments during dry conditions in September 2010 (Outback Ecology 2011). Although no specimens were collected during May 2011, the salinity of the lake was well within the tolerance range of this species (with an upper limit of >160,000 µS/cm) (Timms 2010, Timms *et al.* 2009). It is possible that *Parartemia laticaudata* have not yet hatched, and will take advantage of higher salinities as water levels begin to recede (when only few invertebrate taxa remain and competition for resources will decrease).

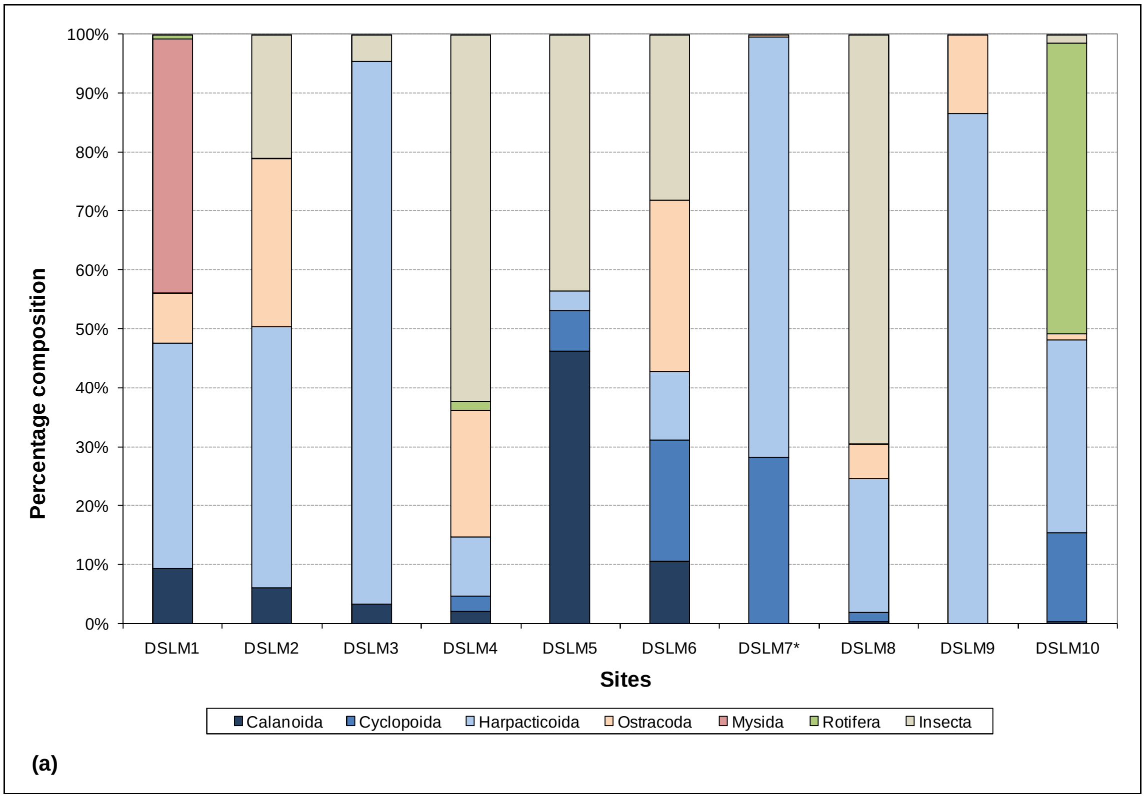
All of the aquatic invertebrates identified from the lake are also known to occur more widely in Australia, and most species have an almost cosmopolitan distribution (Gomez *et al.* 2003, Hamond 1973, Mielke 2000, Mohamed *et al.* 2008, Pinder *et al.* 2002, Segers 2007, Vhargese and Krishnan 2010, Williams and Kokkinn 1988). The taxa found are also euryhaline, reflecting the broad range of salinities and various habitats in which they occur around the world.

The connectivity of Lake MacLeod to coastal waters results in permanent aquatic habitats in the northern area of the lake, and temporary aquatic habitats in the south. The aquatic invertebrate fauna therefore comprises cosmopolitan marine species, and temporary groups associated with inland salt lakes. For example, the harpacticoid copepod *Cletocamptus deitersi* is a widely distributed, permanent inhabitant of brines, rivers and estuaries around the world (Gomez *et al.* 2003). Conversely, Chironomidae representatives are transient species with mobile adult stages that lay eggs in lake waters (Gooderham and Tsyrlin 2002). A number of ostracod taxa are associated with inland salt lakes and produce desiccation-resistant resting stages, which enable them to survive during prolonged dry periods, hatching when conditions are suitable (Halse and McRae 2004).

Although salinities were higher at sites north of DSL operations, this was not reflected in any apparent differences in species diversity across the lake (**Figure 16b**). Hierarchical classification confirmed the consistency of invertebrate assemblages, with all sites having at least 35 % similarity in species composition (**Figure 17**). The overall species diversity for the lake was also comparable to inland salt lakes in the wheatbelt region (Pinder *et al.* 2005) and studies on the Northern Ponds in similar salinity ranges (Department of Environment and Conservation 2009).

Table 10: Distribution (abundance and diversity) of aquatic invertebrates identified from Lake MacLeod, May 2011 (* juvenile/damaged specimen, unable to be identified further).

Taxon	DSLM1W	DSLM2W	DSLM3W	DSLM4W	DSLM5W	DSLM6W	DSLM7W	DSLM8W	DSLM9W	DSLM10W
Copepoda										
Calanoida										
Acartia sp. B1 (=DEC sp. 357 (CB))	26	4	5	3	71	9		1		1
Cyclopoida										
Apocyclops dengizicus				1	3	5	14	1		10
Harpacticoida										
Cletocamptus confluens							1			
Cletocamptus deitersi				2				1	4	10
(Harpacticoida)*	9	5	40							
Nitokra sp. B2 (nr *lacustris pacifica*)	21									
Onychocamptus bengalensis	2	1	58		9	18	9	80	30	10
Robertsonia sp. B1 (nr *propinqua*)	5	1	1							
(Copepoda nauplii)*										20
Mysida										
(Mysidacea)*	1									
Ostracoda										
Reticypris aff. *kurdimurka*	30	24		39		32	1	17	9	3
Rotifera										
Brachionus rotundiformis	1			1						50
Insecta										
Chironomidae										
Chironomini				1	1					
Chironominae								2		
Tanytarsus barbitarsus		4	2	8	2	7		11		1
Number of invertebrate specimens	**95**	**39**	**106**	**55**	**86**	**71**	**25**	**113**	**43**	**105**
Species diversity	**8**	**6**	**5**	**7**	**5**	**5**	**4**	**7**	**3**	**8**



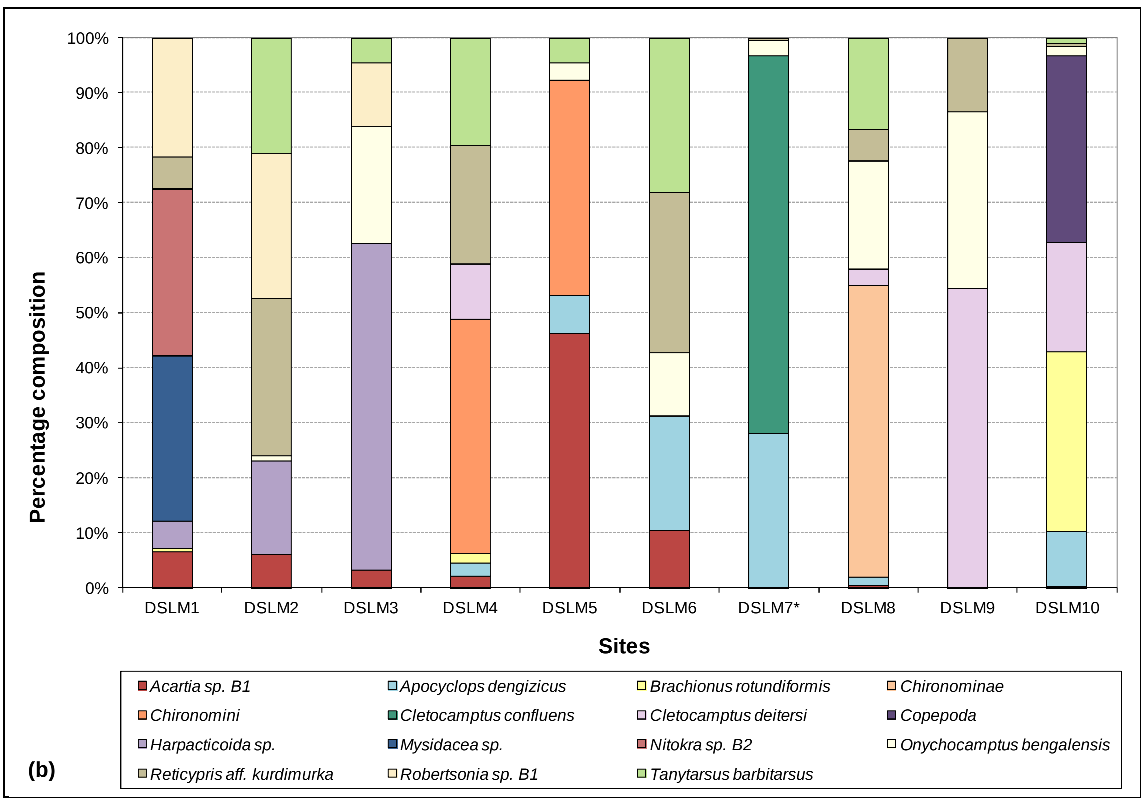


Figure 16: Percentage composition of invertebrates from Lake MacLeod in May 2011, represented by (a) major groups and (b) taxa.

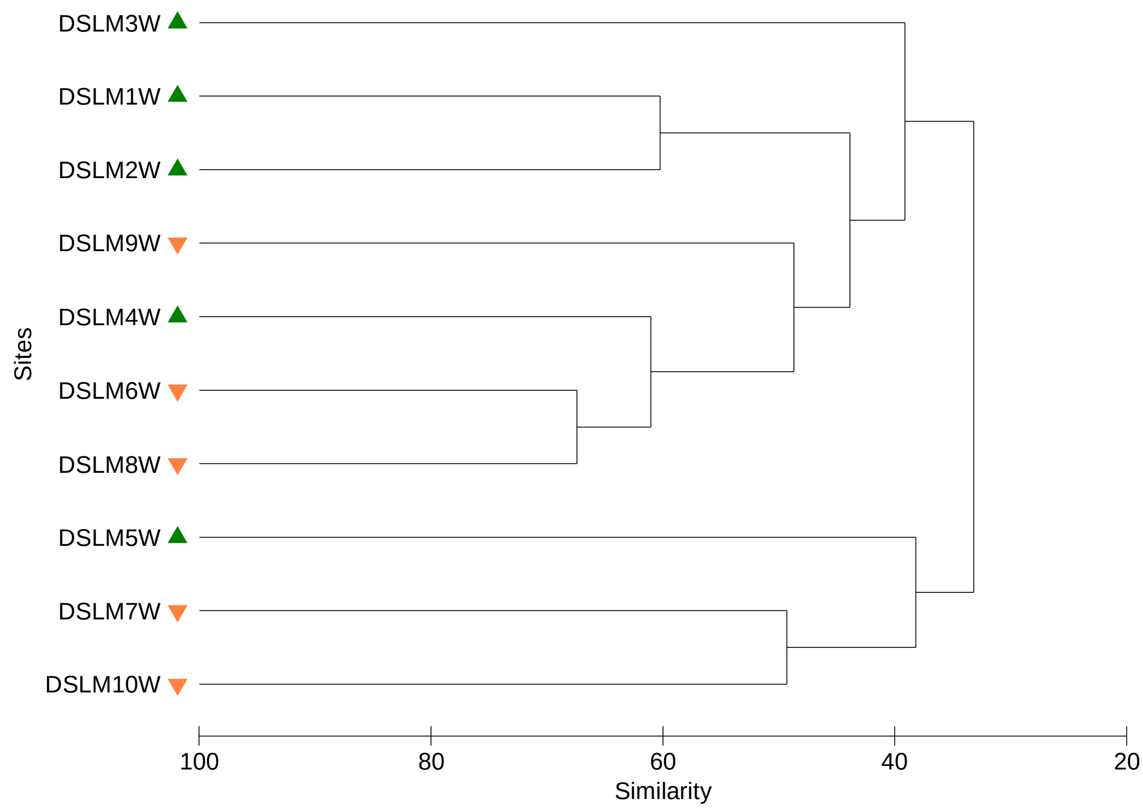


Figure 17: Dendrogram showing site classification (▲= north and ▼ = south of DSL operation) according to aquatic invertebrate communities at Lake MacLeod, May 2011.

4. CONCLUSIONS

4.1 Water and Sediment Quality

During the filling event of May 2011, Lake MacLeod was mesosaline to hypersaline, with a salinity concentration approximately 1.5 times that of seawater. The dominant ions were Na and Cl, with relatively high concentrations of Ca and SO_4 likely related to the dissolution of gypsum. Concentrations of TN were higher than TP, associated with the release of nutrients in the initial stages of inundation. Concentrations of most metals and trace elements were low, and well below the ANZECC guidelines for marine waters. Concentrations of Cu were an exception, being elevated at all sites and likely reflecting local enrichment within the catchment.

Sediments were classified as alkaline, typical of inland salt lakes in Western Australia. Nutrient concentrations were low, as were the concentrations of salts, metals and trace elements. This appears to be related to flooding, with the concentrations of most parameters notably less than recorded in the previous dry assessment of Lake MacLeod, due to mobilisation from sediments into surface waters. It is expected that as surface waters begin to recede and evapoconcentration occurs, salts will increase substantially in the sediments.

4.2 Phytoplankton and Periphyton (Diatoms)

Thirteen phytoplankton taxa were recorded from Lake MacLeod, all of which represent cosmopolitan, salt tolerant genera. The community was dominated by the Bacillariophyta and Cyanophyta groups, with a high degree of similarity in species composition throughout the area. The diversity of taxa was comparable to that recorded for other salt lakes in Western Australia. Samples were dominated by periphyton, with few true planktonic taxa identified, a characteristic of hypersaline waters.

The periphyton assemblage included twenty-three taxa, with several prominent genera including *Amphora*, *Navicula* and *Nitzschia* representatives. Sites located in close proximity to each other recorded the most similar diatom assemblages, a reflection of habitat availability and colonisation preferences. All of the taxa recorded were common and widespread, having been found locally and overseas in both saline and coastal environments.

4.3 Aquatic Invertebrates

The invertebrate fauna included 15 taxa dominated by crustaceans, particularly harpacticoid copepods. Other fauna included calanoid and cyclopoid copepods, ostracods, a rotifer, mysid shrimp and chironomid representatives. There were no clear differences between assemblages across the lake, with similarities observed from sites north and south of DSL operations. All of the taxa recorded are widespread, and have been recorded elsewhere in Australia and the world. A number of immature fish larvae were also collected in the invertebrate samples, likely to be common estuarine or marine species.

4.4 Summary of Risks to Aquatic Biota

Sampling Lake MacLeod during the recent flood[1] provided a unique opportunity to understand the diversity and productivity of a coastal marine system that fills only once every ten years. Although the lake has a strong marine influence and receives freshwater input from rainfall, the salinity was higher than that of sea water, and the biota present were associated with oceanic and inland saline environments. The taxa found reflect the contiguous habitat of the lake during flood, with a high degree of similarity in biological assemblages, comprising common and widespread taxa, which occur locally and overseas. As long as some parts of the southern basin are retained, allowing aquatic biota to emerge and complete their lifecycles during a filling event, there appears to be no identifiable risks to the aquatic communities from the proposed expansion of DSL operations. In line with this, DSL should also maintain the surface and groundwater hydrology of the area where possible, allowing for the natural drainage of the lake during flood.

[1] *Refer to **Appendix D** for additional September 2011 sampling results.*

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Appendix A

Field Water Quality Data

Site	pH	EC (mS/cm)	Salinity (ppt)	DO (ppm)	Temp (℃)	Depth (cm)	Redox (mV)
DSLM1W	8.44	66.7	46.6	8.47	23.3	62	117
DSLM2W	8.29	70.4	49.5	8.45	26.3	20	85
DSLM3W	8.41	70.1	49.5	7.68	22.1	30	193
DSLM4W	8.26	66.2	46.3	11.02	27.2	25	67
DSLM5W	8.43	58.1	40.6	10.6	25.4	43	144
DSLM6W	8.66	56.0	38.9	7.19	22.0	51	75
DSLM7W	8.44	54.3	36.4	7.06	25.9	41	93
DSLM8W	8.75	53.8	37.1	7.03	25.2	55	108
DSLM9W	8.67	56.1	38.5	7.48	22.9	30	87
DSLM10W	8.73	55.2	37.9	6.46	24.6	11	107

NB: Measurements taken with TPS 90 FLMV field meter (DO refers to dissolved oxygen).

Appendix B

ANOVA Results (Water and Sediment Quality)

Water Quality Results

Parameter	ANOVA Results		Mean Values	
	Significant	p-value	North	South
pH	*	0.025	8.0	8.2
EC	*	0.003	72060	57760
HCO3	NS	>0.05	83.6	74.8
SO4	*	0.001	5884	4872
Ca	*	0	1608	1424
TN	NS	>0.05	1.82	1.94
Chl a	*	0.013	2.4	5
Ba	*	0.005	0.1102	0.0602
Cu	Not normally distributed			
Mn	*	0.02	0.0038	0.0286

Sediment Quality Results

Parameter	ANOVA Results		Mean Values	
	Significant	p-value	North	South
pH	NS	>0.05	7.8	8.1
CO3	NS	>0.05	9.2	11.8
TSS	NS	>0.05	12284	11800
MC	NS	>0.05	33.1	32.8
SO4	NS	>0.05	15040	12616
Si	NS	>0.05	7.1	10.3
Ca	NS	>0.05	5734	4728
TN	NS	>0.05	462	348
TP	NS	>0.05	109	205
TOC	NS	>0.05	0.23	0.19
Ba	Not normally distributed			
Cr	NS	>0.05	7.0	12.6
Fe	NS	>0.05	4766	8134
Mn	NS	>0.05	48.0	118.2
Ni	NS	>0.05	2.8	4.8
V	NS	>0.05	11.9	21.0
Zn	Not normally distributed			

NB: North refers to sites located north of current DSL operations, while south indicates sites located south of current DSL operations.

Appendix C

Aquatic Invertebrates; Selected Taxon Images

Plate 3: Mysidacea specimen from DSLM1W.

Plate 4: Chironomidae specimen from DSLM5W.

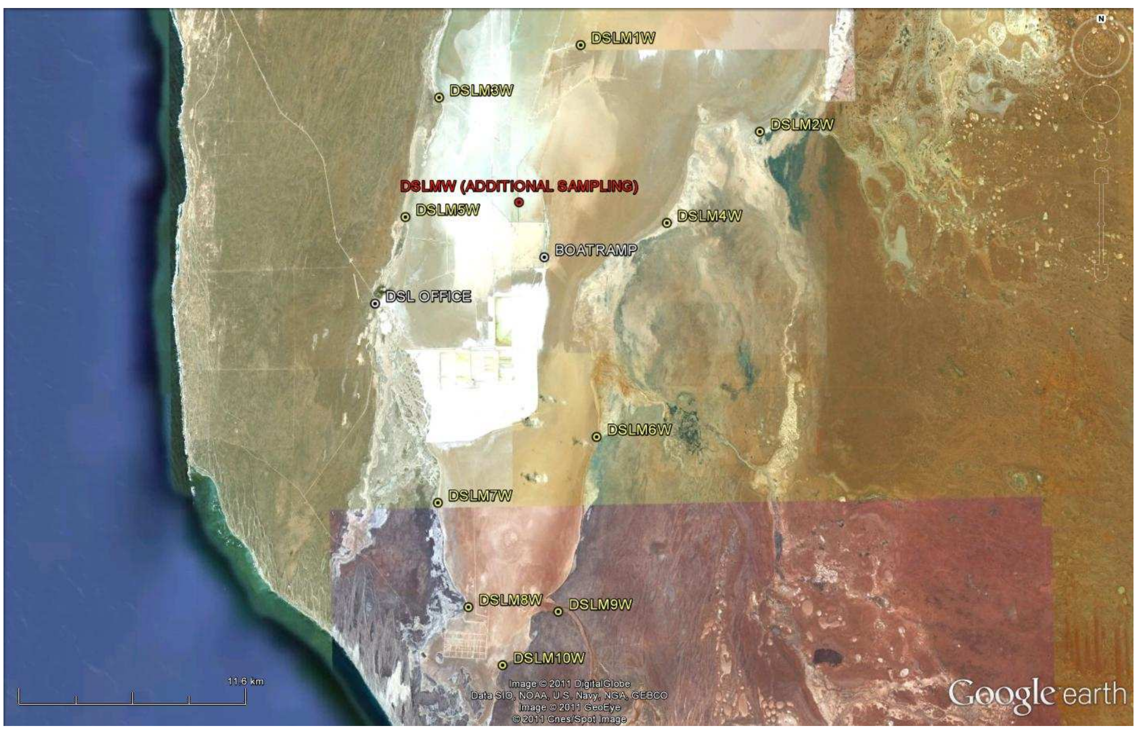
Appendix D

Additional Sampling Results, September 2011

Summary of additional sampling results, September 2011

Due to the extended nature of the flood at Lake MacLeod, DSL personnel obtained additional samples from the lake in September 2011, from one site only (DSLMW). This site differed in location to those previously sampled in May 2011. The results from water and sediment analysis showed that most parameters were within the range recorded from the May sampling event, with the exception of electrical conductivity, anions and cations, and copper concentrations in surface waters. Salts and copper had increased, due to evapoconcentration, as water levels receded. In particular the concentration of copper was more than five times the ANZECC guideline value for the protection of 80 % species in marine waters, although likely attributed to naturally high background levels. All sediment quality data was within the previous range of values recorded for Lake MacLeod. Assessment of algal samples showed that phytoplankton and diatom taxa had mostly been identified from the lake during the May sampling event, although there was a shift in species composition due to elevated salinities, and differences in habitat availability for colonisation. No aquatic invertebrates were collected for comparison. Overall, the September sampling results indicated similarities to May 2011, with changes attributed to receding water levels, and the increased concentration of salts in surface waters.

Location of DSLMW (additional sampling point)



Basic water quality parameters, major ions and nutrients

Analyte	DSLMW
pH (unit)	7.83
EC (µS/cm)	98400
TDS	76400
Na	28800
Mg	3040
Ca	2040
K	1180
Cl	44300
SO_4	4920
Alkalinity	126
HCO_3	126
CO_3	BD
NO_2	BD
NO_3	0.02
NO_2/NO_3	0.02
TKN	2.8
TN	2.8
TP	BD
Chl. *a* (mg/m^3)	3

Metals and trace elements in surface waters

Analyte	DSLMW
As	BD
Ba	0.162
Be	BD
Cd	BD
Co	BD
Cr	BD
Cu	0.043
Fe	BD
Hg	BD
Mn	BD
Ni	0.031
Pb	BD
Si	BD
V	BD
Zn	BD

Basic sediment quality parameters, major ions and nutrients

Analyte	DSLMW
pH (unit)	8.20
Alkalinity	7
TSS	12200
MC (%)	37.7
SO_4	16100
Cl	12100
Ca	6170
Mg	850
Na	7510
K	420
NO_2	BD
NO_3	0.2
NO_2/NO_3	0.2
TKN	120
TN	120
TP	69
TOC (%)	0.09

Metals and trace elements in sediments

Analyte	DSLMW
As	5
Ba	BD
Be	BD
Cd	BD
Cr	4
Co	BD
Cu	BD
Fe	2470
Pb	BD
Mn	22
Ni	BD
V	6
Zn	BD
Hg	BD

Phytoplankton results

Taxon	DSLMW
Bacillariophyta	
Gyrosigma sp.	7
Gomphonema sp.	1
Navicula sp.	2
Cyanophyta	
Nodularia sp.	3
Chlorophyta	
Mougeotia sp.	1
Pseudosphaerocystis sp.	1
Abundance of cells	15
Species diversity	6

Diatom results

Taxon	DSLMW
Bacillariophyceae	
Amphora coffeaeformis	22
Amphora luciae	2
Mastogloia pumila	34
Mastogloia smithii	4
Navicella pusilla	24
Nitzschia punctata	8
Pleurosigma elongatum	6
Abundance of frustules	**100**
Species diversity	**7**