Environment Protection Authority

Water quality in the Lower Lakes during a hydrological drought

Water quality monitoring report

EPA

South Australia

Water quality in the Lower Lakes during a hydrological drought: water quality monitoring report

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Cover picture: Acidified surface water (pH 3) over cracked clays in the Boggy Lake region of Lake Alexandrina

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Abbreviations

CSIRO	Commonwealth Scientific and Industrial Research Organisation
DENR	Department of Environment and Natural Resources
DEWNR	Department of Environment, Water and Natural Resources
EPA	South Australian Environment Protection Authority

Summary

The Murray–Darling Basin has recently experienced the worst drought conditions in over 100 years of records (Timbal 2009). Basin-wide climatic shifts and water management decisions resulted in a period of extreme low river flows (hydrological drought) to the lower reaches of the River Murray and Lower Lakes in South Australia from 2007–09. Average lake levels (–0.38 m AHD Lake Alexandrina, –0.19 m AHD Lake Albert) in the drought period (2007–09) were approximately 1 m lower than the long-term average (0.7 m AHD) and represented a 35% and 55% reduction in water volume respectively. The lowest water levels (–1.05 m AHD Alexandrina, –0.55 m AHD Albert) during the drought were reached in April 2009 and represented a 64% and 73% reduction in lake volume respectively.

Water quality was investigated at 15 ambient sites which were regularly (fortnightly–monthly) monitored from August 2008–July 2010. These sites also incorporate three long-term monitoring sites; two in Lake Alexandrina (Milang and Goolwa), and one in Lake Albert (Meningie). Event-based water quality sampling was also undertaken in selected localised regions that have experienced acidification or are at risk of acidification. The selection of event-based sites was based upon acid sulfate soil risk assessments. The event-based information was required to determine the need for management actions, such as limestone dosing, which has the capacity to reduce the acidity hazard and mitigate further metal release.

The water quality parameters considered in this report were general water quality parameters (salinity, temperature, pH, turbidity), nutrients (total nitrogen, TN; ammonia, NH4; oxidised nitrogen, NOx; total phosphorus, TP; soluble filtered reactive phosphorus, FRP), a measure of total green algae (chlorophyll *a*), algal speciation (at selected sites), dissolved oxygen, colour, dissolved organic carbon, and total and soluble (<0.4 µm) metals (primarily iron and aluminium, but other metals measured during acidification events). Hydrological parameters (river flow, lake level and volume) were also assessed as potential drivers of water quality change.

A complete lack of lake flushing occurred from 2007–09 as no discharge occurred over the barrages to the Coorong and Murray Mouth. This resulted in a concentration of dissolved and particulate material in the lakes driven by evaporation and the associated large reductions in lake volume. Salinity increases were very large, particularly in the southern regions of the lake furthest from the river inflow and closest to the barrages, which leaked seawater into the lakes (due to sea levels being higher than the lakes for much of drought period). As a consequence of these salinity increases, major losses of freshwater species occurred and the water became unsuitable for irrigation. The lack of lake flushing also resulted in the observation of very high concentration of nutrients and algae, and increasing dominance of cyanobacteria. The lake was classed as hyper-eutrophic during the low flow period. Turbidity also increased during the drought period (particularly in Lake Albert) due to concentration of particulate material and increased wind resuspension.

Several surface water acidification events also occurred during the 2008–10 drought period. These areas were on the shallow lake margins, often in embayments which have limited connection with the main lake water body. The total area that acidified was estimated to be 2,173 ha, which represented about 3% of the Lower Lakes surface water area. Different severities and durations (ranging from weeks to months) of acidification were observed. Neutralisation of acidification was accomplished naturally in several areas by dilution and alkalinity input following a rapid rise in lake levels following Murray–Darling Basin floodwater inflows during 2010. Treatment of acidification via aerial limestone addition occurred in two areas, Currency Creek and Boggy Lake, and was highly successful in achieving neutralisation over large areas. Additional limestone barriers were placed in the acidified regions of Upper Finniss River.

Further assessment of water quality during future low flow events is recommended in our study area, as well as the time period for recovery from the recent event. Along with many other arid and semi-arid river systems, median river flows in the southern Murray–Darling Basin are predicted to decline further (13% decrease by 2030) over the next 20 years due to climate change. Hence extreme low flow periods will likely become more frequent and intense in these vulnerable systems. Careful water resource planning and management will be required to prevent water quality deteriorating to the point where socio-economic and environmental values are threatened. The findings in this report strongly support that a substantial increase in environmental flows are required to maintain system flushing, water levels and quality in the lower reaches of the system during low flow conditions.

1 Introduction

The Murray–Darling Basin has recently experienced the worst drought conditions in over 100 years of records (Timbal 2009). Basin-wide climatic shifts and water management decision resulted in a long period (2007–09) of extreme low flows (hydrological drought), in the lower reaches of the river system in South Australia. The Lower Lakes (Alexandrina and Albert) are located at the end of the freshwater portion of the Murray–Darling Basin. These lakes support several important socio-economic and aquatic ecosystem values, termed environmental values. This region contains the townships of Goolwa, Milang and Meningie and several smaller communities. It is also contains several large irrigated agricultural areas, including major vineyards (Langhorne and Currency Creeks) and dairy farming. The lakes are also an important recreational area for activities such as sightseeing, swimming, boating, fishing, and bird watching. The Lower Lakes and Coorong area is recognised as one of Australia's most significant ecological assets and is designated a wetland of international importance under the *Ramsar Convention* (Phillips et al 2005). This area is also of high cultural importance, particularly for the indigenous Ngarrindjeri people (Ngarrindjeri 2006). The protection of the environmental values of the Lower Lakes depends on maintaining suitable water quality.

The primary aim of this report is to assess the water quality changes in the Lower Lakes that have occurred during the severe hydrological drought of 2007–09. Longer-term water quality changes are also assessed.

Currency Creek region during the 2007–09 drought period showing exposed and acidified sediment areas (Source: DENR 2009).

2 Methods

Description of the Murray–Darling Basin and Lower Lakes study area

The study area comprised the two lakes, Albert and Alexandrina, collectively known as the Lower Lakes (Figure 1). These lakes comprise the most downstream freshwater region of the Murray–Darling Basin which is Australia's largest river system with a total catchment area of 1,061,469 km^2, equivalent to 14% of Australia's total area. Most of the Basin is situated in extensive arid to semi-arid plains with a low undulating topography, mostly below 200 metres above sea level. The catchment is characterised by low rainfall and runoff and susceptibility to drought (Murphy and Timbal 2008). Since the early 20th century, Basin-wide water resource development for agriculture and flow regulation has reduced total river flow at the Murray River Mouth by 61% and the river now ceases to flow through the mouth 40% of the time compared to 1% of the time in the absence of water resource development (CSIRO 2008). Surface water availability is predicted to decline further in the southern part of the Basin over the next 20 years due to climate change—median of 13% decrease by 2030 (CSIRO 2008).

The three major river systems in the Murray–Darling Basin are the Darling (2,740 km), Murray (2,530 km) and Murrumbidgee (1,690 km) which are Australia's three longest rivers. A series of locks, weirs and storages regulate water flows throughout the Murray–Darling Basin. There are no major tributaries to the Murray River downstream of Lock 1, which is the last river regulating structure along its reach. Below Lock 1, the Lower Murray River flows for approximately 250 km before discharging into the Lower Lakes which are the end of the freshwater region of the Murray–Darling Basin.

The Lower Lakes are large (821.7 km^2 total surface area) and very shallow. Lake Alexandrina (650.2 km^2), the deeper of the two lakes, has a maximum depth of approximately 4.1 m and a mean depth of 2.9 m at full capacity (Geddes 1984). Lake Albert (171.5 km^2) is much shallower with a maximum depth of approximately 2.3 m and a mean depth of 1.4 m at full capacity. Wind action over the large fetch on these lakes typically results in a highly turbid system with little stratification (Geddes 1984, Aldridge et al 2009). The Lower Lakes are eutrophic, with high retention of fluvial nitrogen and phosphorus, low concentrations of soluble nutrients, high productivity and periodic toxic algal blooms (Geddes 1984, Cook et al 2010). Under sufficient flows, water exits from the Lower Lakes over a series of barrages separating the lakes from the Coorong (a coastal lagoon), Murray River Mouth and Southern Ocean (see Figure 1). The barrages are gated structures completed in the late 1940s to prevent seawater intrusion into the lakes as water resource development in the Murray–Darling Basin began to exacerbate this effect. The sediment diatom record demonstrates that these lakes were predominantly freshwater systems over the last several thousand years (Fluin et al 2007) and the barrages have maintained relatively low salinity conditions during the 20th century.

Several government management actions have taken place in the study area from 2008–09. These included:

- the construction of a temporary bund in the Narrung Narrows in March 2008 in order to pump water (April 2008–June 2009 170 GL, January 2010–June 2010 90 GL) from Lake Alexandrina to maintain water levels above –0.5 m AHD in Lake Albert
- construction of temporary flow regulators in July 2009 at Clayton and Currency Creek and pumping (27.5 GL September–November 2009) from Lake Alexandrina which coupled with retention of Currency Creek and Finniss River tributary flows behind the regulators aimed to raise water levels in the Goolwa channel above +0.7 m AHD
- revegetation of large areas of exposed lake bed.

The major objective of these projects has been to prevent the further exposure of, or to remediate, acid sulfate soils as water levels declined and exposed large areas on the lake margins (Fitzpatrick et al 2008, 2010). The exposure to oxygen and subsequent oxidation of pyrite (FeS_2) in acid sulfate soils generates acidity (hydrogen ions, dissolved iron and aluminium) in the upper soil profile. If severe acid conditions (pH<4) develop in the soil, precipitation of secondary acidic minerals (eg Jarosite) often occurs and weathering of alumino-silicate (eg clay) minerals is enhanced. High concentrations of soluble aluminium are a common outcome of this weathering process. The rewetting of acid sulfate soils can mobilise acidity and metals into the water column (Simpson et al 2010).

Following return of substantial River Murray inflows to the Lower Lakes, the Narrung bund was partially breached 19 September 2010 and the two lakes equalised at +0.73 m AHD on 12 October 2010. The Goolwa Channel temporary flow regulator was partially breached on 25 September 2010.

Samples sites and water quality parameters

Water quality was investigated at 15 ambient sites which were regularly (fortnightly–monthly) monitored from August 2008–July 2010 (Fig. 1). These sites also incorporate three long-term monitoring sites; two in Lake Alexandrina (Milang and Goolwa), and one in Lake Albert Meningie which in some cases have records back to the 1970s (Figure 1). Event-based water quality sampling was also undertaken in selected localised regions that have experienced acidification or are at risk of acidification. The selection of sites was based upon acid sulfate soil risk assessment, in accordance with available data on the distribution of sulfidic and sulfuric materials as well as research and modelling into potential acidity fluxes. High risk locations were initially screened to identify the presence and extent of any acidity, and the frequency of further monitoring was determined from these results. The information is used to determine the need for management actions, such as limestone dosing, which has the capacity to reduce the acidity hazard and mitigate further metal release. All water quality data was extracted from the EPA water quality database.

The water quality parameters considered in this report were general water quality parameters (salinity, temperature, pH, turbidity), nutrients (total nitrogen, TN; ammonia, NH4; oxidised nitrogen, NOx; total phosphorus, TP; soluble filtered reactive phosphorus, FRP), a measure of total green algae (chlorophyll *a*), algal speciation (at selected sites), dissolved oxygen, colour, dissolved organic carbon, and total and soluble (<0.4 µm) metals (primarily iron and aluminium, but other metals measured during acidification events). Hydrological information (river flow, water level) data downstream of Lock 1 was obtained from the Department for Water (South Australia). Annual Murray–Darling Basin rainfall was obtained from the Australian Bureau of Meteorology website.

A brief description of some of the key water quality parameters

pH is an indicator of acidity or alkalinity. Neutral water has a pH of 7, acidic solutions have lower values and alkaline solutions have higher values.

Alkalinity is a measure of the buffering capacity of water, or the capacity of the water to neutralise acids and resist pH change. Alkalinity within water bodies is consumed as acid released from acid sulfate soils. Adding limestone contributes alkalinity to waters, helping to neutralise any acid released from the sediments.

Salinity is a measure of the amount of dissolved salts in the water. Saline water conducts electricity more readily than freshwater, so electrical conductivity (EC, µS/cm) is routinely used to measure salinity. As salinity increases, it may become toxic to native freshwater organisms.

Major ions such as calcium, magnesium, sodium, chloride and sulfate are the components that comprise the salinity of the water. The sulfate:chlorideratiois used to give an indication of any sulfate inputs to the water body from acid sulfate soils. Chloride concentration is largely determined by evaporation and dilution. An increase in the ratio of sulfate:chloride indicates likely external sulfate inputs from acid sulfate soils.

Turbidity is a measure of the cloudiness or haziness in water caused by suspended solids (eg sediment, algae). Turbidity is expressed in nephelometric turbidity units (NTU) and is measured using a relationship of light reflected from a given sample. Turbidity is very variable in the Lower Lakes and influenced primarily by wind events.

Nutrients are total nutrients (total nitrogen, TN and phosphorus, TP) and dissolved nutrients (ammonia, NH_4; oxidised nitrogen (nitrate and nitrite), NO_x; filtered reactive phosphorus, FRP). Nitrogen can be present in different forms (eg organic nitrogen in plant material, ammonia, nitrate and nitrite). Phosphorus can also be present in different forms (eg organic phosphorus, phosphate/FRP). TN and TP are the total amount of nitrogen and phosphorus present respectively in the water body and high concentrations indicate excessive growth (or eutrophication) of aquatic plants such as phytoplankton, cyanobacteria, macrophytes and filamentous algae. The availability of soluble nutrients, in particular FRP, determine rates of algal growth.

Chlorophyll a is the main photosynthetic pigment in green algae. The concentration of chlorophyll gives an indication of the volume of aquatic plants present in the water column. Levels in excess of 15 µg/L are considered very high (hyper-eutrophic) and nuisance algae and plant growth can occur (ANZECC 2000).

Metals such as iron and aluminium are measured primarily to determine interactions between sediments and the lake water body. During concentration events (ie evaporation and low inputs) volumes of metals are expected to increase. Similarly during large wind events total metal levels might also increase as they form part of the suspended solids composition. Alternatively during floodwater inflows the concentration of metals may be diluted. Additional to this, if exposed acid sulfate sediments acidify and the soil pH is reduced, metals that have been previously unavailable and bound up within sediment are released. Any subsequent increase in metal concentration in the water body can be used as an indicator of acid sulfate soil impacts.

Dissolved oxygen is a measure of the quantity of oxygen gas dissolved in the water. Aquatic animals, plants and many bacteria need oxygen for respiration, as well as for some biogeochemical reactions. A low level of dissolved oxygen is harmful to aquatic life and can result in major ecosystem impacts such as fish kills. Oxygen is replenished primarily from the atmosphere and this process is enhanced by wind-mixing.

Sampling and analytical methods

Grab sampling at the Lower Lakes sites (Figure 1) were collected at the shoreline or from vessels (boat, hovercraft). New sample bottles, washed and rinsed with deionised water, were used for all analyses. Samples were collected by rinsing the bottle with the sample, and collecting the sample according to standard methods (APHA 2005 and previous editions). Following collection, the water samples were transported to the Australian Water Quality Centre (AWQC) laboratory in Adelaide in ice-filled cooler boxes and then stored at 4ºC. AWQC is a National Association of Testing Authorities (NATA) accredited laboratory. The laboratory has been accredited for chemical testing since 1974 which covers almost the entire dataset used in this study. NATA accreditation requires maintenance and documentation of strict quality control procedures.

Temperature, pH, ORP, EC and dissolved oxygen were measured at the time of sample collection using calibrated instruments. Total alkalinity in the field and laboratory was measured by titration to a pH 4.5 end-point. The field titrations were performed using a commercially available test kit (HACH model AL–DT). Acidity in the laboratory was measured by titration to pH 8.3 at 25^{o}C following hot peroxide digestion. Acidity in the field was measured using a commercially available test kit (HACH model AC-DT). Salinity was measured according to manufacturers' instructions using calibrated conductivity meters. Turbidity was measured by a nephelometer. Water samples for dissolved nutrients (NH4, NOx, FRP) were filtered through 0.45 µm membrane filters immediately following collection. All nutrient samples were kept refrigerated at 4ºC and analysed within seven days as per standard colorimetric methods (APHA 2005 and earlier additions). Water alkalinity was measured by titration with a pH 4.5 end-point for total alkalinity (APHA 2005 and earlier editions). Dissolved oxygen was measured by both a TPS90 oxygen probe and a YSI field probe. Dissolved organic carbon samples were analysed through very high temperature combustion using a Shimadzu VCHS. Colour was analysed through spectrophotometric methods (at 456 nm). Total and dissolved (<0.4 µm) metal concentrations were measured by ICP-Mass Spectrometry.

Data analysis

Non-parametric summary statistics were calculated for the water quality data. The median value was used to summarise the centre of the dataset and the interquartile range (IQR, 75th percentile minus the 25th percentile) used to represent the data spread.

In order to make statistical comparisons of the current drought water quality with the long-term dataset, it was necessary to define hydrological drought and reference periods. Monthly flow duration curves were produced from the daily river flow record at Lock 1 for the period 1970–2010 (Figure 2, data provided by the Department for Water, South Australia). The flow duration curve plots the cumulative frequency of river flow as a function of the percentage of time that the flow is exceeded. The 90th percentile flow (Q_{90}) was used as the monthly flow threshold for drought conditions, as recommended for non-ephemeral river systems by Hisdal et al (2004). This approach revealed a threshold monthly flow of 54.5 GL, with a 33-month hydrological drought period defined from March 2007–November 2009.

The March 2003–November 2005 period was defined as the non-drought reference period. This reference period is the same length as the drought period but contains flows within the interquartile range and is thus representative of long-term average flow conditions (Figure 2). However, this reference period does not contain any of the higher winter–spring flow peaks (above Q_{25}) that were a feature prior to 2000 and this illustrates the recent decadal scale climatic and hydrological shifts that have occurred in the Murray–Darling Basin (Ummenhofer et al 2010). The relatively short time period between the reference and drought periods minimises the likelihood that any landuse or water regulation changes in the catchment have impacted on water quality patterns.

The significance of differences in water quality between the drought and reference periods was determined using the non-parametric Mann-Whitney U test (Helsel and Hirsch 2002). These tests were performed in the Microsoft Excel add-in program XLSTAT^{TM} with statistical significance ascribed to p values less than 0.05. As this test is based on ranks, any of the dissolved nutrient data below the detection limit was able to be treated as the value of the detection limit in the statistical test. Some of the sites had insufficient datasets to enable statistical comparisons for all parameters.

Water quality sampling in the Upper Currency Creek region in 2009

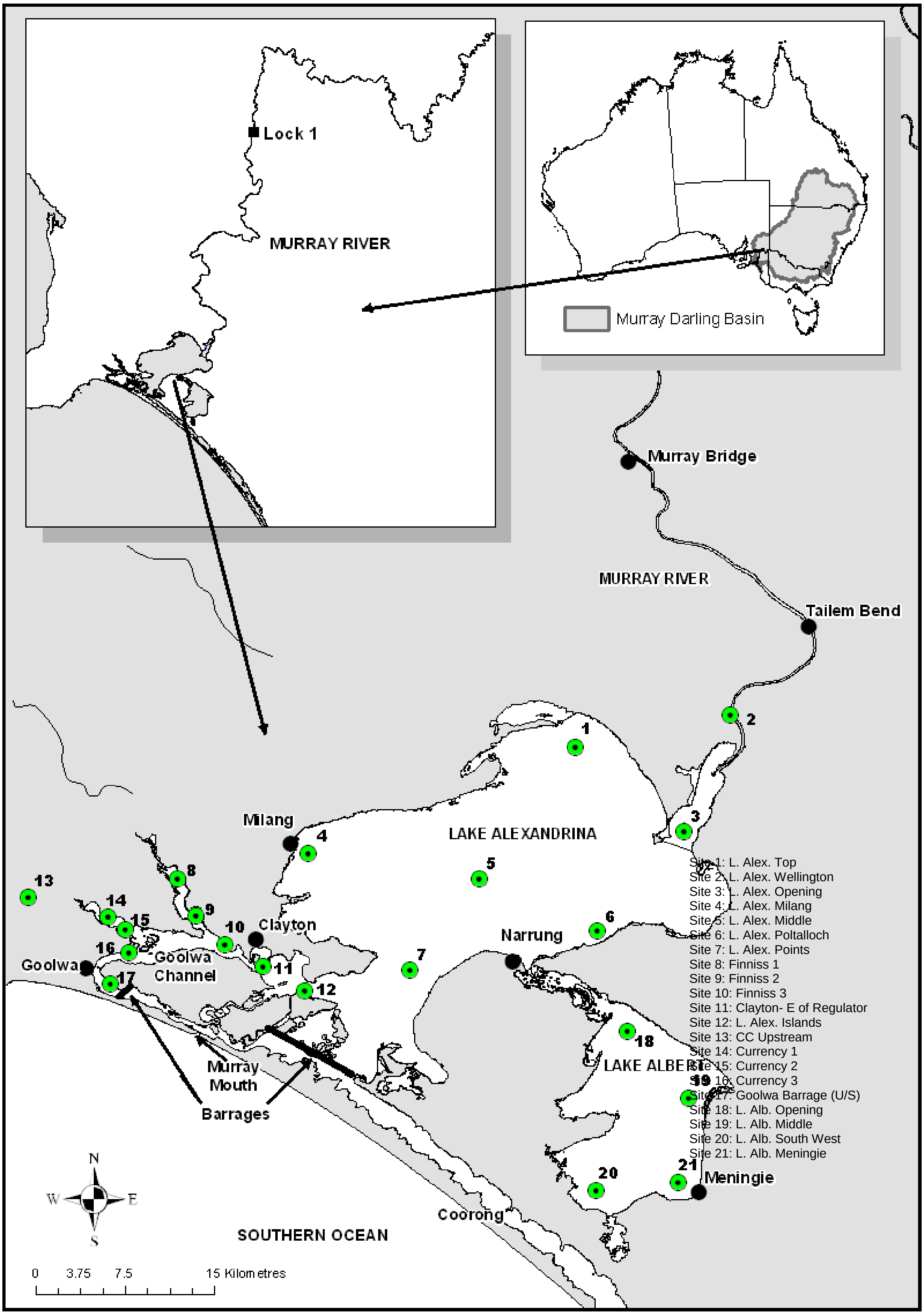


Figure 1 **Sampling sites (green dots) within the Lower Lakes study area and the Murray–Darling basin. Also shown are the townships (black dots), flow and water level monitoring station at Lock 1, the barrages and Murray Mouth. Additional telemetry data stations can be found at the website <www.waterconnect.sa.gov.au/RMWD>**

3 Results

Hydrology

River Murray flow at Lock 1 was extremely low during 2007–09 (Figure 2), approximately one-tenth of the long-term average flows (MDBA 2010). The water levels in the Lower Lakes fell substantially from 2007 to late 2009 as a consequence of the low river inflows (Figure 2). Average lake levels (–0.38 m AHD Alexandrina, –0.19 m AHD Albert) in the drought period (2007–09) were approximately 1 m lower than the long-term average (0.7 m AHD) and represented a 35% and 55% reduction in water volume respectively. The lowest water levels (–1.05 m AHD Alexandrina, –0.55 m AHD Albert) during the drought were reached in April 2009 and represented a 64% and 73% reduction in lake volume respectively.

Figure 2 also shows the water level in Lake Alexandrina, Lake Albert and the Goolwa Channel during the drought period illustrating hydrological disconnection (except for pumping) from March 2008 for Lake Albert (disconnected from Alexandrina) and from July 2009 for the Goolwa Channel (disconnected from Lake Alexandrina at Clayton). Both these regions were at risk of almost completely drying out prior to these projects being implemented.

Due to floods in the Darling River system, an increase in river flows occurred in December 2009 (Figure 2). This was followed by floods in the Murray River system to mid-2010. The combination of these two events resulted in a rapid recovery of water levels in the Lower Lakes (Figure 2).

Lake Alexandrina

The water quality in Lake Alexandrina between 2008 and 2010 is summarised in Tables 1–3 and Figures 3–10. Salinity levels followed a general increasing trend during the drought period, with slight decreases during winter months, until a substantial dilution and flushing from river floodwater inflows occurred from late 2009 (Figure 3). During the drought a distinct spatial variation in salinity was observed (Figure 3) with very high levels in the southern regions of the lake (Pt McLeay site, and Goolwa and Tributaries) grading to lower levels at (Wellington, Opening) and near the River Murray entrance (Poltalloch and Top sites). Following the increased river inflows in 2010 this spatial variation was accentuated.

Alkalinity remained quite stable at high levels with relatively little spatial variation until late 2009. From this time the inflowing flood waters had low alkalinity levels and resulted in a dilution of alkalinity and greater spatial variability across Lake Alexandrina. pH exhibited some minor temporal and spatial variability with an increase occurring in late 2009 corresponding to the arrival of floodwaters and refill of the lake. The pH subsequently decreased at several sites as the lower pH in the inflowing flood water mixed with the lake water.

Temperature was similar at all sites with a distinct seasonal variation (Figure 3). Turbidity was at high levels and showed a great deal of variability, particularly at the Milang site.

The nutrients and chlorophyll *a* concentrations in Lake Alexandrina are shown in Table 2 and Figures 4–5. Total nitrogen, total phosphorus and chlorophyll *a* followed a general increasing trend over the drought period, until a substantial dilution from River Murray floodwater inflows occurred from late 2009. During 2009 there was quite a large spatial variation apparent in total nutrient levels, with lower levels at or near the river inflow sites. Soluble nutrients (ammonia, oxidised nitrogen and filtered reactive phosphorus) remained at very low levels throughout the monitoring period apart from higher levels in the river inflows. Chlorophyll *a* showed minimal spatial variation and no clear seasonal trends (Figure 5). The phytoplankton population was dominated by blue-green algae (cyanobacteria), predominantly Planktolyngbya species (Figure 6). Green algal species showed some increases in late 2009, coinciding with increased floodwater inflows to the Lower Lakes and diatoms show seasonal trends (highest in winter).

Dissolved oxygen was maintained at near-saturation (7–8 mg/L) through the drought in Lake Alexandrina, with slightly lower levels at the Wellington site representing the River Murray inflow (Figure 7). Colour shows little seasonal variation but a large increase is seen at the sites closest to the river in late 2009 to 2010, representing the inflow of floodwaters from the Murray–Darling Basin (Figure 7). Dissolved organic carbon was only measured in 2009 but shows a seasonal variation peaking in the summer months.

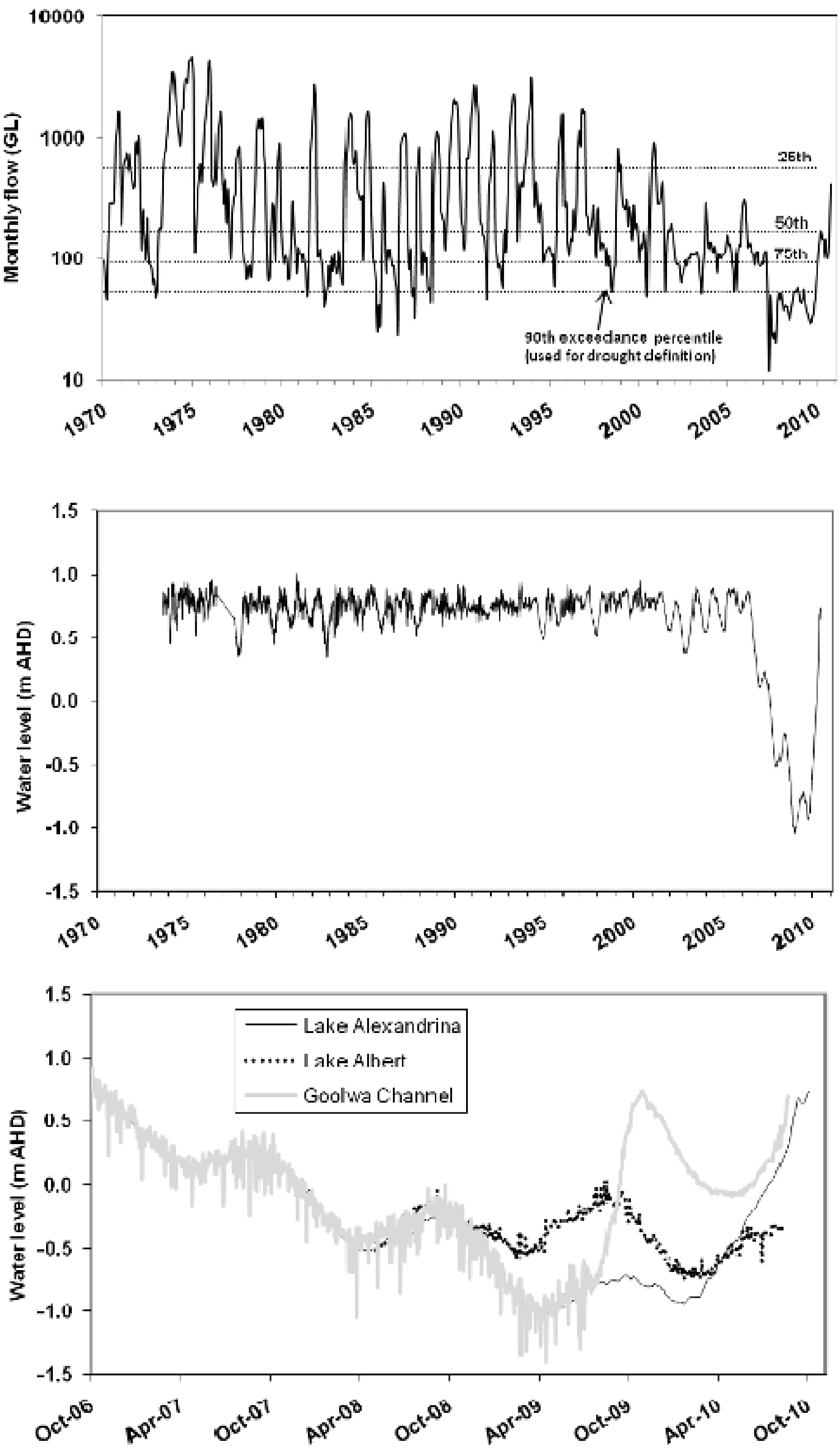


Figure 2 River Murray monthly flow over Lock 1 (TOP) and water level in Lake Alexandrina from January 1970–October 2010 (MIDDLE), and water level in Lake Alexandrina, Lake Albert and the Goolwa Channel during the drought period illustrating hydrological disconnection (BOTTOM). The 25th, 50th, 75th and 90th (used for drought definition) flow exceedance percentiles are displayed on the flow plot (note log scale). Source: DEWNR data.

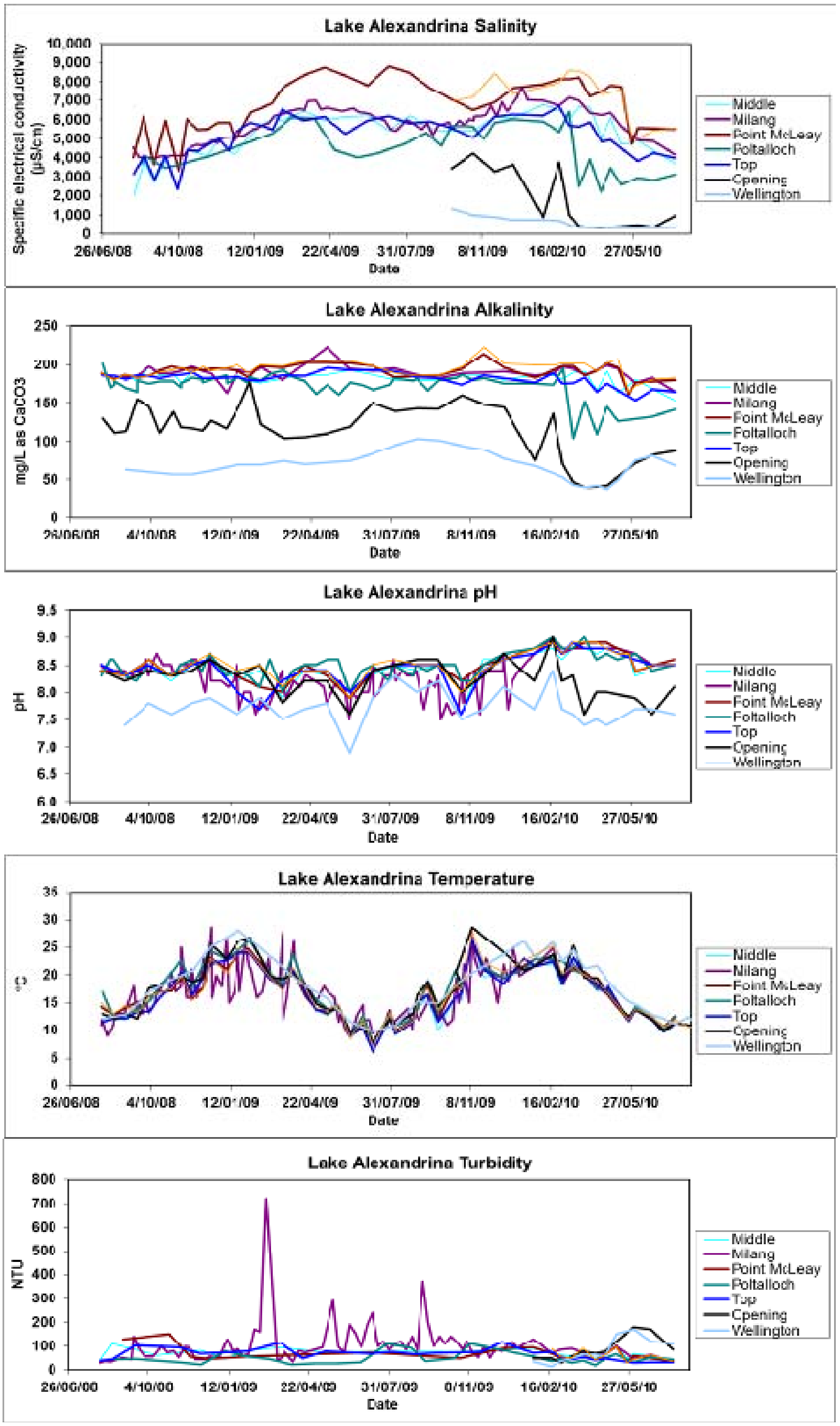


Figure 3 Lake Alexandrina – general water quality parameters

Table 1 Lake Alexandrina – summary statistics for general water quality parameters

Parameter	Statistic	Middle	Milang	Points	Poltalloch	Top	Wellington	Opening	Islands
Salinity (µs/cm)	median	5,410	5,865	6,900	4,530	5,385	360	943	7,320
	25th percentile	4,360	5,098	5,830	3,643	4,370	322	357	359
	75th percentile	6,090	6,385	7,790	5,638	5,915	762	3,393	5,888
	no of samples	37	86	38	32	36	15	14	15
Alkalinity (mg/L)	median	184	190	193	177	183	69	118	196
	25th percentile	180	186	186	169	179	57	100	187
	75th percentile	187	194	197	182	186	77	142	201
	no of samples	37	36	38	54	36	29	36	37
pH	median	8.5	8.3	8.5	8.5	8.5	7.7	8.3	8.5
	25th percentile	8.3	8.0	8.3	8.3	8.4	7.6	8.0	8.4
	75th percentile	8.7	8.5	8.8	8.6	8.6	7.9	8.4	8.7
	no of samples	30	101	31	47	29	29	29	30
Temperature (°C)	median	16.3	16.0	16.9	17.4	16.4	16.9	16.9	16.5
	25th percentile	12.4	13.0	13.1	13.0	12.2	12.8	12.4	13.2
	75th percentile	19.9	20.0	20.1	21.1	19.9	21.2	19.6	19.9
	no of samples	49	120	47	46	48	37	52	54
Turbidity (NTU)	median	72	86	57	43	67	63	73	56
	25th percentile	60	56	47	31	44	42	51	43
	75th percentile	81	118	81	53	76	115	82	76
	no of samples	23	26	19	28	26	11	10	11

Table 2 Lake Alexandrina – summary statistics for nutrients and chlorophyll *a*

Parameter	Statistic	Middle	Milang	Points	Poltalloch	Top	Wellington	Opening	Islands
Total Nitrogen (mg/L)	median	2.85	3.08	2.66	2.19	2.88	0.7	1.45	2.78
	25th percentile	2.44	2.27	2.24	1.80	2.29	0.61	1.04	2.25
	75th percentile	3.15	3.58	3.02	2.71	3.19	0.80	1.88	3.47
	no of samples	29	29	30	51	28	26	28	29

Parameter	Statistic	Middle	Milang	Points	Poltalloch	Top	Wellington	Opening	Islands
Ammonia (as N mg/L)	median	0.009	0.008	0.008	0.008	0.011	0.017	0.010	0.008
	25th percentile	0.007	0.007	0.006	0.006	0.007	0.010	0.005	0.005
	75th percentile	0.015	0.02	0.011	0.012	0.015	0.025	0.015	0.012
	no of samples	21	21	22	21	21	20	21	22
Oxidised Nitrogen (as N mg/L)	median	0.005	0.006	0.008	0.005	0.006	0.036	0.005	0.005
	25th percentile	0.005	0.005	0.006	0.005	0.005	0.01725	0.005	0.005
	75th percentile	0.01	0.008	0.011	0.008	0.010	0.079	0.007	0.006
	no of samples	19	19	20	41	19	18	19	19
Total Phosphorus (mg/L)	median	0.190	0.241	0.161	0.148	0.193	0.059	0.120	0.182
	25th percentile	0.156	0.173	0.149	0.116	0.151	0.055	0.094	0.137
	75th percentile	0.223	0.292	0.201	0.189	0.211	0.087	0.159	0.249
	no of samples	30	30	31	52	29	31	29	30
FRP (as P mg/L)	median	0.005	0.005	0.005	0.005	0.005	0.009	0.005	0.005
	25th percentile	0.005	0.005	0.005	0.005	0.005	0.008	0.005	0.005
	75th percentile	0.006	0.005	0.005	0.006	0.005	0.013	0.005	0.005
	no of samples	30	30	31	50	29	29	29	30
Chlorophyll *a* (µg/L)	median	69.9	60.0	76.1	48.1	66.4	12.3	24.9	70.5
	25th percentile	64.1	46.8	66.6	38.3	53.5	7.0	16.5	56.2
	75th percentile	79.5	69.3	91.8	73.0	76.1	17.4	38.2	117.0
	no of samples	11	30	11	21	11	12	11	11

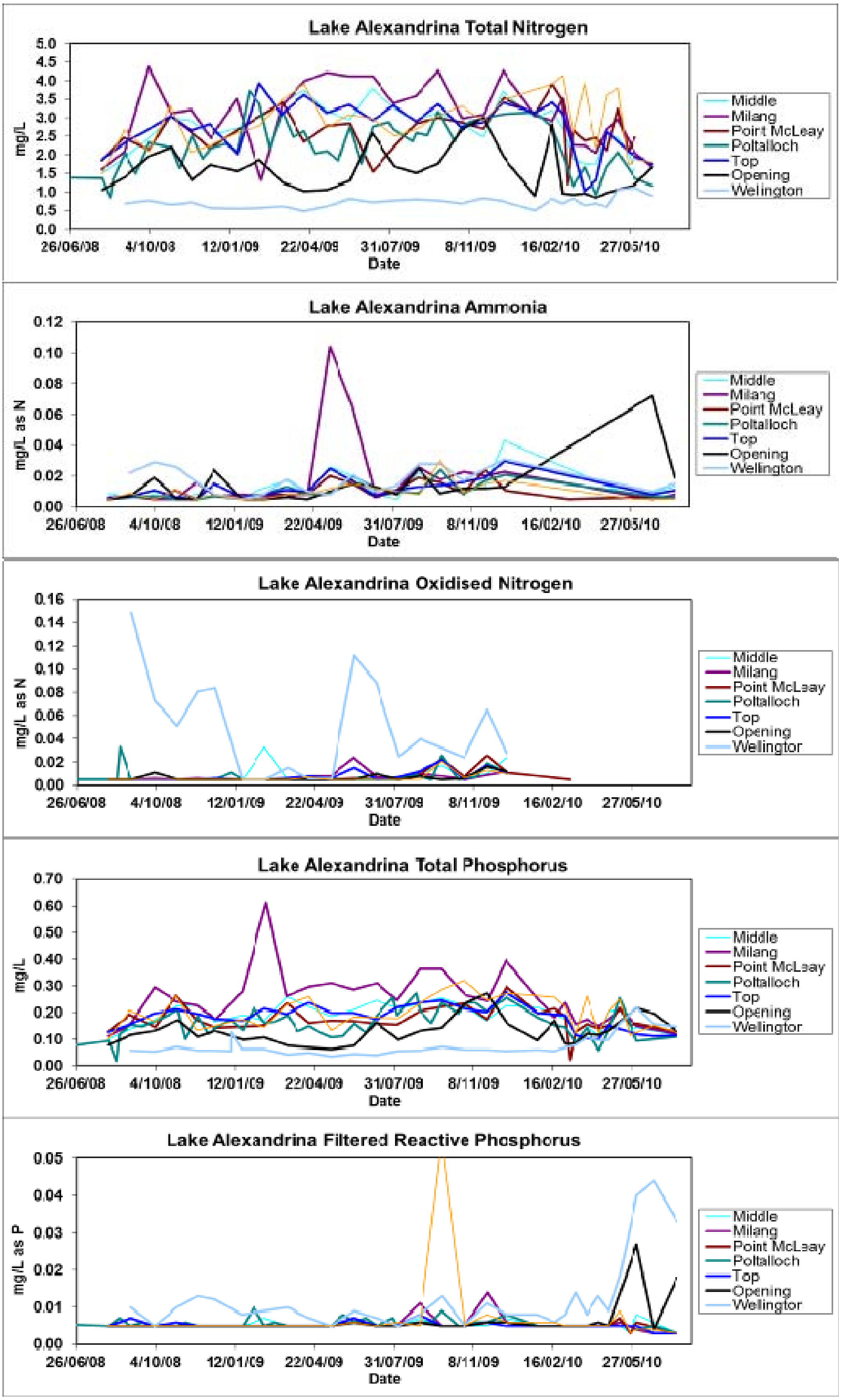


Figure 4 Lake Alexandrina – nutrients

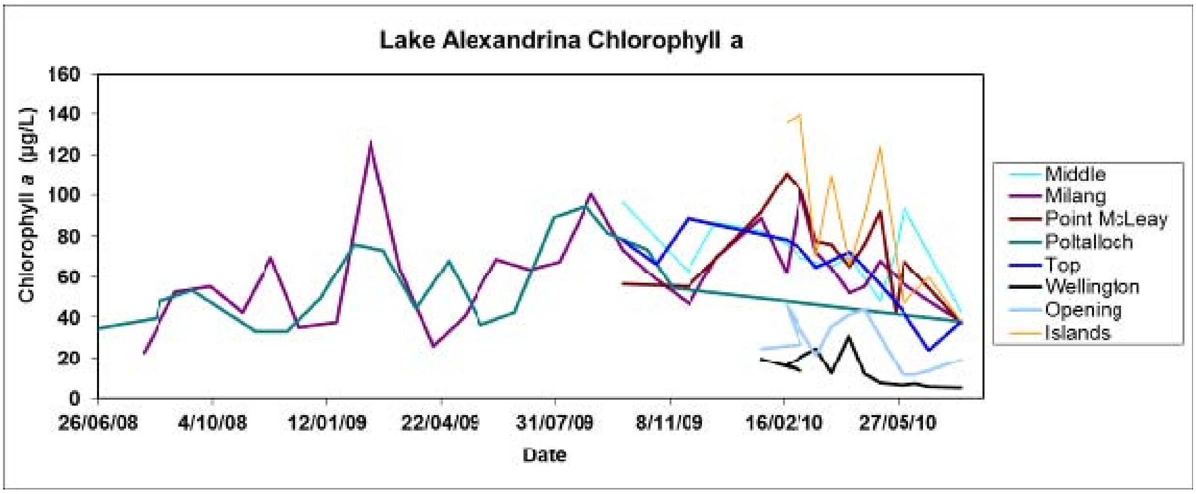


Figure 5 Lake Alexandrina – chlorophyll *a*

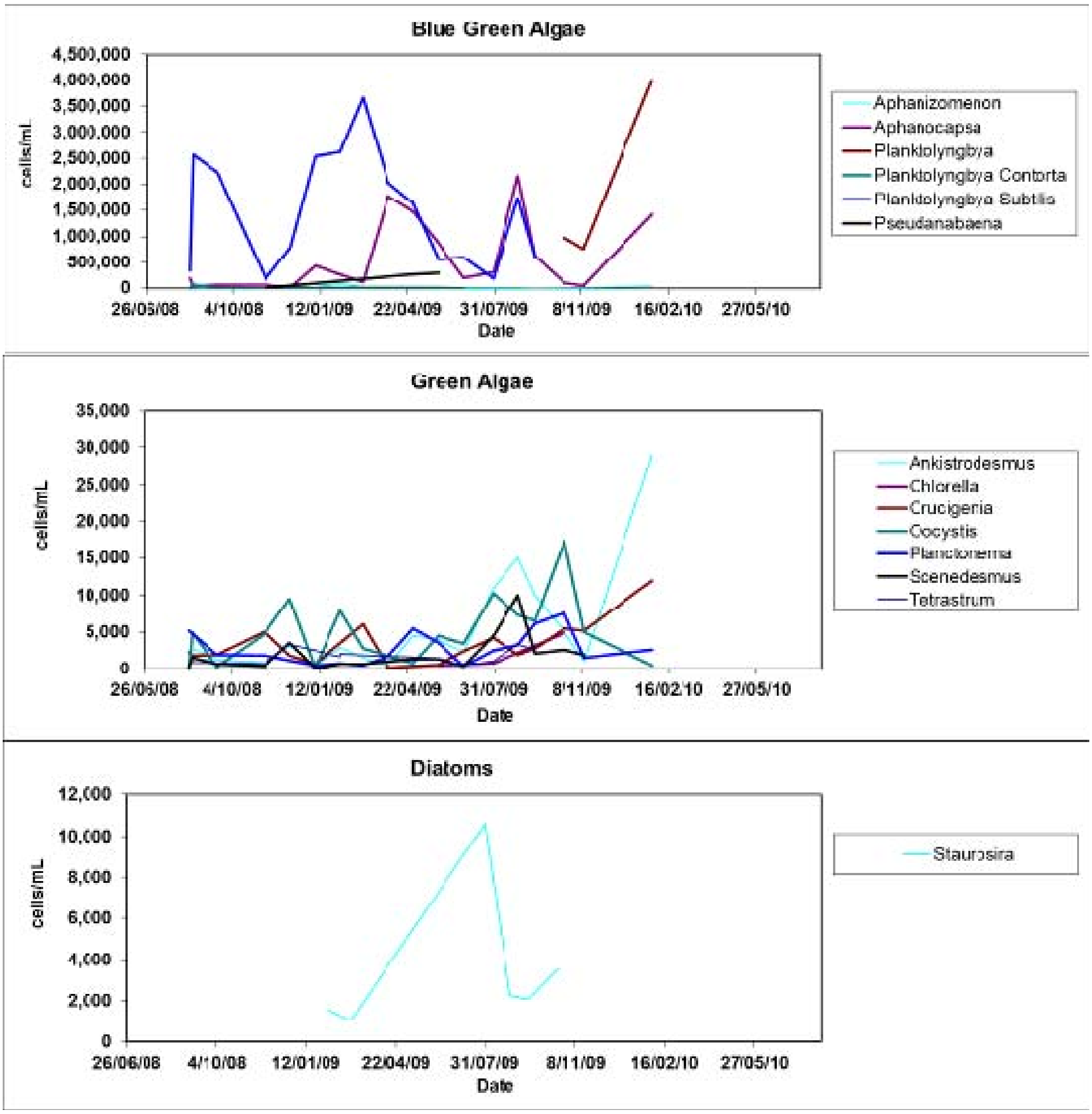


Figure 6 Lake Alexandrina – algal speciation (Poltalloch Plains)

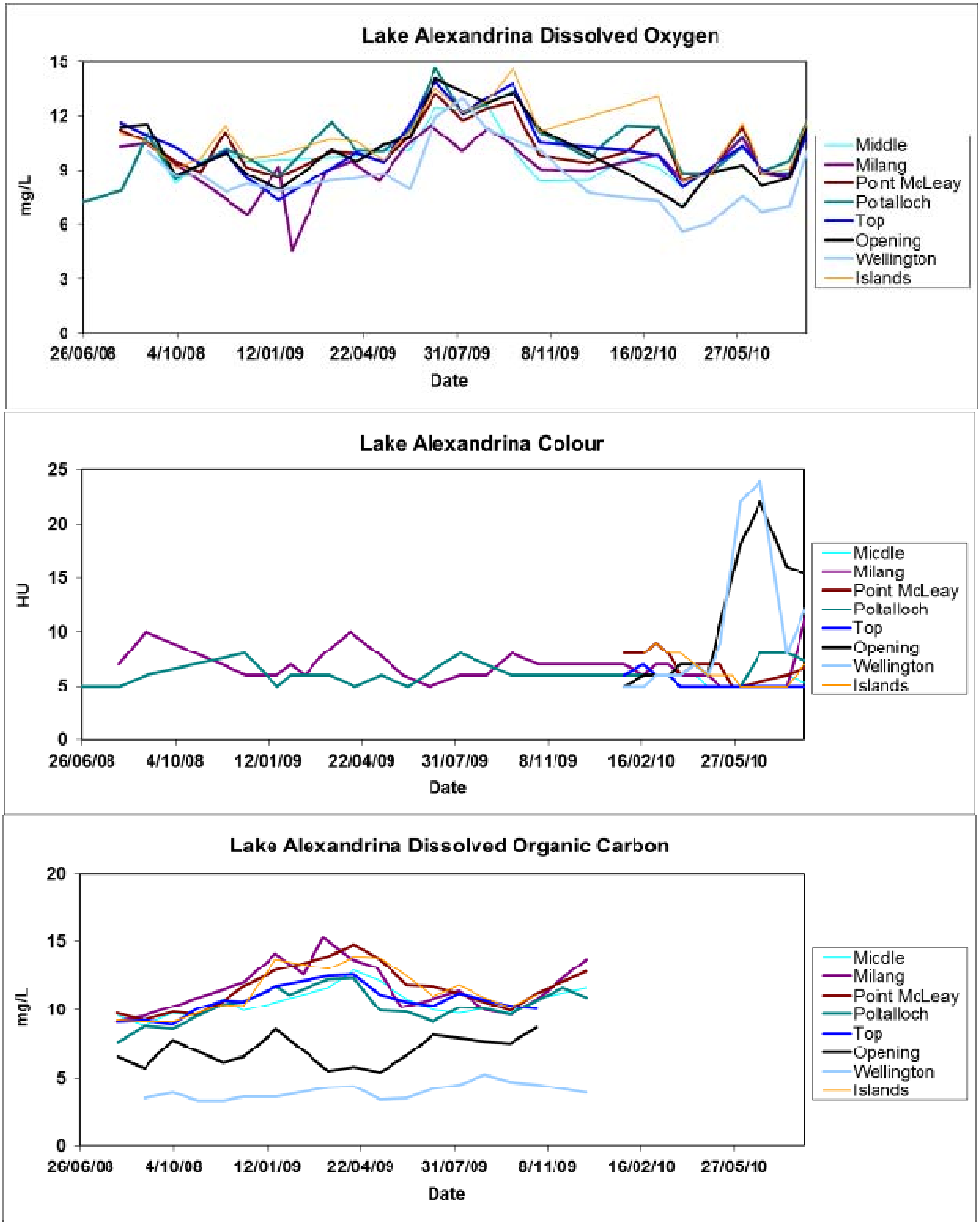


Figure 7 **Lake Alexandrina– dissolved oxygen, colour, dissolved organic carbon**

The concentration of major ions over the drought period is shown in Figure 8 and Table 3. As expected major ions followed a similar trend to salinity, with slight decreases during winter months, until a substantial dilution from river floodwater inflows occurred from late 2009. Similar spatial patterns to salinity were also observed with lower major ion levels in the northern regions of the lake and higher levels in the southern region. The concentration of major ions versus the concentration of chloride is shown in Figure 9. Most major ions showed a linear increasing trend with chloride concentration. The exception to this was bicarbonate which only showed increases in the northern lake region during the early drought period. Although calcium showed an initial increasing trend, the slope of this increase levelled off to be much less than for the other major cations (magnesium, potassium, sodium).

The sulfate:chloride and alkalinity:chloride ratio are shown in Figure 8. The sulfate:chloride ratio was stable until the flood water inflows resulted in some minor decreases and one unexplained downwards spike at Poltalloch. The alkalinity:chloride ratio showed temporal (decreases over summer and increases over winter) and spatial (higher in northern regions) variations.

Table 3 Lake Alexandrina – summary statistics for major ions and metals

Parameter	Statistic	Middle	Milang	Points	Poltalloch	Top	Wellington	Opening	Islands
Calcium (mg/L)	median	61	66	73	56	62	19	38	75
	25th percentile	56	64	69	48	58	15	19	69
	75th percentile	65	70	82	59	67	21	46	86
	no of samples	27	10	30	27	28	28	28	29
Magnesium (mg/L)	median	116	148	166	95	123	16	54	161
	25th percentile	98	129	121	74	106	9	19	119
	75th percentile	143	162	186	112	138	18	72	195
	no of samples	27	10	30	27	28	28	28	29
Potassium (mg/L)	median	34	42	46	27	34	5	15	48
	25th percentile	30	31	37	22	30	3	7	35
	75th percentile	40	45	51	33	38	6	20	54
	no of samples	28	11	30	28	29	29	29	30
Sodium (mg/L)	median	944	1,140	1,300	719	898	110	394	1,270
	25th percentile	766	992	983	557	776	60	143	922
	75th percentile	1,070	1,230	1,420	900	991	135	508	1,410
	no of samples	27	10	30	27	28	28	28	29
Chloride (mg/L)	median	1,645	1,940	2,255	1,275	1,660	164	668	2,230
	25th percentile	1,318	1,715	1,743	1,055	1,270	69	227	1,588
	75th percentile	1,886	2,038	2,428	1,703	1,800	215	853	2,528
	no of samples	30	23	31	40	29	29	29	30

Parameter	Statistic	Middle	Milang	Points	Poltalloch	Top	Wellington	Opening	Islands
Sulfate (mg/L)	median	246	264	324	218	244	40.5	117	327
	25th percentile	201	217	263	173	202	21	43	238
	75th percentile	263	301	374	248	273	45	137	371
	no of samples	29	30	31	47	29	29	29	30
Bicarbo-nate (mg/L)	median	209	213	216	198	211	84	140	211
	25th percentile	203	205	208	137	202	69	122	202
	75th percentile	218	222	227	213	219	94	164	219
	no of samples	37	37	38	54	34	29	36	37
Total Iron (mg/L)	median	1.59	1.58	1.49	1.38	1.50	0.71	1.36	1.36
	25th percentile	1.09	1.03	1.02	0.92	0.88	0.51	0.68	0.92
	75th percentile	2.49	2.39	2.07	2.00	2.18	1.34	2.05	2.43
	no of samples	29	11	31	27	29	29	29	30
Total Aluminium (mg/L)	median	1.31	1.19	1.31	1.12	1.30	0.84	0.88	1.30
	25th percentile	0.94	0.71	0.82	0.67	0.67	0.49	0.56	0.67
	75th percentile	2.14	2.28	1.85	1.71	2.15	1.24	1.80	2.15
	no of samples	29	11	31	21	29	29	29	30

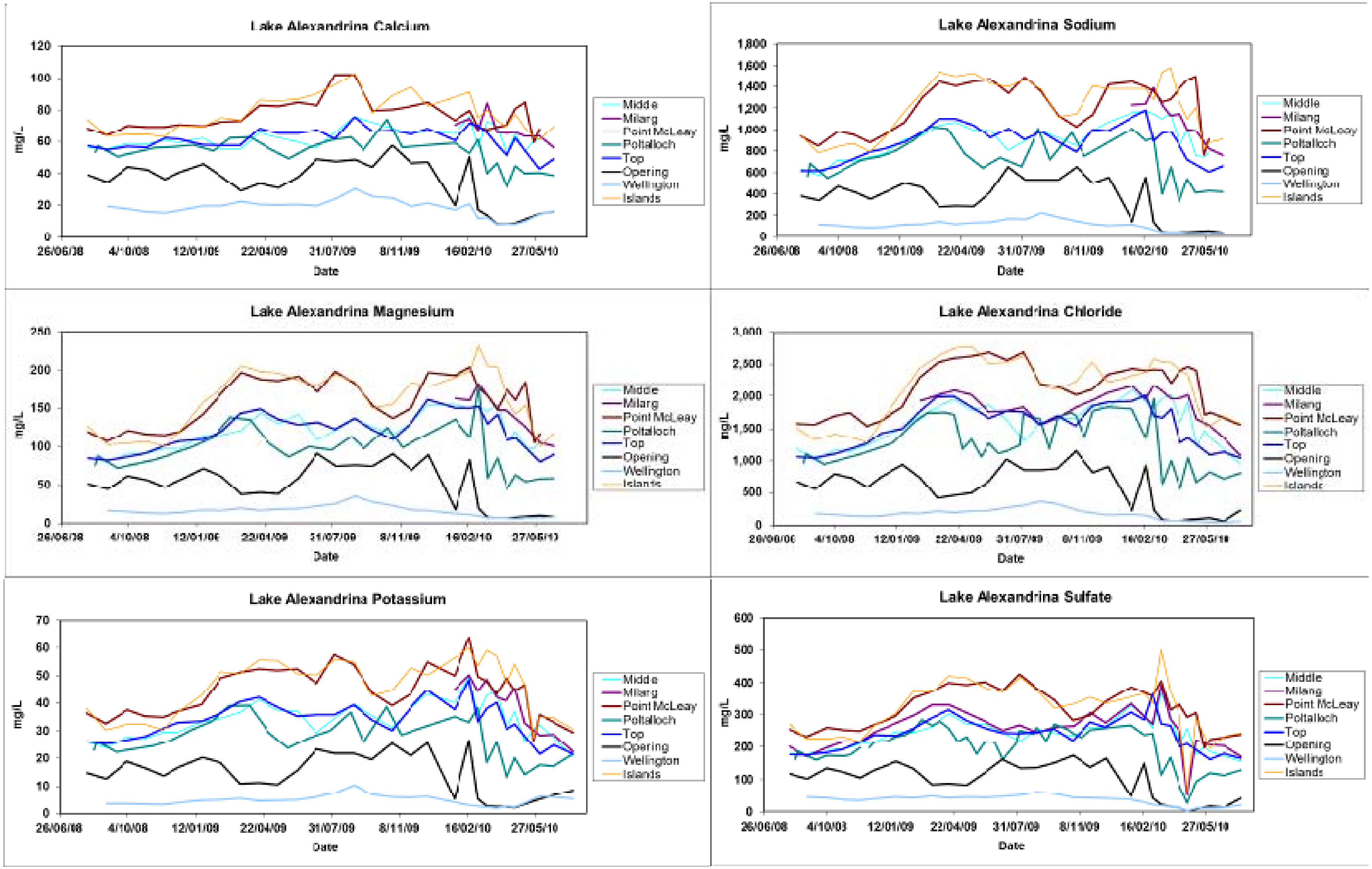


Figure 8 Lake Alexandrina – major ions

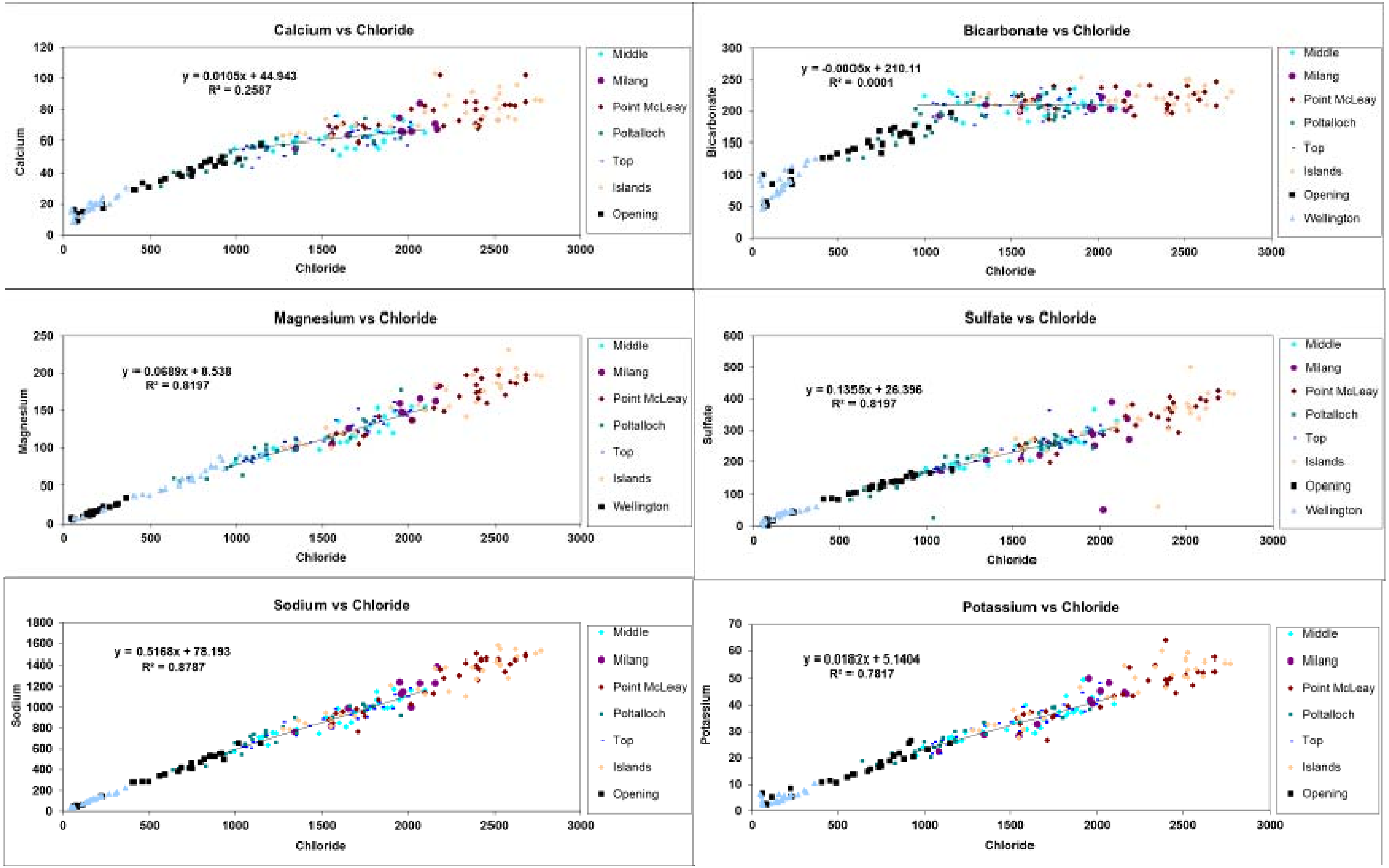


Figure 9 **Lake Alexandrina – major ions versus chloride. A linear trendline is fitted for the middle of the lake.**

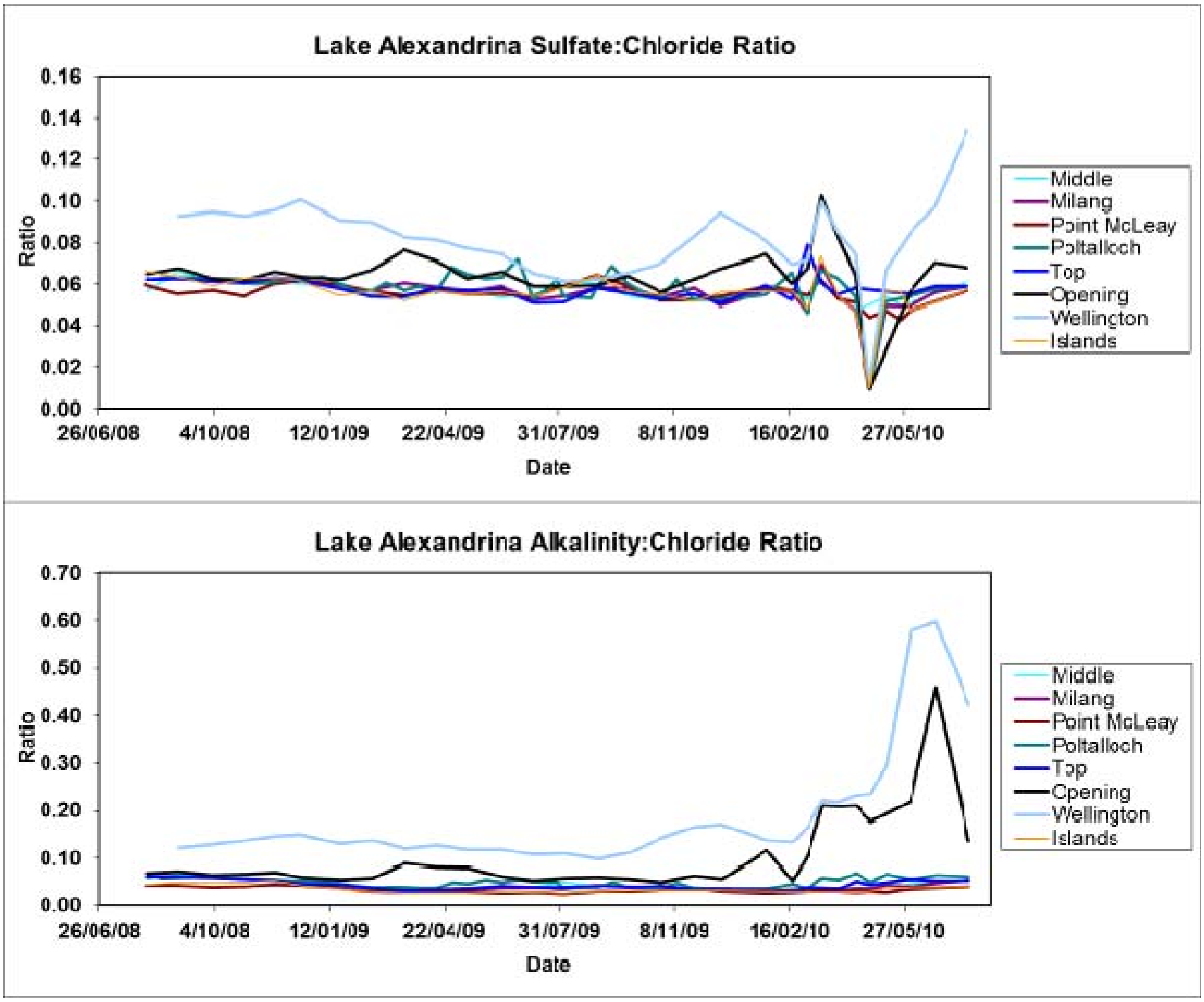


Figure 10 **Lake Alexandrina – sulfate:chloride and alkalinity:chloride ratio (molar units)**

The total metal (iron and aluminium) concentrations in Lake Alexandrina are shown in Figure 11. Levels were variable throughout 2008–09 but appear to be higher in winter months. However metal concentrations appear to be greatly reduced in winter 2010. These metals are plotted versus turbidity and each other in Figure 12 to assess whether the variability is related to turbidity, and hence water levels and wind events. There is not a strong relationship between metal levels and turbidity although the aluminium and iron were strongly correlated to each other.

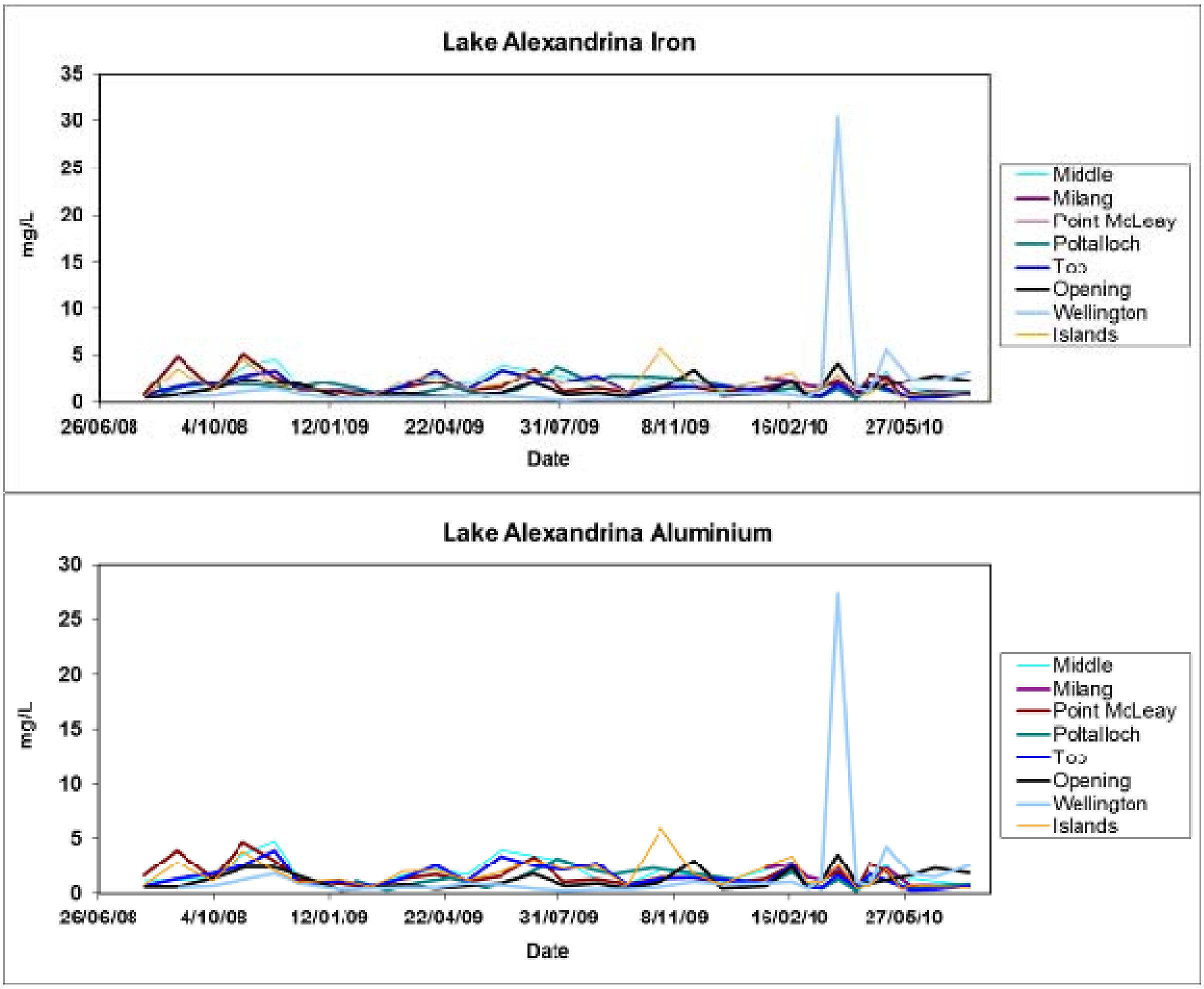


Figure 11 Lake Alexandrina – Metals (total iron and aluminium)

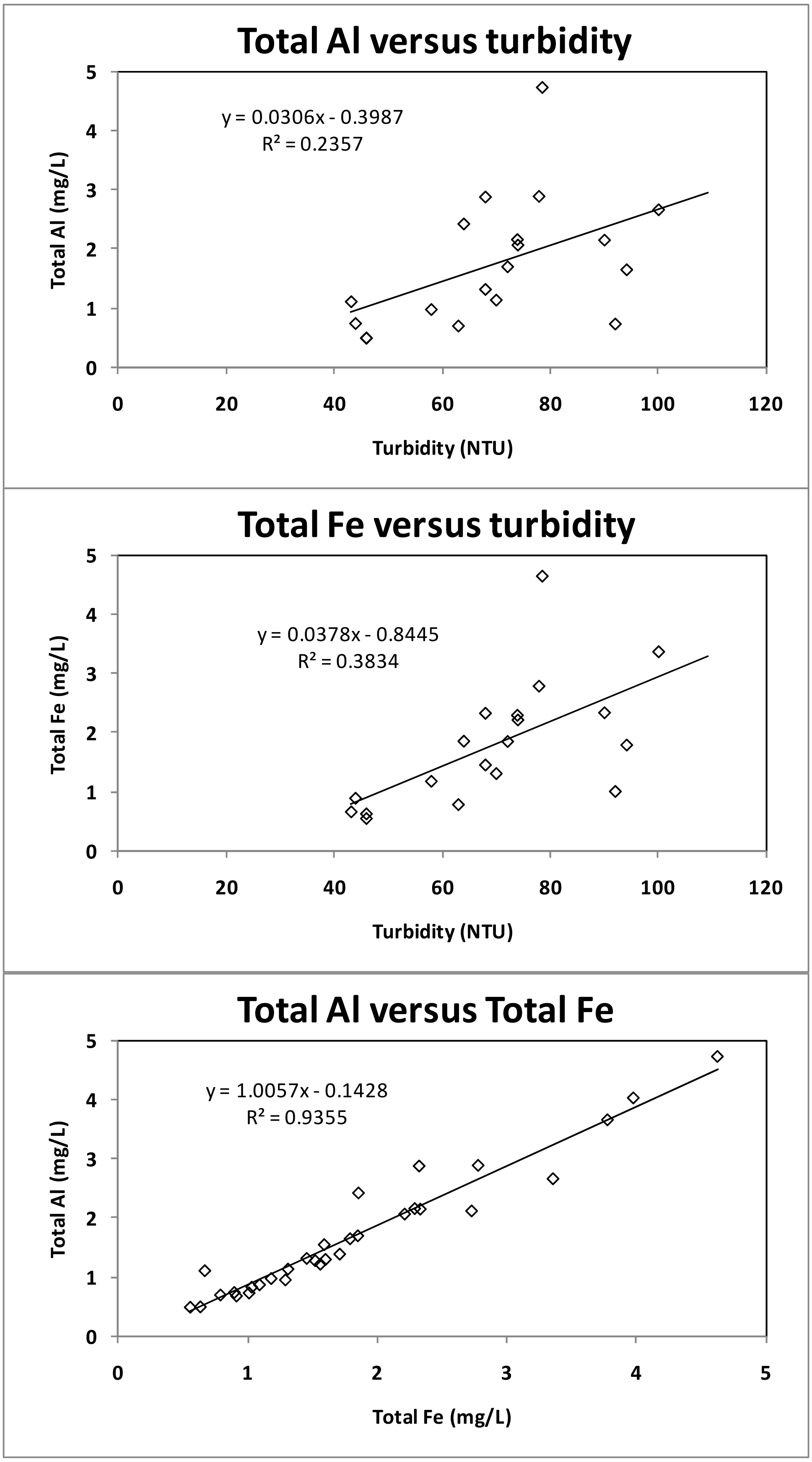


Figure 12 Lake Alexandrina (Middle) – Total Al and Fe versus turbidity

Lake Albert

The water quality in Lake Albert from 2008–10 is summarised in Tables 4–6 and Figures 13–22. Salinity levels followed a rapidly increasing trend from 2008–09, with slight decreases during winter months, until a substantial decrease occurred in 2010 (Figure 13). This decrease resulted from dilution following pumped inflow of a substantial amount of low salinity in the Lake Alexandrina water and winter rainfall. During the drought a distinct spatial variation in salinity was observed when pumping from Lake Alexandrina occurred with lower levels near the Narrung Narrows (Opening site) grading to higher levels in the southwest region (South West and Meningie sites). Following the breaching of the bund this spatial variation was accentuated.

pH exhibited some minor temporal variability but little spatial variability, and was maintained within ANZECC guideline levels (pH 6.5–9.0) throughout the drought period. Alkalinity was quite temporally variable with lower levels generally in winter months and a marked increase in early 2010. There was also a distinct spatial variability in alkalinity with lower levels at the Opening site when inflows from Lake Alexandrina occurred via pumping in the summers of 2008–09 and 2009–10. Temperature was similar at all sites with a distinct seasonal variation. Turbidity showed a great deal of temporal variability, but relatively little spatial variation. A reduction in turbidity occurred during 2010.

The nutrient and chlorophyll *a* concentrations in Lake Albert are shown in Table 5 and Figures 14–15. Total nitrogen, total phosphorus and chlorophyll *a* were at high levels and followed a general increasing trend over the drought period. There was some seasonal variation in these parameters, particularly in TN and chlorophyll *a* levels, but no consistent spatial variation. A marked reduction in levels of these parameters occurred across all sites following the removal of the Narrung embankment. Soluble nutrients (ammonia, oxidised nitrogen and filtered reactive phosphorus) generally remained at very low levels throughout the monitoring period, with the exception of some increases in soluble nitrogen and ammonia from mid-2010 at the Water Level Recorder site.

The phytoplankton population was dominated by blue-green algae (cyanobacteria), predominantly Planktolyngbya, Aphanocapsa and Planctonema species although a large, potentially toxic *Nodulariaspumigena* bloom occurred during late 2009 (Figure 16, note log scale). Green-algal species showed some increases in late 2009, coinciding with increased floodwater inflows to Lake Alexandrina (pumped to Albert from January to June 2010) and diatoms show seasonal trends (generally highest in winter).

Dissolved oxygen was maintained at near-saturation (8–9 mg/L) throughout the drought in Lake Albert (Figure 17). Colour shows some seasonal variation (highest in summer) and this trend is more pronounced for the dissolved organic carbon data collected during 2009 (Figure 17).

Table 4 Lake Albert – summary statistics for general water quality parameters

Parameter	Statistic	Meningie	Opening	Southwest	Water Level Recorder
Salinity (µs/cm)	median	10,160	7,730	11,000	9,805
	25th percentile	5,965	5,500	9,390	5,610
	75th percentile	12,110	9,860	13,320	11,500
	no of samples	79	65	57	70
Alkalinity (mg/L)	median	251	239	251	247
	25th percentile	235	221	241	237
	75th percentile	264	248	266	257
	no of samples	80	69	61	74

Parameter	Statistic	Meningie	Opening	South West	Water Level Recorder
pH	median	8.6	8.6	8.5	8.5
	25th percentile	8.4	8.4	8.4	8.4
	75th percentile	8.6	8.7	8.6	8.7
	no of samples	84	69	60	64
Temperature (°C)	median	14.1	14.8	14.3	14.6
	25th percentile	11.8	12.4	12.5	12.2
	75th percentile	18.1	18.3	18.3	18.3
	no of samples	35	21	27	26
Turbidity (NTU)	median	89	90	105	91
	25th percentile	58	57	77	60
	75th percentile	120	114	130	117
	no of samples	75	63	55	66

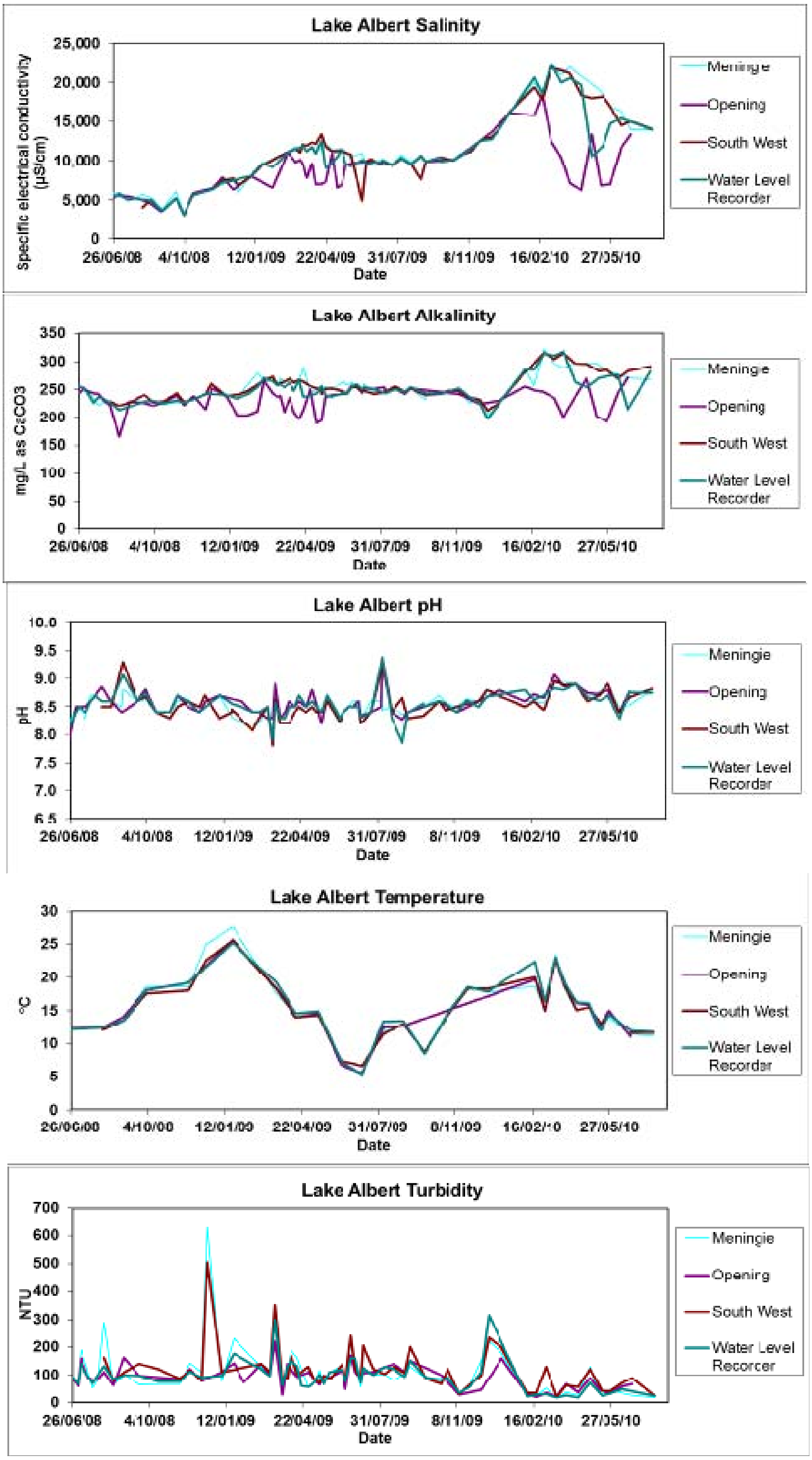


Figure 13 Lake Albert – general water quality parameters

Table 5 Lake Albert – summary statistics for nutrients and chlorophyll *a*

Parameter	Statistic	Meningie	Opening	Southwest	Water Level Recorder
Total Nitrogen (mg/L)	median	3.74	3.58	4.07	3.72
	25th percentile	3.11	2.98	3.54	3.20
	75th percentile	4.36	4.14	4.54	4.24
	no of samples	74	68	1	70
Ammonia (as N mg/L)	median	0.012	0.010	0.009	0.011
	25th percentile	0.009	0.008	0.009	0.008
	75th percentile	0.016	0.013	0.014	0.023
	no of samples	16	17	24	23
Oxidised Nitrogen (as N mg/L)	median	0.006	0.006	0.007	0.007
	25th percentile	0.005	0.005	0.005	0.005
	75th percentile	0.008	0.008	0.010	0.010
	no of samples	75	69	59	71
Total Phosphorus (mg/L)	median	0.190	0.205	0.218	0.202
	25th percentile	0.155	0.166	0.167	0.155
	75th percentile	0.222	0.246	0.265	0.234
	no of samples	75	68		71
FRP (as P mg/L)	median	0.005	0.005	0.005	0.005
	25th percentile	0.005	0.005	0.005	0.005
	75th percentile	0.006	0.006	0.006	0.005
	no of samples	73	67	59	70
Chlorophyll *a* (µg/L)	median	72	89	84	79
	25th percentile	54	76	70	53
	75th percentile	93	111	112	112
	no of samples	61	53	43	58

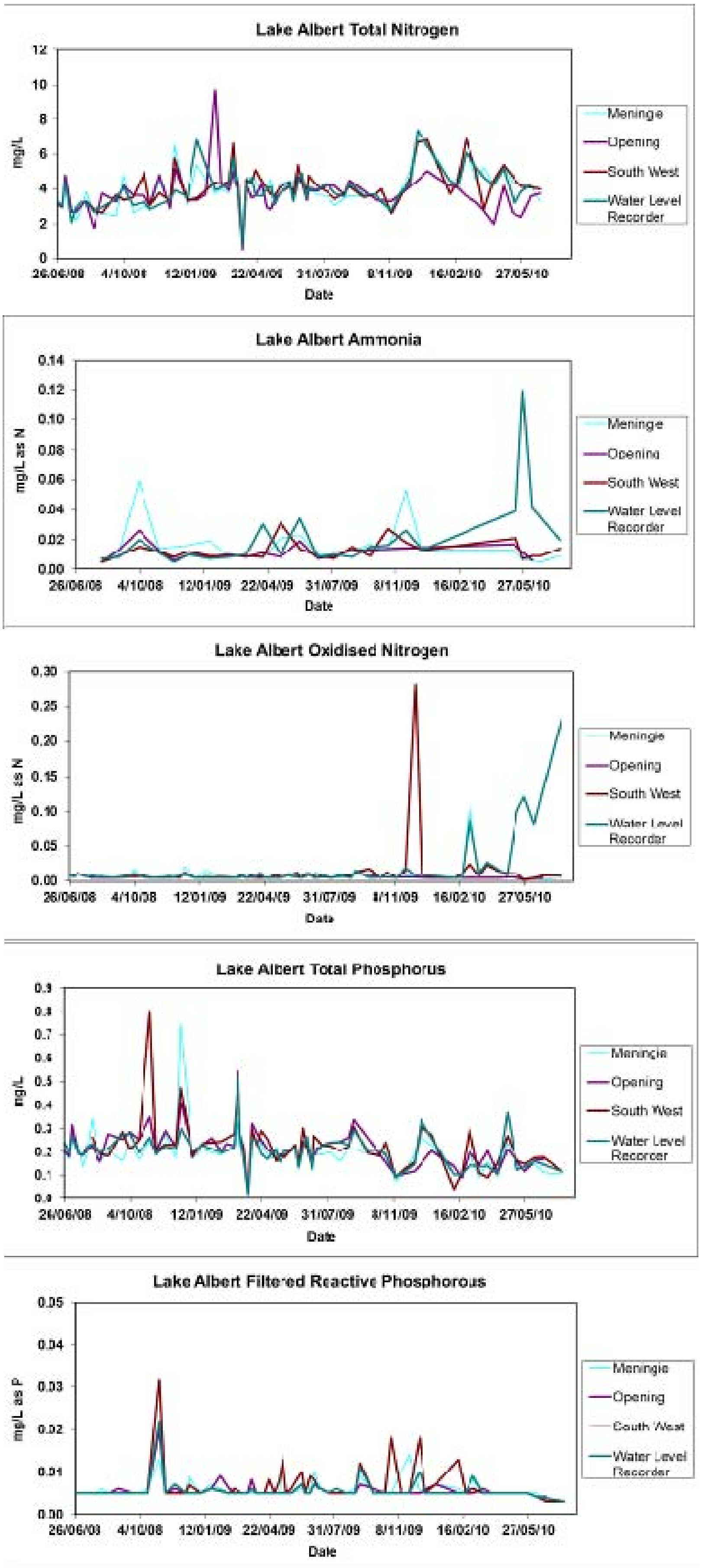


Figure 14 Lake Albert – nutrients

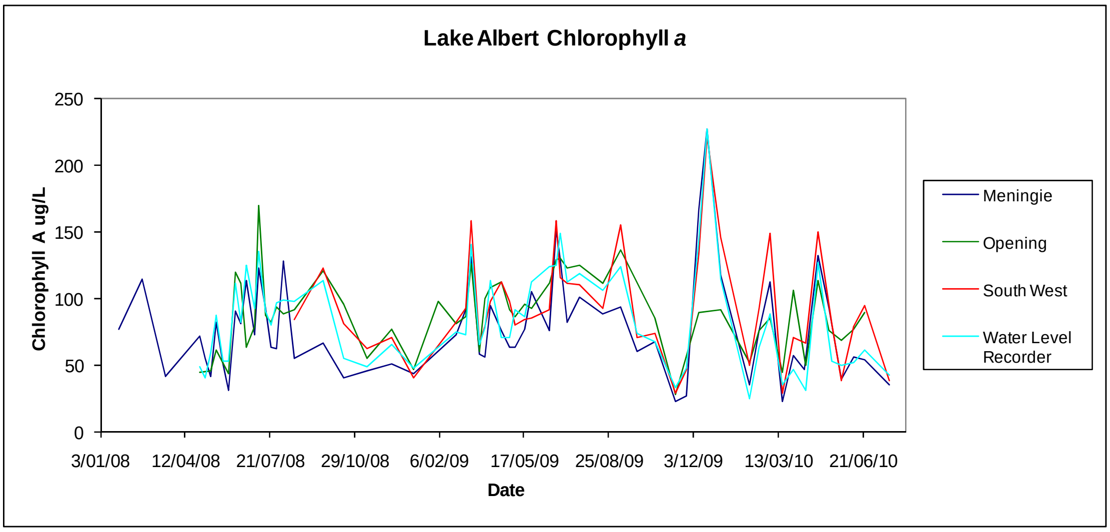
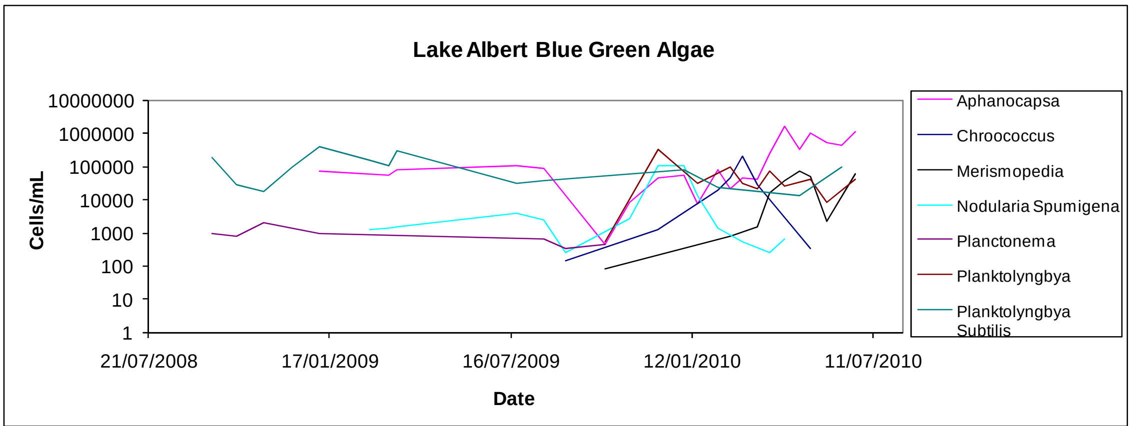
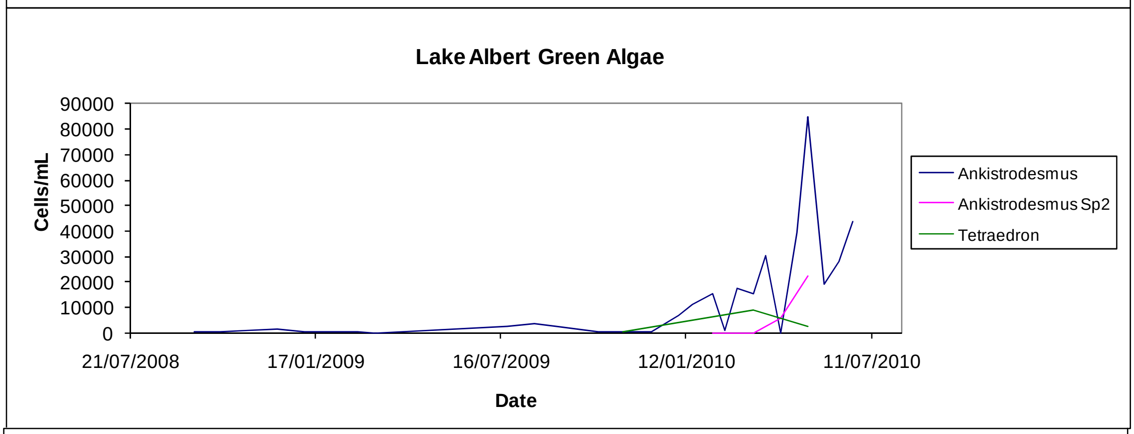


Figure 15 Lake Albert – Chlorophyll *a*





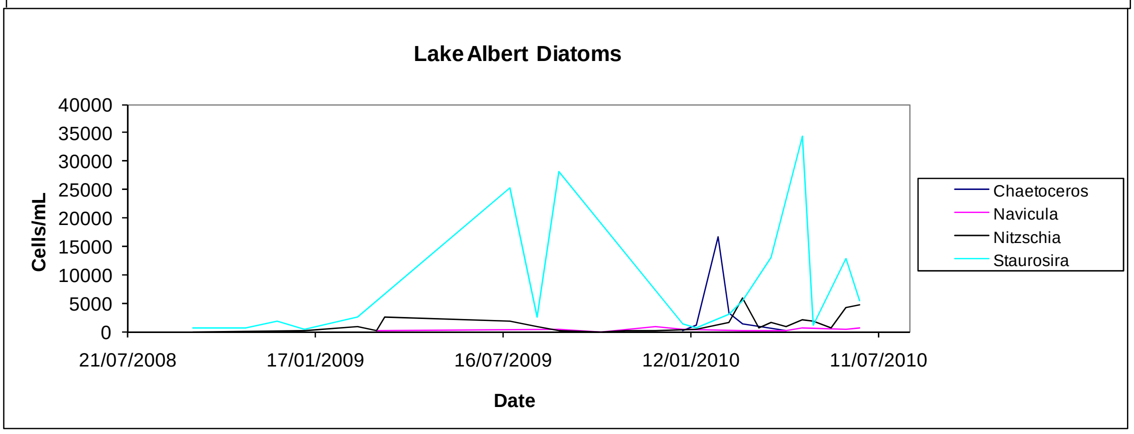


Figure 16 Lake Albert – algal speciation (Southwest site). Note log scale used for blue-green algae.

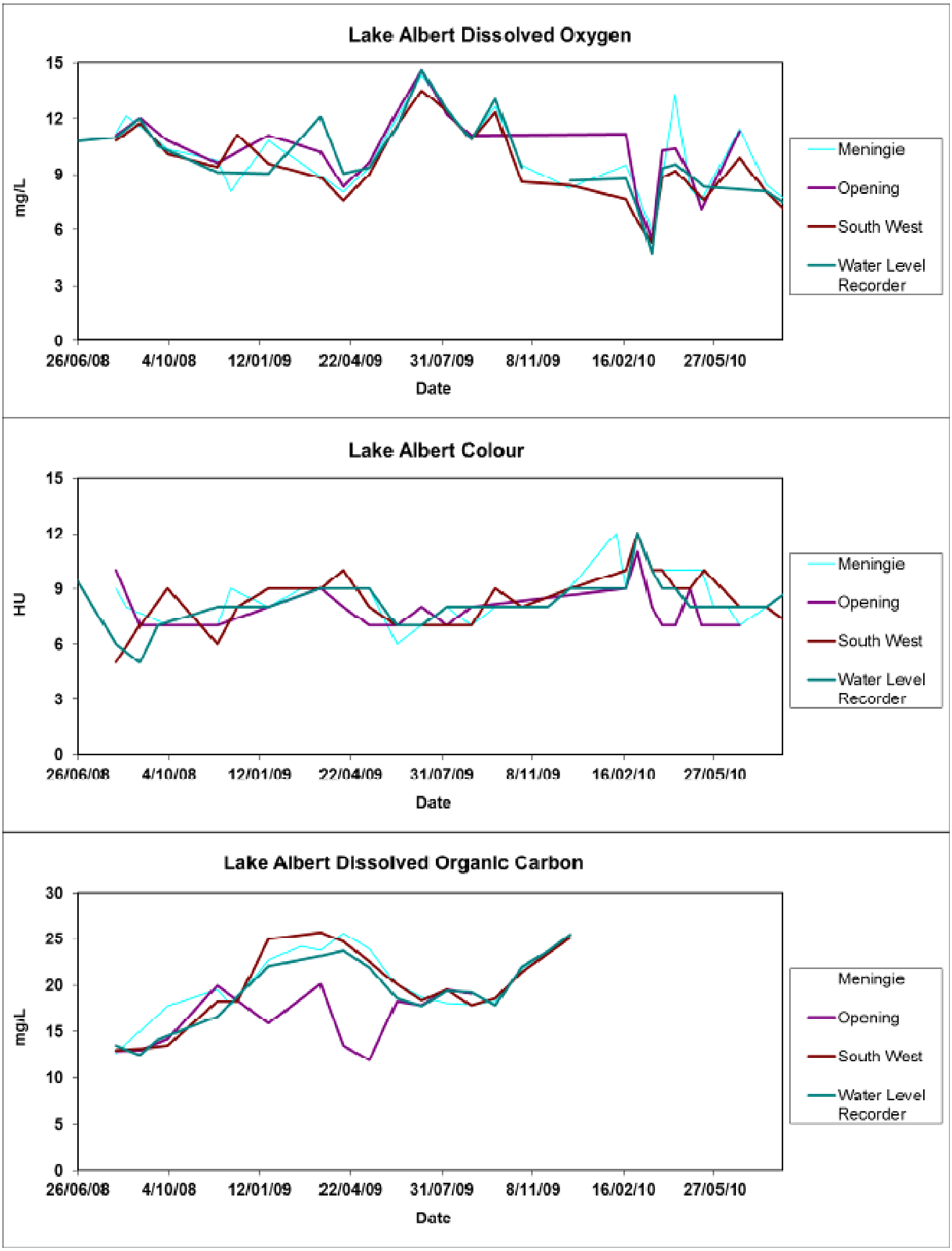


Figure 17 Lake Albert – dissolved oxygen, colour, dissolved organic carbon

The concentration of major ions over the drought period is shown in Figure 18 and Table 6. As expected major ions followed a similar trend to salinity, with a general increasing trend over 2008–09 and slight decreases during winter months. Following the pumping of lower salinity water during 2010, major ion concentrations rapidly decreased due to dilution from the large volumes of less saline Lake Alexandrina water entering.

Similar spatial patterns to salinity were observed with lower major ion levels in the northern regions of the lake near the Narrung Narrows (Opening site) following pumping and higher levels in the southern region (Meningie and South West sites). The concentration of major ions versus the concentration of chloride is shown in Figure 19. Most major ions showed a linear increasing trend with chloride concentration. The exception to this was bicarbonate which showed only very minor increases. Although calcium showed an increasing trend the slope of this increase was less than for the other major cations (magnesium, potassium, sodium).

The sulfate:chloride and alkalinity:chloride ratios are shown in Figure 20. The sulfate:chloride ratio was relatively stable until the pumping in early 2010 decreased the ratio. However, in mid-2010 this ratio markedly increased and is now similar to the ratio found at the site nearest (Poltalloch) to the Narrung Narrows in Lake Alexandrina (Figure 8). The alkalinity:chloride ratio showed temporal (decreases over summer and increases over winter) and spatial (higher at Opening site during pumping) variations.

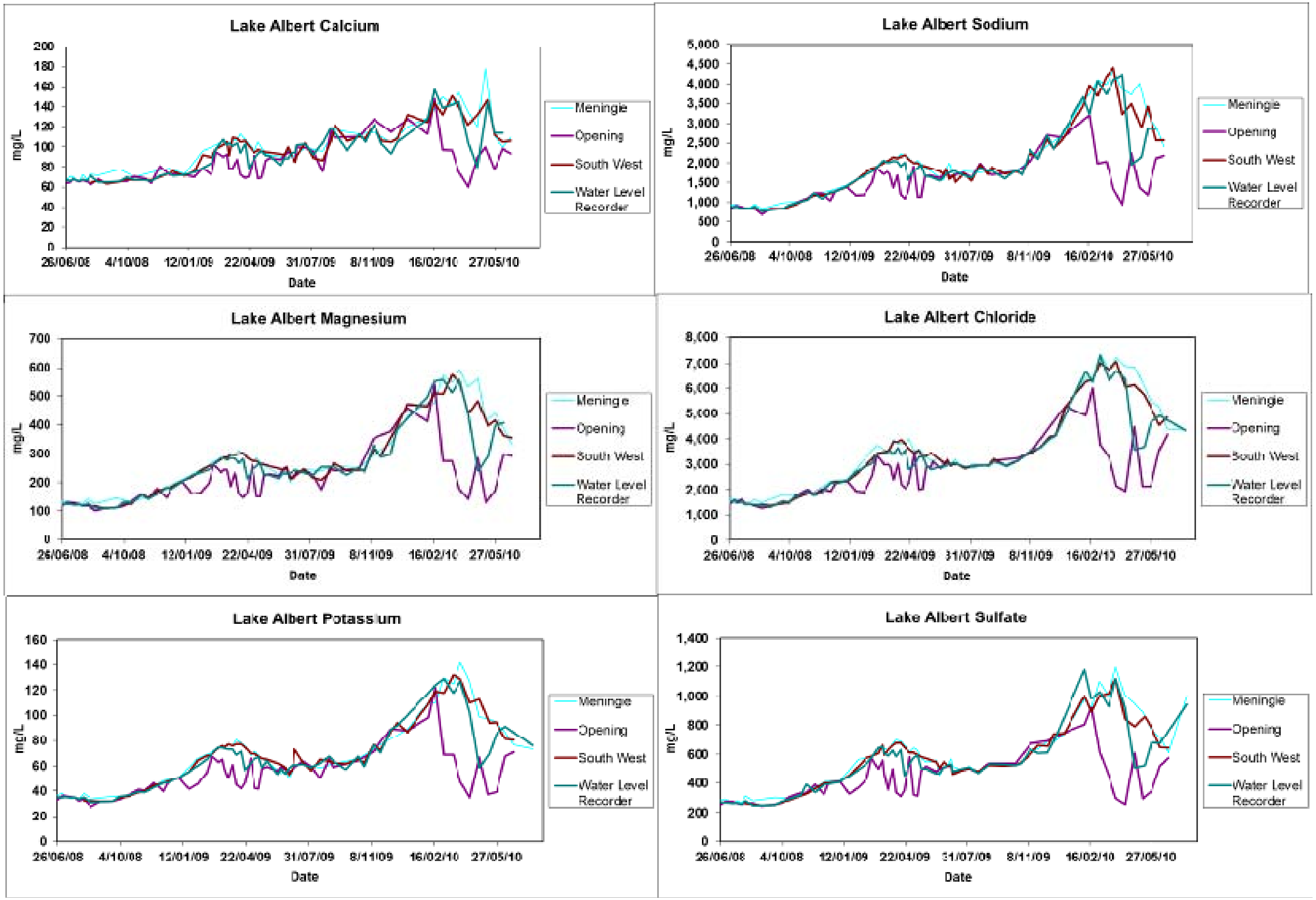


Figure 18 Lake Albert – major ions

Table 6 Lake Albert – summary statistics for major ions and metals

Parameter	Statistic	Meningie	Opening	Southest	Water Level Recorder
Calcium (mg/L)	median	96	77	100	91
	25th percentile	70	67	88	68
	75th percentile	109	94	108	104
	no of samples	57	68	59	70
Magnesium (mg/L)	median	245	178	262	121
	25th percentile	142	129	218	218
	75th percentile	303	242	309	309
	no of samples	57	68	59	70
Potassium (mg/L)	median	62	47	118	59
	25th percentile	39	36	68	37
	75th percentile	76	61	260	71
	no of samples	58	68	60	71
Sodium (mg/L)	median	1,790	1,690	1,890	1,685
	25th percentile	984	1,100	1,570	931
	75th percentile	2,160	2,010	2,215	2,010
	no of samples	57	68	59	70
Chloride (mg/L)	median	3,165	2,270	3,340	2,960
	25th percentile	1,735	1,620	2,930	1,545
	75th percentile	3,863	3,030	4,030	3,515
	no of samples	68	69	59	71
Sulfate (mg/L)	median	5,46	369	582	507
	25th percentile	312	273	486	280
	75th percentile	663	519	663	600
	no of samples	69	69	59	71
Bicarbonate (mg/L)	median	279	266	287	276
	25th percentile	266	244	268	264
	75th percentile	295	280	302	296
	no of samples	66	69	60	71

Parameter	Statistic	Meningie	Opening	Southest	Water Level Recorder
Total Iron (mg/L)	median	1.34	2.05	3.06	1.85
	25th percentile	0.82	1.05	1.63	1.06
	75th percentile	2.95	3.92	4.93	3.94
	no of samples	58	69	59	71
Total Aluminium (mg/L)	median	0.96	1.67	2.49	1.50
	25th percentile	0.63	0.76	1.20	0.83
	75th percentile	2.51	3.36	4.45	3.72
	no of samples	54	69	57	71

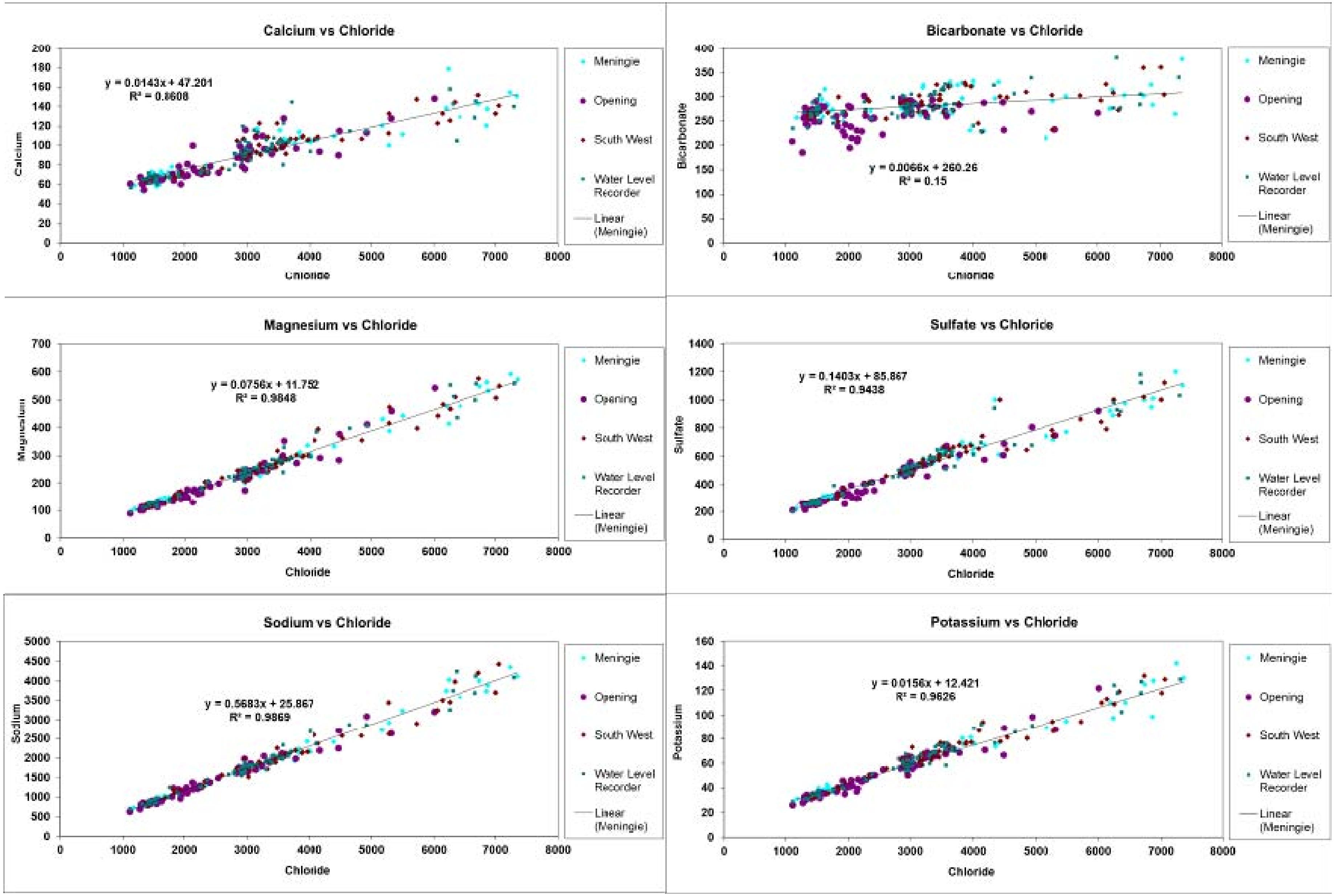


Figure 19 Lake Albert – major ions versus chloride. A linear trendline is fitted for the Water Level Recorder site.

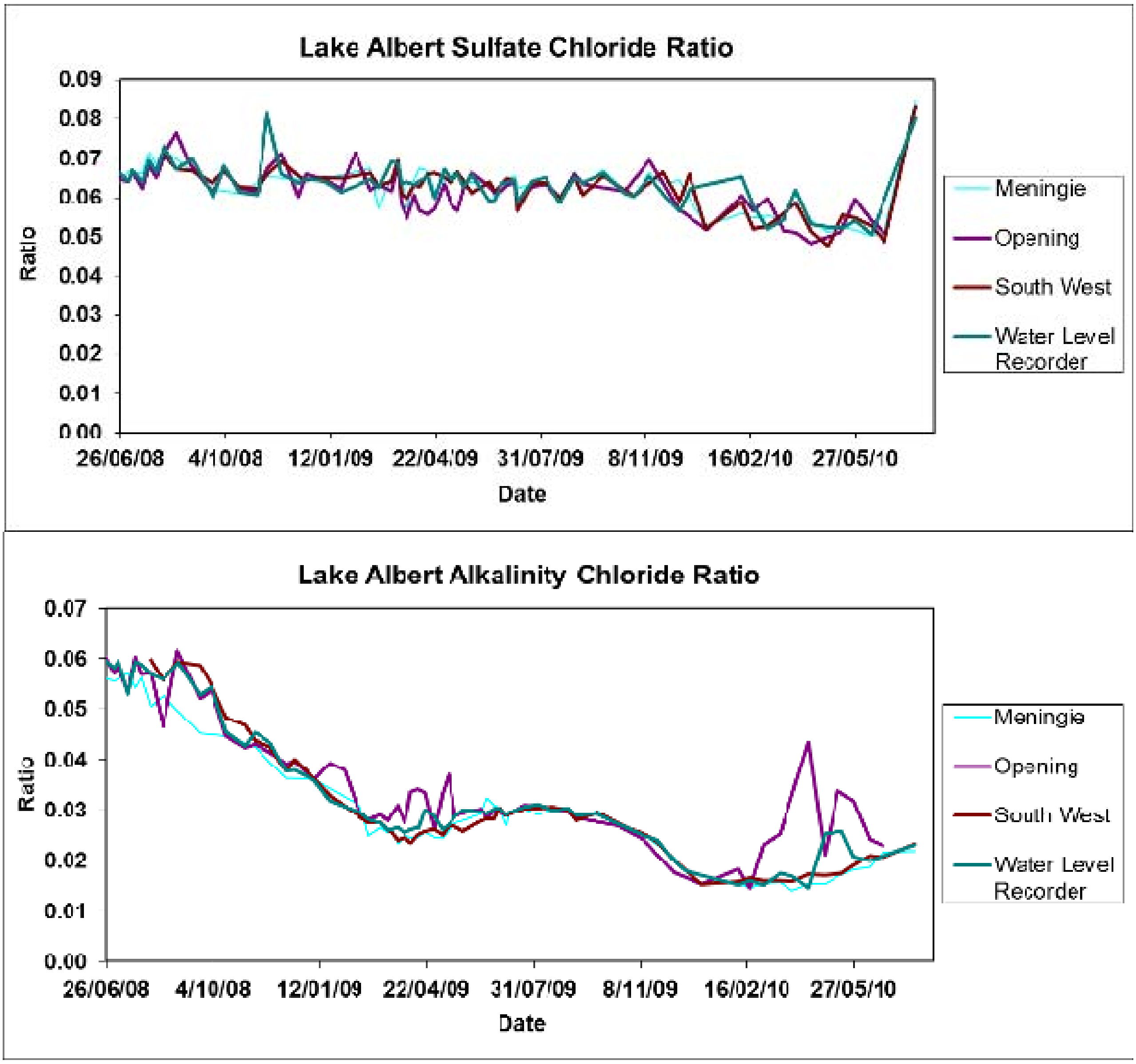


Figure 20 Lake Albert – sulfate:chloride and alkalinity:chloride ratio

The total metal (iron and aluminium) concentrations in Lake Albert are shown in Figure 21. Levels were variable throughout 2008–09 but appear to be higher in winter months. Metal concentrations decreased and remained relatively low since the beginning of 2010. These metals are plotted versus turbidity and each other in Figure 22 to assess whether the variability is related to turbidity, and hence water levels and wind events. There is a poor relationship between metal levels and turbidity although the aluminium and iron were strongly correlated to each other.

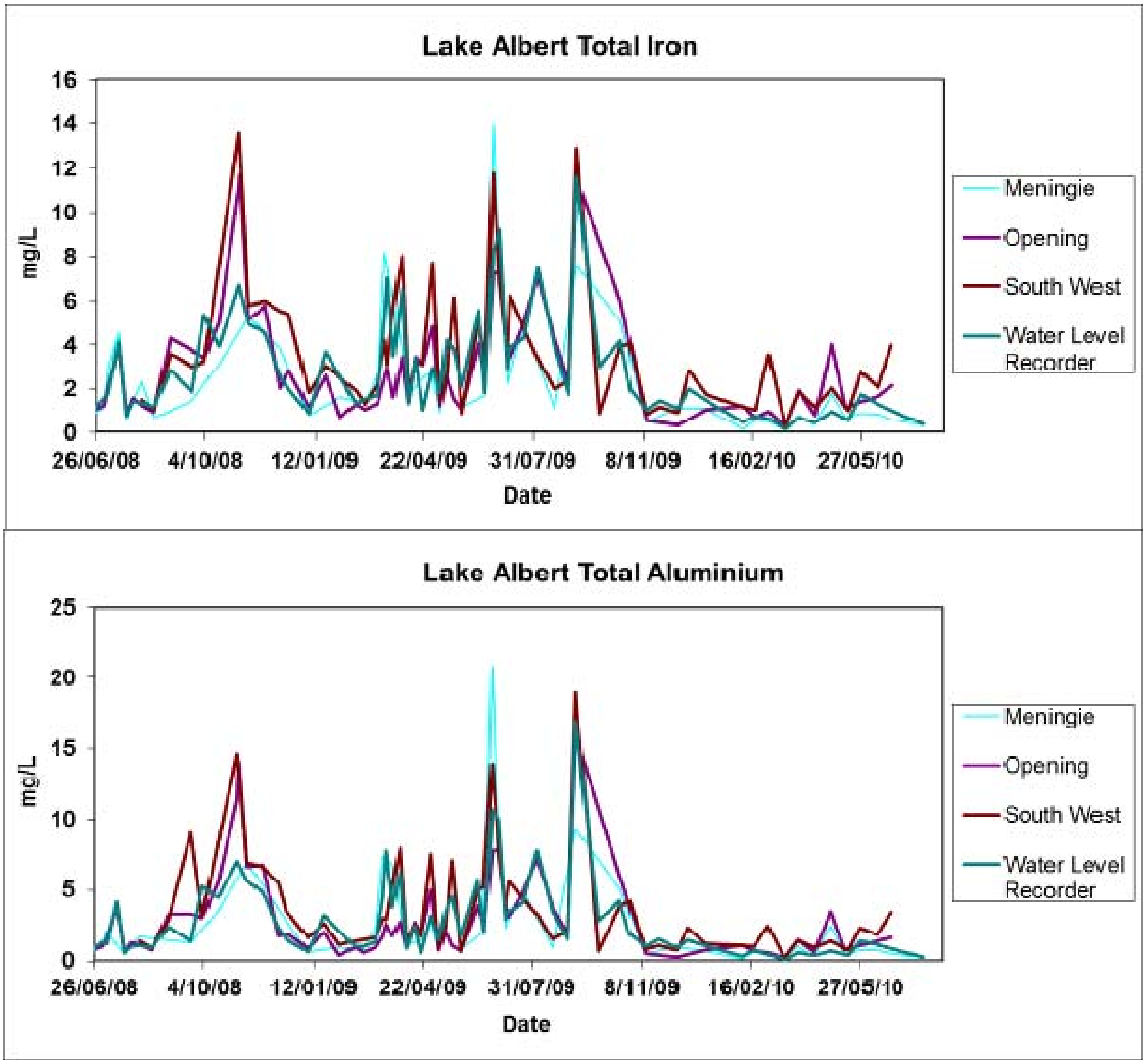


Figure 21 Lake Albert – metals (total iron and aluminium)

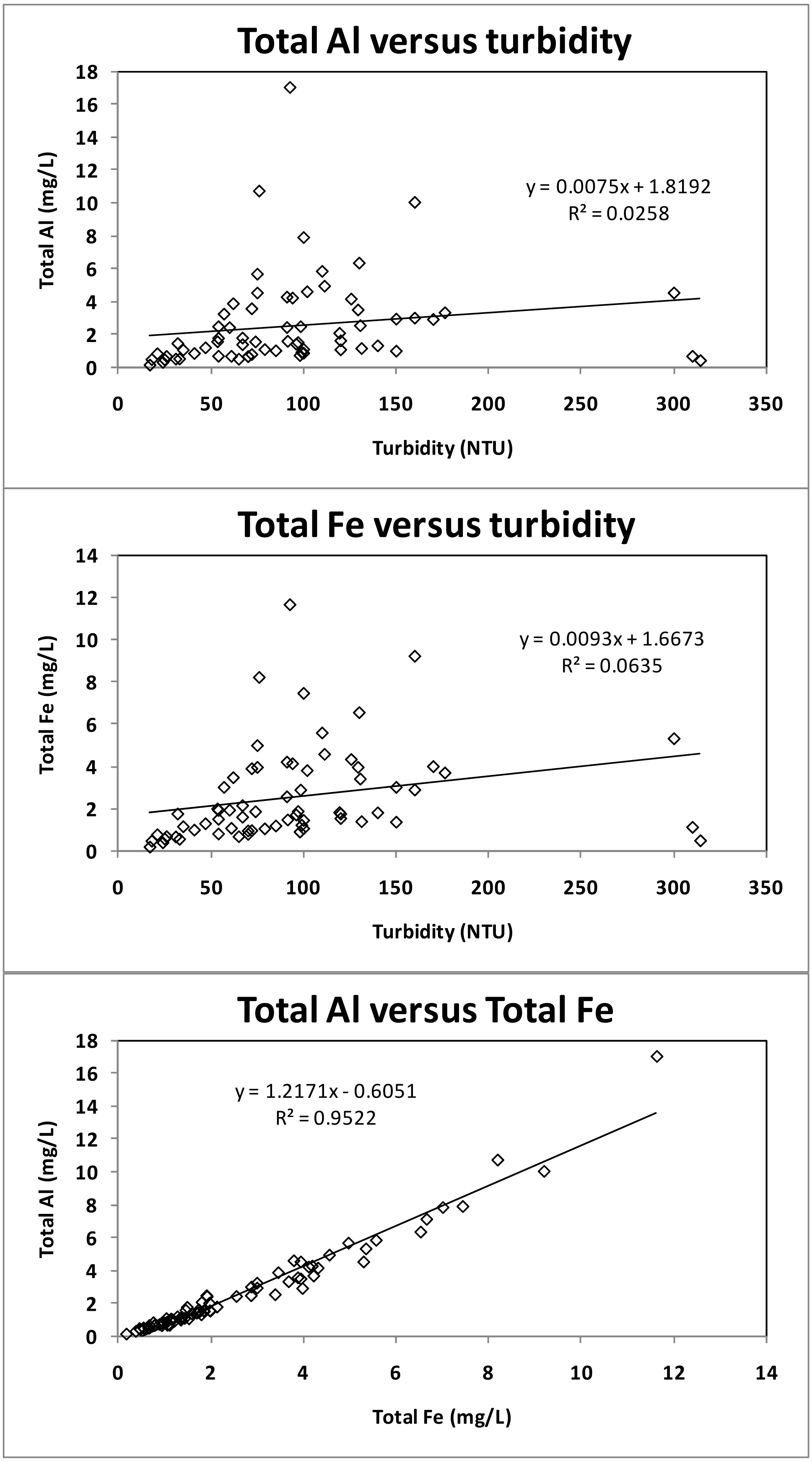


Figure 22 **Lake Albert (Water Level Recorder) – Total Al and Fe versus turbidity**

Currency Creek, Finniss River and Goolwa Channel region

From 2008–10, the water quality in the Goolwa Channel, Currency Creek and Finniss River tributaries region is summarised in Tables 7–10 and Figures 23–32. Salinity levels followed a general increasing trend until the Goolwa Channel temporary flow regulator construction in mid-2009 (Figure 23). As the pool behind the regulator rapidly filled from less saline tributary flows, salinity levels decreased due to dilution from mid- to late-2009. Salinity increased again from early 2010, as water levels decreased over the summer months and then decreased when the tributary flows occurred again in winter. A distinct spatial variation in salinity was observed with higher levels in the Goolwa Channel region (Clayton and Goolwa sites) grading to lower levels near the Currency Creek and Finniss River entrances (Currency 1 and Finniss 1 sites).

Alkalinity increased as the water level declined from 2008 to early 2009. At time of the first winter rains in late April 2009, the entire Currency Creek region had dried out with large areas of acid sulfate soils exposed and oxidised. As this area refilled with winter rainfall a large decrease in alkalinity occurred and many sites completely lost alkalinity. This resulted in pH well below ANZECC (2000) guideline levels (pH 6.5–9.0) to protect freshwater aquatic ecosystems (Figure 23).

Following trials of aerial, mounded, barrier and slurry limestone dosing (3,000 tonnes), alkalinity was restored and pH neutralised at all sites. The construction of the Goolwa Channel temporary flow regulator then resulted in a rapid rise in water levels and higher alkalinities. In the summer of 2009–10 water levels declined again and alkalinity became very low in the Upper Currency Creek region (Currency 1, 2 and upstream sites). These low levels increased during the winter of 2010. With the exception of when alkalinity was absent in the water body, pH levels were quite stable.

Temperature was similar at all sites with a distinct seasonal variation (Figure 23). Turbidity was at high levels and showed a great deal of variability, particularly in the upper Finniss region during the water level declines and sediment drying of the 2008–09 summer (Figure 19). Following construction of the Clayton and Currency temporary flow regulators, turbidity levels were much lower.

The nutrient and chlorophyll *a* concentrations in the Goolwa Channel and Tributaries region are shown in Table 8 and Figures 24–25. Nutrient and chlorophyll *a* concentrations followed a general increasing trend over the early drought period (2008–09 summer). Following rewetting of the area (and acidification in Currency Creek region) in winter 2009, large total and soluble nutrient releases occurred (Figure 24). Algal productivity also increased as evidenced by the chlorophyll *a* results (Figure 25). When the pool behind the regulator filled, nutrient and chlorophyll *a* levels declined and stabilised. The exception to this was the Clayton site which showed some large increases in total nitrogen and phosphorus.

The phytoplankton population was dominated by green algae through 2009, predominantly the *Chlorella* species (Figure 26, note log scale). In 2010, blue-green algae (cyanobacteria) became more dominant, predominantly *Synechocystis* and *Synechococcus* species (Figure 26, note log scale). There were also a small but notable number of flagellates recorded during 2010 (Figure 26).

Dissolved oxygen was maintained at near-saturation (7–8 mg/L) throughout the drought in the Goolwa Channel and Tributaries region (Figure 27). Dissolved organic carbon shows a seasonal variation peaking in the summer months (Figure 27).

Table 7 Goolwa Channel and Tributaries – summary statistics for general water quality parameters

Parameter	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Salinity (µS/cm)	median	10,800	16,154	15,300	16,700	9,500	10,600	13,100	20,,600	16,800
	25th percentile	8,055	10,300	10,700	13,900	4,910	7,360	9,585	16,683	11,650
	75th percentile	11,700	20,600	19,300	22,050	12,900	14,900	17,450	22,350	20,500
	no of samples	47	53	59	39	59	59	55	30	35
Alkalinity (mg/L)	median	205	86	81	175	121	146	175	175	42
	25th percentile	181	62	58	154	80	114	168	166	33
	75th percentile	215	106	110	183	137	154	180	181	48
	no of samples	51	57	61	38	65	67	52	40	35
pH	median	8.40	8.70	8.60	8.30	8.20	8.20	8.50	8.30	8.40
	25th percentile	8.10	7.60	7.80	8.10	7.80	7.95	8.20	8.20	7.65
	75th percentile	8.70	8.90	8.98	8.60	8.30	8.40	8.60	8.50	8.70
	no of samples	44	50	54	31	57	59	45	33	35
Temperature (ºC)	median	16.4	18.2	17.8	16.9	16.6	17.6	17.4	16.3	17.2
	25th percentile	12.6	14.5	14.5	14.3	13.5	14.2	14.6	13.0	13.6
	75th percentile	19.7	21.7	21.6	22.0	23.1	23.1	22.2	20.3	21.7
	no of samples	38	46	45	46	46	48	56	43	29
Turbidity (NTU)	median	31	23	16	15	97	54	13	4	n/a
	25th percentile	25	11	7	8	65	22	5	3	n/a
	75th percentile	46	44	24	21	163	100	24	8	n/a
	no of samples	33	18	15	34	12	17	56	25	n/a

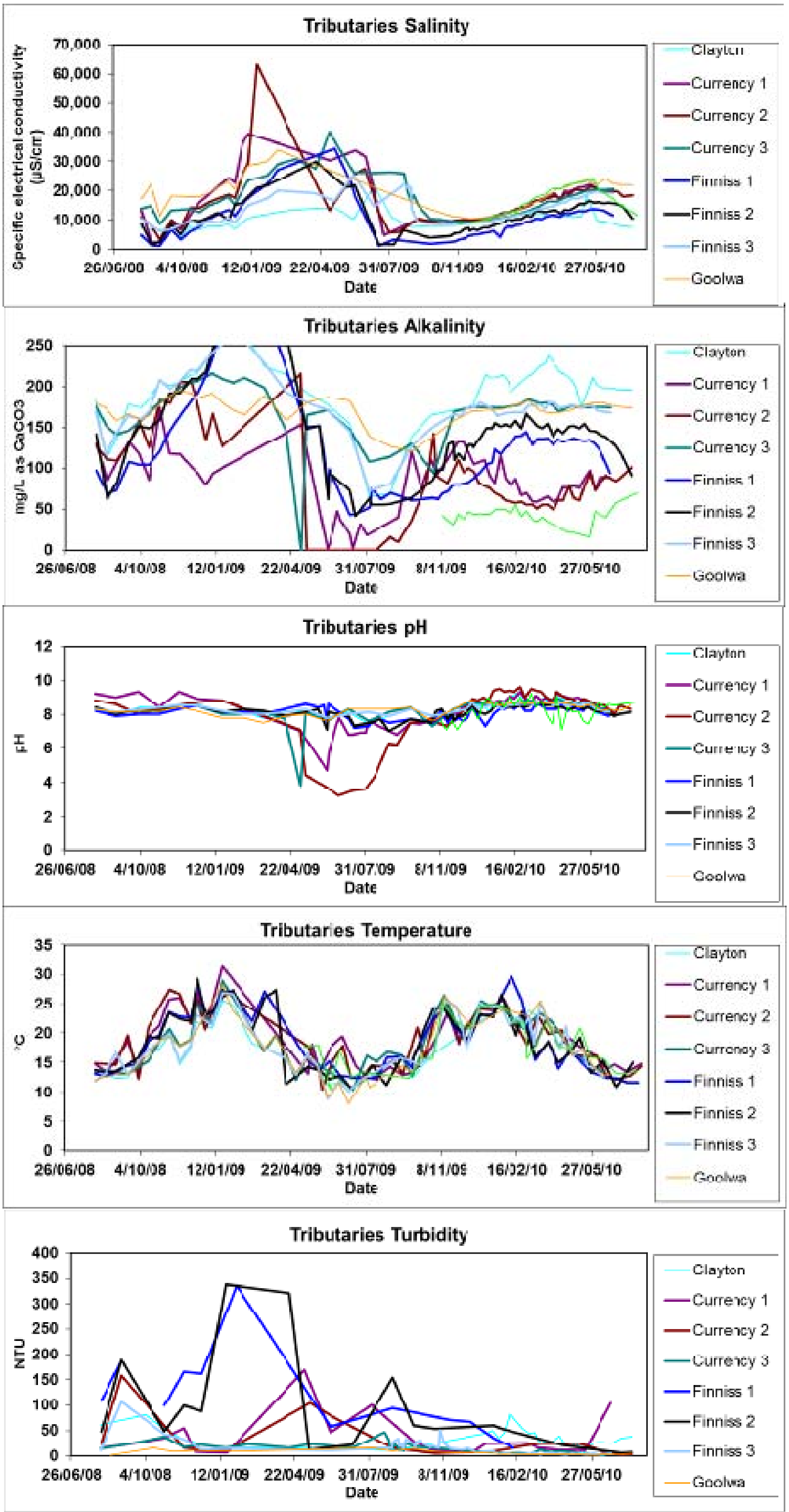


Figure 23 Goolwa Channel and Tributaries – general water quality parameters

Table 8 Goolwa Channel and Tributaries – summary statistics for nutrients and chlorophyll *a*

Parameter	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Total nitrogen (mg/L)	median	3.33	2.02	1.93	2.10	2.07	2.05	2.15	2.04	1.97
	25th percentile	2.24	1.78	1.78	1.93	1.82	1.83	2.01	1.81	1.77
	75th percentile	4.93	2.55	2.27	2.50	2.34	2.38	2.38	2.39	2.12
	no of samples	42	50	50	30	58	57	46	35	34
Ammonia (as N mg/L)	median	0.013	0.012	0.010	0.014	0.010	0.012	0.017	0.019	0.009
	25th percentile	0.009	0.008	0.007	0.009	0.008	0.007	0.010	0.009	0.007
	75th percentile	0.016	0.027	0.022	0.060	0.025	0.032	0.032	0.047	0.016
	no of samples	44	50	52	30	57	59	46	33	35
Oxidised nitrogen (as N mg/L)	median	0.005	0.005	0.007	0.006	0.005	0.006	0.007	0.013	n/a
	25th percentile	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	n/a
	75th percentile	0.150	0.005	0.016	0.034	0.012	0.105	0.034	0.026	n/a
	no of samples	19	50	26	30	58	36	46	23	0
Total phosphorus (mg/L)	median	0.155	0.056	0.053	0.087	0.073	0.071	0.084	0.104	0.042
	25th percentile	0.127	0.039	0.035	0.065	0.061	0.050	0.057	0.062	0.036
	75th percentile	0.190	0.100	0.094	0.138	0.127	0.104	0.132	0.152	0.058
	no of samples	44	50	52	30	58	59	46	37	35

Parameter	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
FRP (as P mg/L)	median	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	25th percentile	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.003
	75th percentile	0.006	0.005	0.005	0.005	0.006	0.005	0.005	0.006	0.005
	no of samples	39	30	30	29	37	40	37	36	20
Chlorophyll *a* (µg/L)	median	74.8	7.0	9.6	22.5	30.5	27.4	26.9	22.2	n/a
	25th percentile	72.7	3.5	6.4	11.9	16.7	8.4	12.9	20.0	n/a
	75th percentile	76.6	16.1	18.1	31.5	45.2	35.9	59.8	54.1	n/a
	no of samples	3	17	17	35	18	20	28	7	n/a

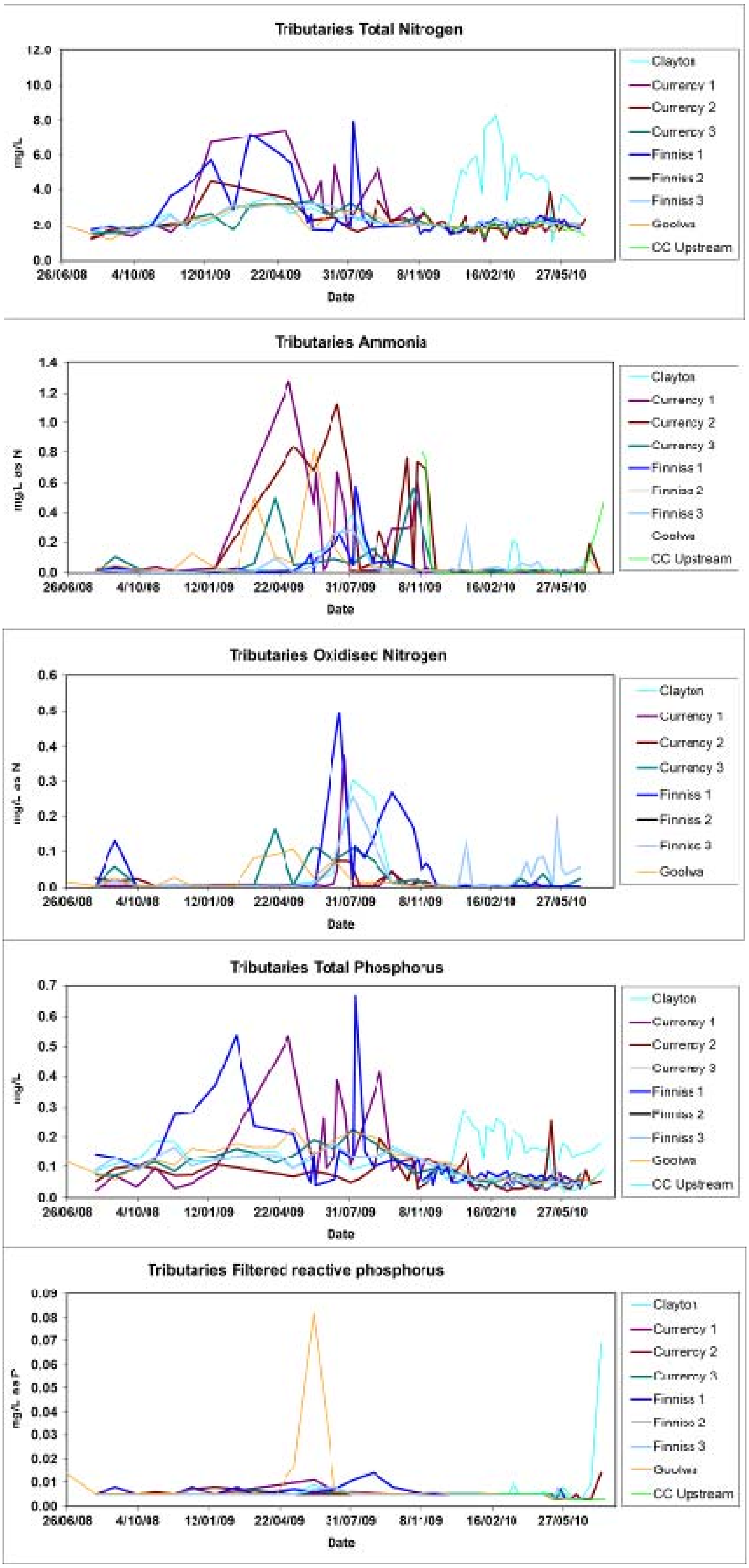


Figure 24 Goolwa Channel and Tributaries – nutrients

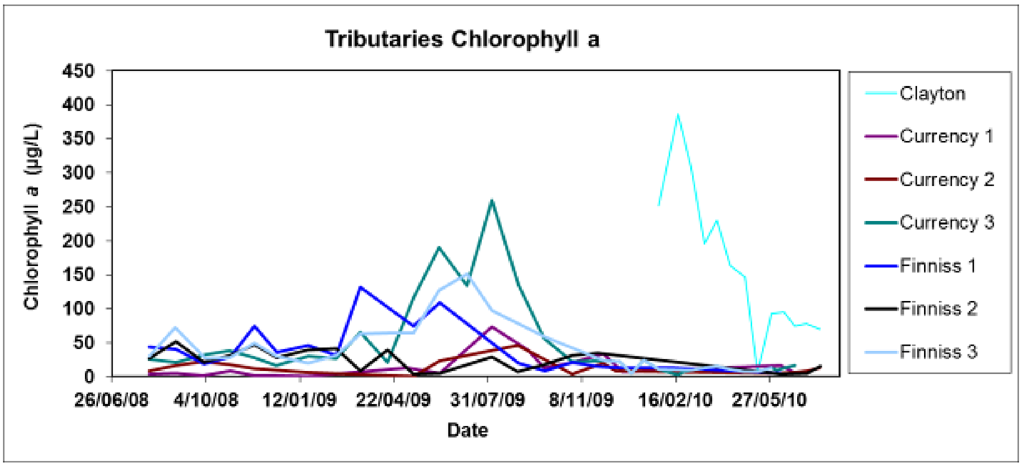


Figure 25 Goolwa Channel and Tributaries – Chlorophyll *a*

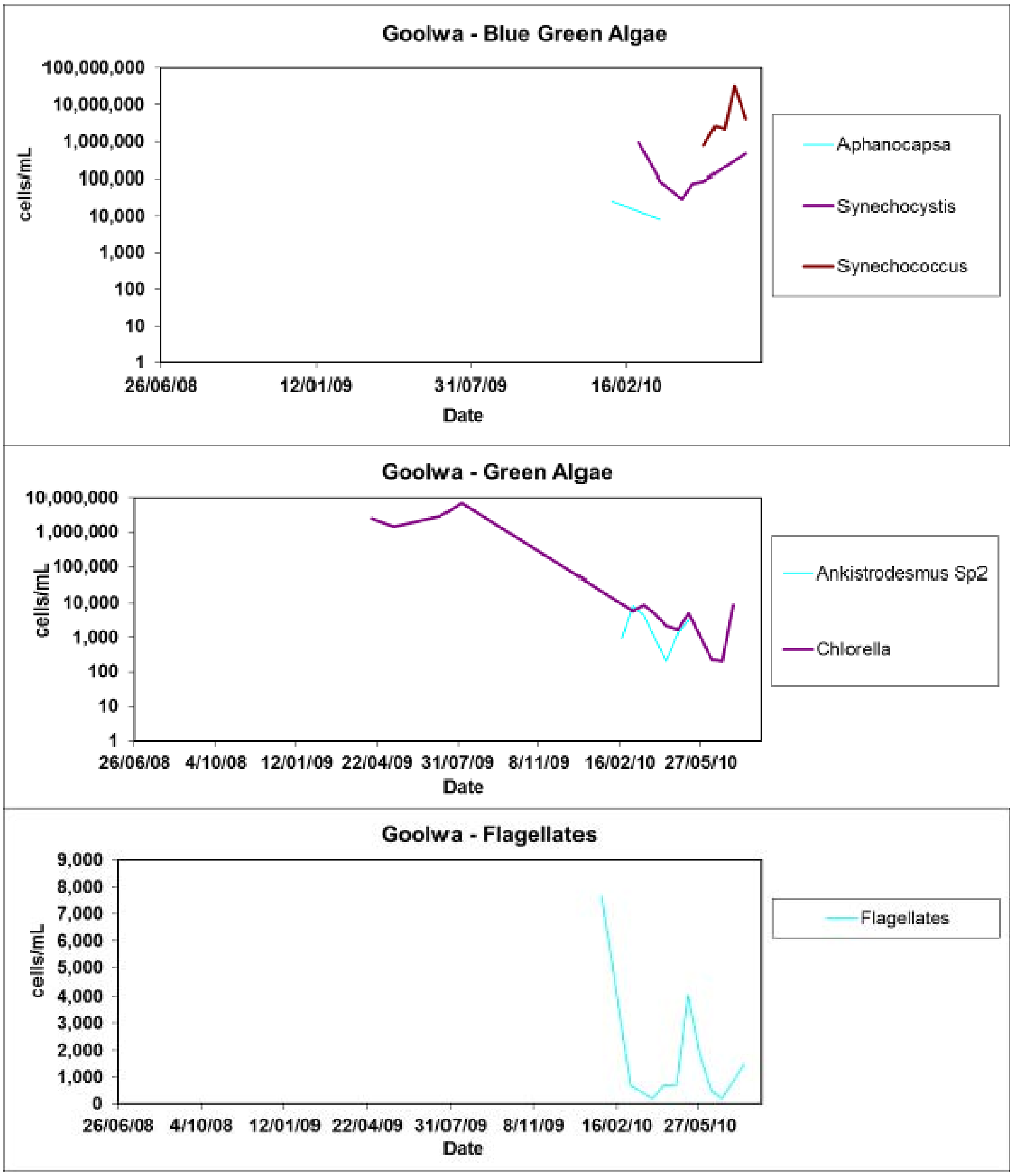


Figure 26 Goolwa Channel and Tributaries – blue-green algae, green algae, and flagellates (at Goolwa site). Note log scale used for blue-green and green algae.

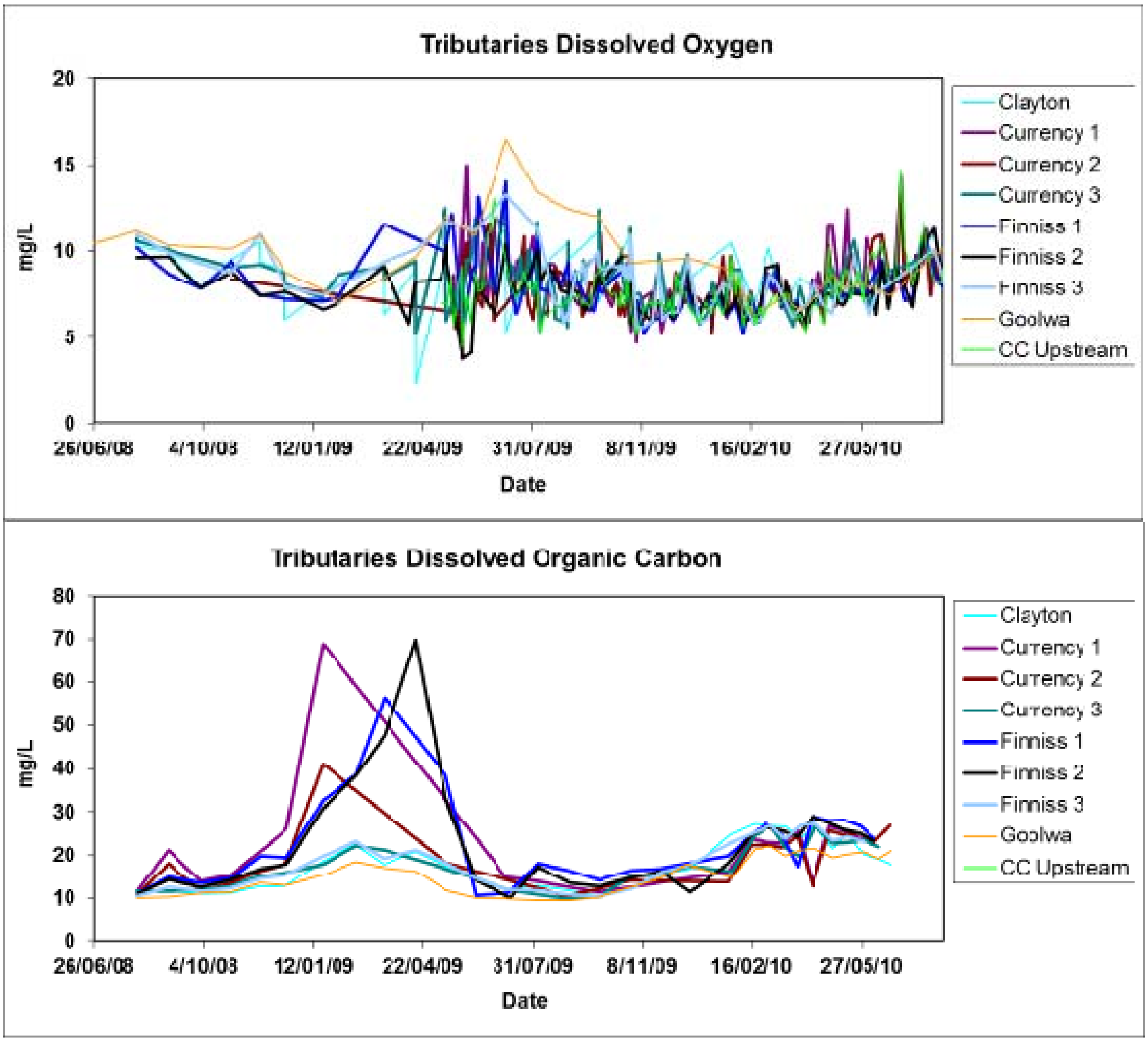


Figure 27 Goolwa Channel and Tributaries – dissolved oxygen and dissolved organic carbon

The concentration of major ions over the drought period is shown in Figure 28 and Table 9. As expected major ions followed a similar trend to salinity, with (1) a rapidly increasing trend over the summer of 2008–2009, (2) decreases during winter 2009 due to tributary flows and refilling of the pool behind the Goolwa Channel temporary flow regulator, and (3) increases over the summer of 2009–10 and (4) decreases in winter 2010 as the Tributaries began to flow again. Similar spatial patterns to salinity were also observed. The concentration of major ions versus the concentration of chloride is shown in Figure 29. For most of the sites, major ions showed a linear increasing trend with chloride concentration. The exception to this was bicarbonate which showed a great deal of variability within and between sites. At the Currency 1, 2 and 3 sites (sites which dried, acidified and were limestone dosed) there were increases in all major ion concentrations above that predicted by the chloride concentration. This suggests a source of these major ions that is not directly related to dilution and evaporative concentration and is likely related to acid sulfate soil influences and/or additional of limestone (predominantly $CaCO_3$ but contains other elements such as Mg) to the water body.

The sulfate:chloride and alkalinity:chloride ratio is shown in Figure 30. The sulfate:chloride ratio was relatively stable until the acidification in winter 2009 when levels increased markedly, particularly at the upper Currency Creek sites. This suggests a likely source of sulfate that is related to acid sulfate soil exposure and rewetting. Following the construction of the regulators this ratio stabilised across all sites. The alkalinity:chloride ratio showed temporal (decreases over summer and increases over winter) and spatial (lower in upper Currency, higher at Clayton) variation.

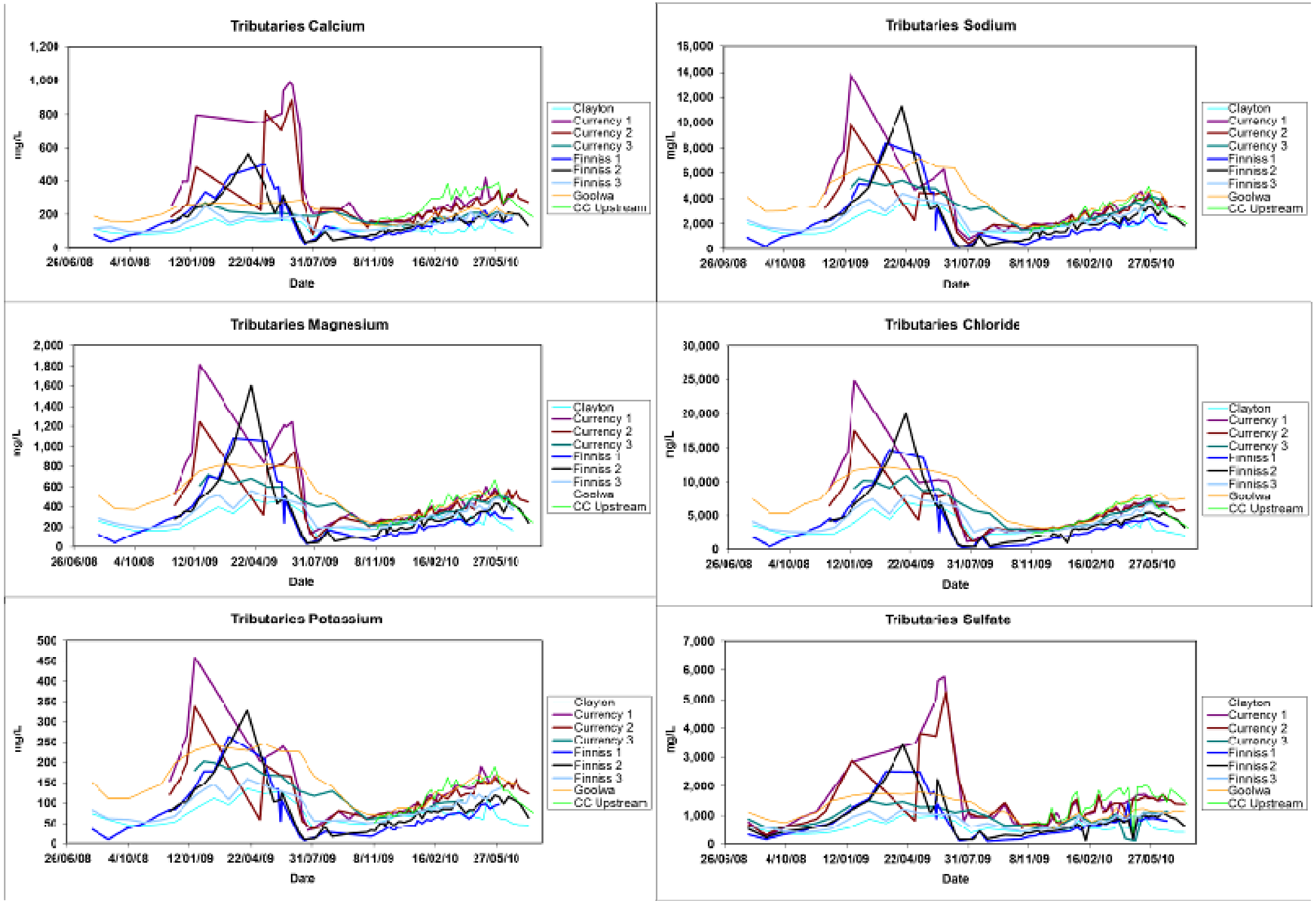


Figure 28 Goolwa Channel and Tributaries – major ions

Table 9 Goolwa Channel and Tributaries – summary statistics for major ions

Parameter	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Calcium (mg/L)	median	109	264	241	198	153	155	155	217	293
	25th percentile	98	202	182	184	94	109	136	176	193
	75th percentile	129	346	286	214	181	196	183	252	337
	no of samples	42	45	49	24	56	57	45	31	35
Magnesium (mg/L)	median	255	409	383	454	231	281	315	508	418
	25th percentile	214	306	280	362	143	181	252	399	265
	75th percentile	305	533	477	597	305	371	401	668	490
	no of samples	42	46	49	24	56	57	45	31	35
Potassium (mg/L)	median	69	123	116	129	62	80	89	146	129
	25th percentile	58	79	77	101	39	52	71	128	77
	75th percentile	83	164	150	180	95	103	116	199	148
	no of samples	44	44	49	18	51	57	44	33	35
Sodium (mg/L)	median	1,890	3,200	2,870	3,585	1,645	2,080	2,390	3,900	3,000
	25th percentile	1,640	2,130	1,950	2,750	999	1,330	1,800	3,085	1,955
	75th percentile	2,360	4,300	3,780	4,780	2,308	2,760	3,110	5,675	3,680
	no of samples	42	45	49	23	56	57	45	31	35

Parameter	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Chloride (mg/L)	median	3,500	5,270	5,030	6,400	2,750	3,700	4,130	7,410	5,220
	25th percentile	2,680	3,360	3,330	4,430	1,585	2,080	2,980	5,380	3,375
	75th percentile	3,793	6,820	6,395	8,650	4,293	5,050	6,015	10,000	6,745
	no of samples	44	47	49	26	60	57	47	33	35
Sulfate (mg/L)	median	545	1,280	1,130	938	594	627	761	1,120	1,490
	25th percentile	461	822	793	642	324	416	542	931	893
	75th percentile	615	1,590	1,525	1,120	843	927	990	1,465	1,810
	no of samples	44	49	53	31	56	59	46	32	35
Bicarbonate (mg/L)	median	229	84	77	201	147	173	202	205	49
	25th percentile	204	59	50	191	98	138	193	191	39
	75th percentile	245	110	112	212	164	184	213	219	56
	no of samples	44	52	56	32	61	62	47	33	35

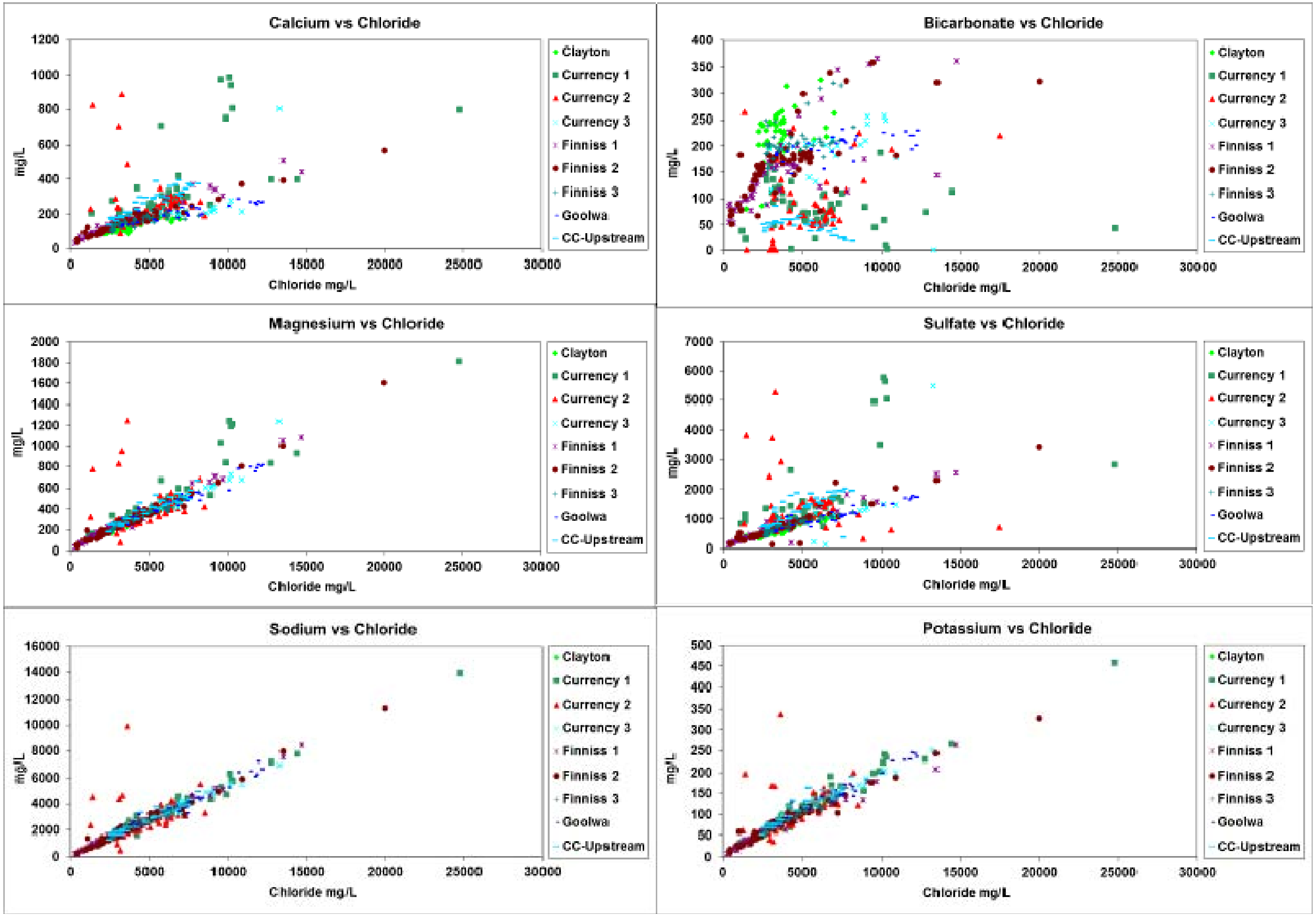


Figure 29 Goolwa Channel and Tributaries – major ions versus chloride

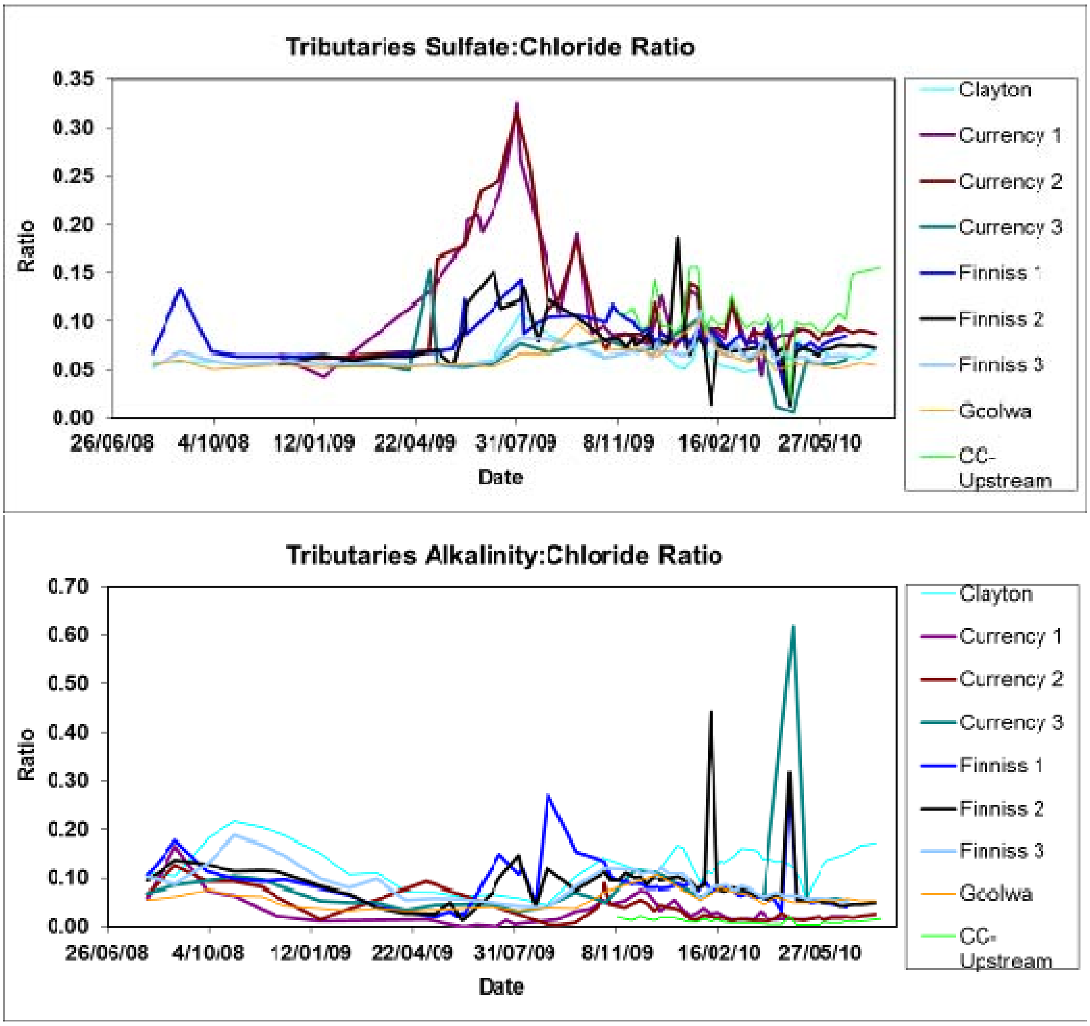


Figure 30 Goolwa Channel and Tributaries – sulfate:chloride and alkalinity:chloride ratio

The metal concentrations in the Goolwa Channel and Tributary region are shown in Figures 31–32 and Table 10. Total metal levels increased gradually throughout the summer of 2008–09, however very large increases occurred following the rewetting of the area in winter 2009. Increases were particularly large at the acidified Currency Creek sites, but were also apparent to a lesser extent at the non-acidic Finniss River sites. Soluble iron and aluminium concentrations were also very high when Currency Creek was acidic (Figure 31). Other soluble and total fraction metals, in particular manganese, cobalt and arsenic also increased during the acidification (Figure 32). Total and soluble metal concentrations have decreased and remained low since the construction of the Goolwa Channel temporary flow regulator.

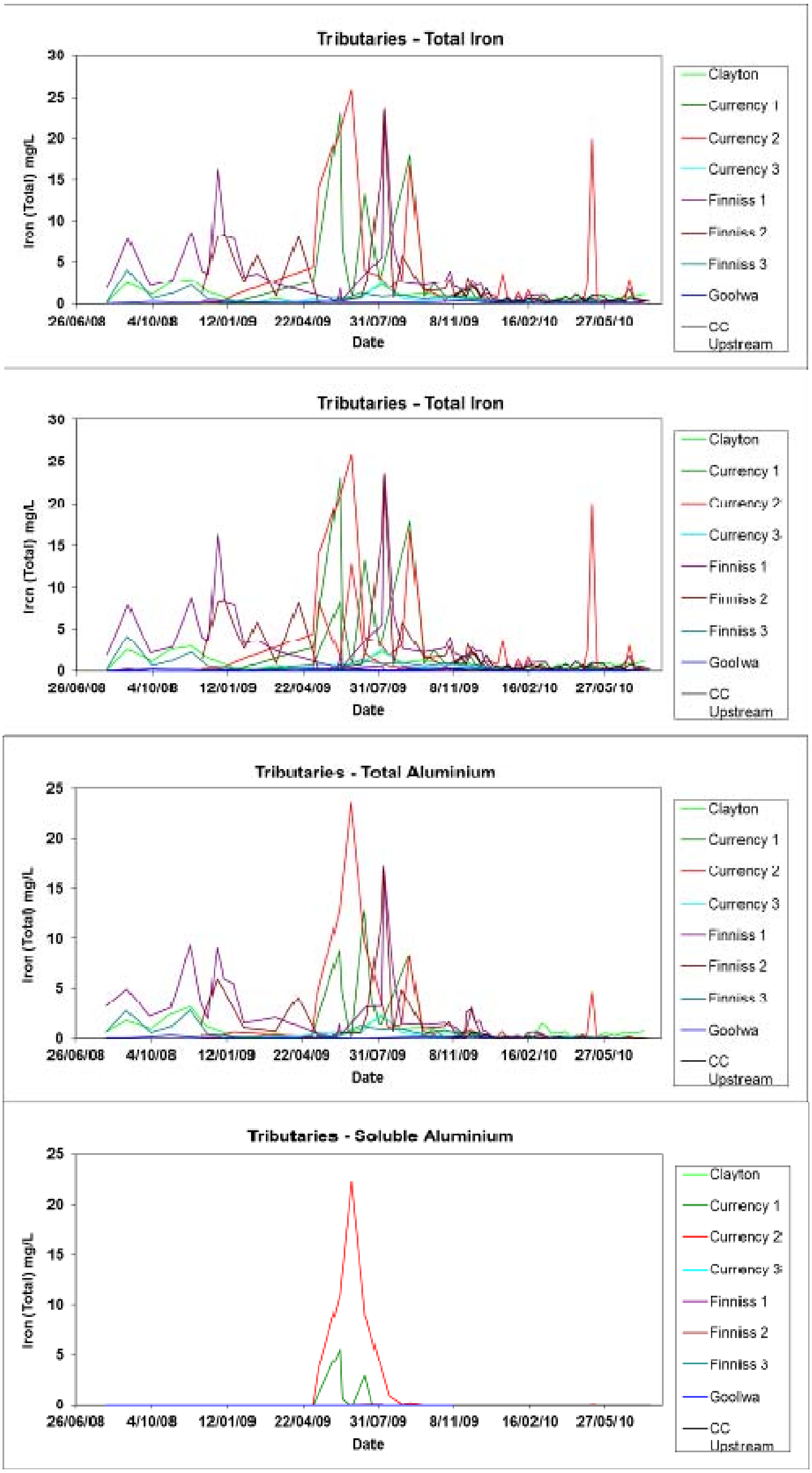


Figure 31 Goolwa Channel and Tributaries – metals (total and soluble iron and aluminium)

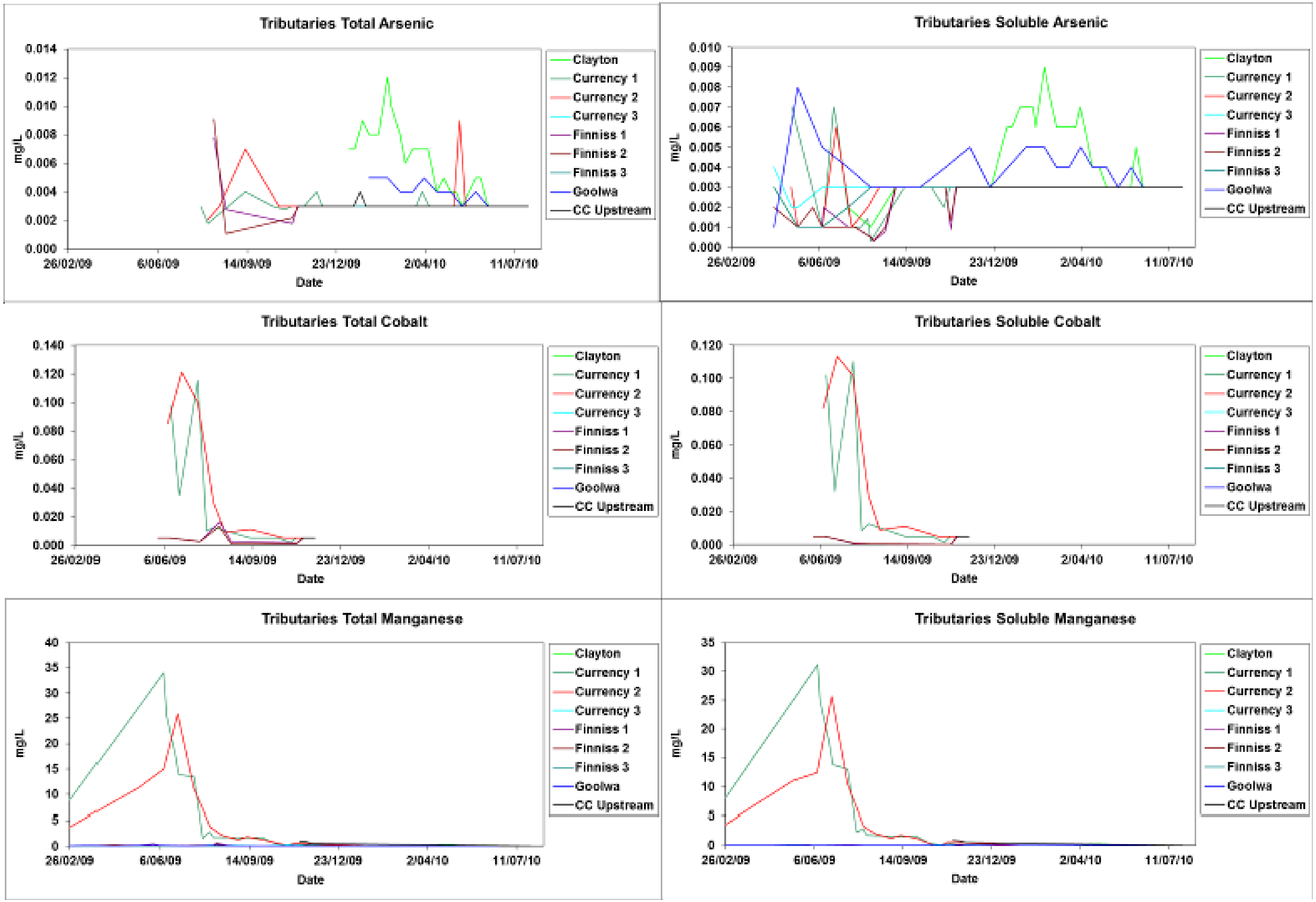


Figure 32 Goolwa Channel and tributaries – metals (total and soluble arsenic, cobalt and manganese)

Table 10 Goolwa Channel and Tributaries – summary statistics for metals (all concentrations in mg/L)

Parameter – mg/L	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Aluminium (soluble)	median	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	25th percentile	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	75th percentile	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	No of samples	42	46	49	26	60	55	47	33	35
Aluminium (total)	median	0.47	0.11	0.21	0.16	0.59	0.30	0.12	0.06	0.06
	25th percentile	0.18	0.05	0.05	0.07	0.17	0.10	0.06	0.02	0.03
	75th percentile	0.74	0.33	0.59	0.25	2.00	1.06	0.39	0.08	0.09
	no of samples	44	47	49	26	59	57	46	32	35
Arsenic (soluble)	median	0.004	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.003
	25th percentile	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	75th percentile	0.006	0.003	0.003	0.003	0.003	0.003	0.003	0.00475	0.003
	no of samples	33	43	45	22	48	48	37	22	35
Arsenic (total)	median	0.007	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.003
	25th percentile	0.004	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	75th percentile	0.008	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.003
	no of samples	25	34	39	11	48	37	25	22	35

Parameter – mg/L	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Chromium (soluble)	median	#N/A	0.001	0.001	#N/A	0.001	0.001	#N/A	#N/A	0.001
	25th percentile	#N/A	0.00055	0.001	#N/A	0.00025	0.0003	#N/A	#N/A	0.001
	75th percentile	#N/A	0.0035	0.005	#N/A	0.001	0.001	#N/A	#N/A	0.001
	no of samples	0	11	9	0	10	9	0	0	3
Chromium (total)	median	#N/A	0.0025	0.0026	#N/A	0.00205	0.002	#N/A	#N/A	0.001
	25th percentile	#N/A	0.001	0.001	#N/A	0.002	0.001	#N/A	#N/A	0.001
	75th percentile	#N/A	0.0045	0.009	#N/A	0.004675	0.0026	#N/A	#N/A	0.001
	no of samples	0	11	9	0	10	9	0	0	3
Cobalt (soluble)	median	#N/A	0.0086	0.011	#N/A	0.005	0.005	#N/A	#N/A	0.005
	25th percentile	#N/A	0.005	0.005	#N/A	0.000325	0.0003	#N/A	#N/A	0.005
	75th percentile	#N/A	0.041	0.082	#N/A	0.005	0.005	#N/A	#N/A	0.005
	no of samples	0	11	9	0	10	9	0	0	3
Cobalt (total)	median	#N/A	0.01	0.011	#N/A	0.005	0.005	#N/A	#N/A	0.005
	25th percentile	#N/A	0.005	0.005	#N/A	0.00335	0.0027	#N/A	#N/A	0.005
	75th percentile	#N/A	0.042	0.085	#N/A	0.005	0.005	#N/A	#N/A	0.005
	no of samples	0	11	9	0	10	9	0	0	3

Parameter – mg/L	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Copper (soluble)	median	#N/A	0.005	0.005	#N/A	0.005	0.005	#N/A	#N/A	0.005
	25th percentile	#N/A	0.00345	0.005	#N/A	0.001525	0.0019	#N/A	#N/A	0.005
	75th percentile	#N/A	0.01	0.01	#N/A	0.00875	0.01	#N/A	#N/A	0.005
	no of samples	0	11	9	0	10	9	0	0	3
Copper (total)	median	#N/A	0.006	0.006	#N/A	0.005	0.005	#N/A	#N/A	0.005
	25th percentile	#N/A	0.0044	0.005	#N/A	0.004475	0.005	#N/A	#N/A	0.005
	75th percentile	#N/A	0.01	0.01	#N/A	0.01	0.01	#N/A	#N/A	0.005
	no of samples	0	11	9	0	10	9	0	0	3
Iron (soluble)	median	0.005	0.021	0.023	0.006	0.013	0.007	0.005	0.006	0.034
	25th percentile	0.005	0.009	0.008	0.005	0.005	0.005	0.005	0.005	0.022
	75th percentile	0.016	0.041	0.074	0.014	0.031	0.019	0.013	0.012	0.062
	no of samples	42	46	49	26	59	54	46	30	35
Iron (total)	median	0.59	0.28	0.75	0.23	1.12	0.67	0.25	0.13	0.52
	25th percentile	0.30	0.17	0.25	0.13	0.38	0.23	0.15	0.07	0.35
	75th percentile	0.93	0.94	2.12	0.45	2.76	1.76	0.58	0.19	0.79
	no of samples	44	47	49	26	60	57	47	32	35
Manganese (soluble)	median	0.003	0.019	0.004	0.002	0.0039	0.003	0.002	0.003	0.657
	25th percentile	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.002	0.38925
	75th percentile	0.0145	1.76	1.335	0.007	0.0075	0.0075	0.005	0.008	0.8085
	no of samples	33	29	28	25	42	36	30	30	4

Parameter – mg/L	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Manganese (total)	median	0.061	0.034	0.05	0.026	0.066	0.05	0.042	0.036	0.664
	25th percentile	0.042	0.016	0.00575	0.017	0.039	0.039	0.026	0.01125	0.40125
	75th percentile	0.082	1.975	1.3825	0.056	0.10525	0.10525	0.056	0.06675	0.819
	no of samples	33	29	28	25	42	36	30	30	4
Nickel (soluble)	median	#N/A	0.026	0.028	#N/A	0.005	0.005	#N/A	#N/A	0.01
	25th percentile	#N/A	0.0085	0.008	#N/A	0.00385	0.00385	#N/A	#N/A	0.0095
	75th percentile	#N/A	0.11925	0.147	#N/A	0.005	0.005	#N/A	#N/A	0.01
	no of samples	0	11	9	0	10	9	0	0	3
Nickel (total)	median	#N/A	0.031	0.029	#N/A	0.0056	0.005	#N/A	#N/A	0.009
	25th percentile	#N/A	0.01	0.008	#N/A	0.005	0.005	#N/A	#N/A	0.009
	75th percentile	#N/A	0.1195	0.154	#N/A	0.006375	0.006375	#N/A	#N/A	0.01
	no of samples	0	11	9	0	10	9	0	0	3
Selenium (soluble)	median	#N/A	#N/A	#N/A	#N/A	0.001	0.004	#N/A	#N/A	0.001
	25th percentile	#N/A	#N/A	#N/A	#N/A	0.001	0.001	#N/A	#N/A	0.001
	75th percentile	#N/A	#N/A	#N/A	#N/A	0.001	0.001	#N/A	#N/A	0.001
	no of samples	0	0	0	0	1	1	0	0	3

Parameter – mg/L	Statistic	Clayton	Currency 1	Currency 2	Currency 3	Finniss 1	Finniss 2	Finniss 3	Goolwa	CC Upstream
Selenium (total)	median	#N/A	0.001	0.001	#N/A	0.001	0.001	#N/A	#N/A	#N/A
	25th percentile	#N/A	0.0007	0.001	#N/A	0.001	0.001	#N/A	#N/A	#N/A
	75th percentile	#N/A	0.001	0.001	#N/A	0.001	0.001	#N/A	#N/A	#N/A
	no of samples	0	11	9	0	10	9	0	0	0
Zinc (soluble)	median	#N/A	0.005	0.016	#N/A	0.005	0.005	#N/A	#N/A	0.005
	25th percentile	#N/A	0.005	0.005	#N/A	0.00155	0.00155	#N/A	#N/A	0.005
	75th percentile	#N/A	0.03	0.153	#N/A	0.02375	0.02375	#N/A	#N/A	0.005
	no of samples	0	11	9	0	10	9	0	0	3
Zinc (total)	median	#N/A	0.0119	0.034	#N/A	0.01075	0.007	#N/A	#N/A	0.005
	25th percentile	#N/A	0.007	0.005	#N/A	0.009275	0.009275	#N/A	#N/A	0.005
	75th percentile	#N/A	0.03495	0.158	#N/A	0.029125	0.029125	#N/A	#N/A	0.0055
	no of samples	0	11	9	0	10	9	0	0	3

Acidification events

In addition to the Currency Creek region, several other surface water acidification events occurred during 2008–2010 (Figure 33 and Table 11). These areas were on the shallow lake margins, often in embayments which have limited connection with the main lake water body (Figure 33). The total area that acidified was estimated to be 2,173 ha, which represented about 3% of the Lower Lakes surface water area. Different severities and durations (ranging from weeks to months) of acidification were observed. Neutralisation of acidification was accomplished naturally in several areas by dilution and alkalinity input following a rapid rise in lake levels following Murray–Darling Basin floodwater inflows during 2010.

Treatment of acidification via aerial, barrier, mound and slurry limestone addition occurred at Currency Creek and aerial limestone addition took place at Boggy Lake, and both exercises were highly successful in achieving neutralisation over large areas. The Currency Creek acidification and management has been discussed above in the Goolwa Channel and Tributaries section. Water quality results from two other sites where substantial acidification occurred, Loveday Bay and Boggy Lake, are discussed in further detail.

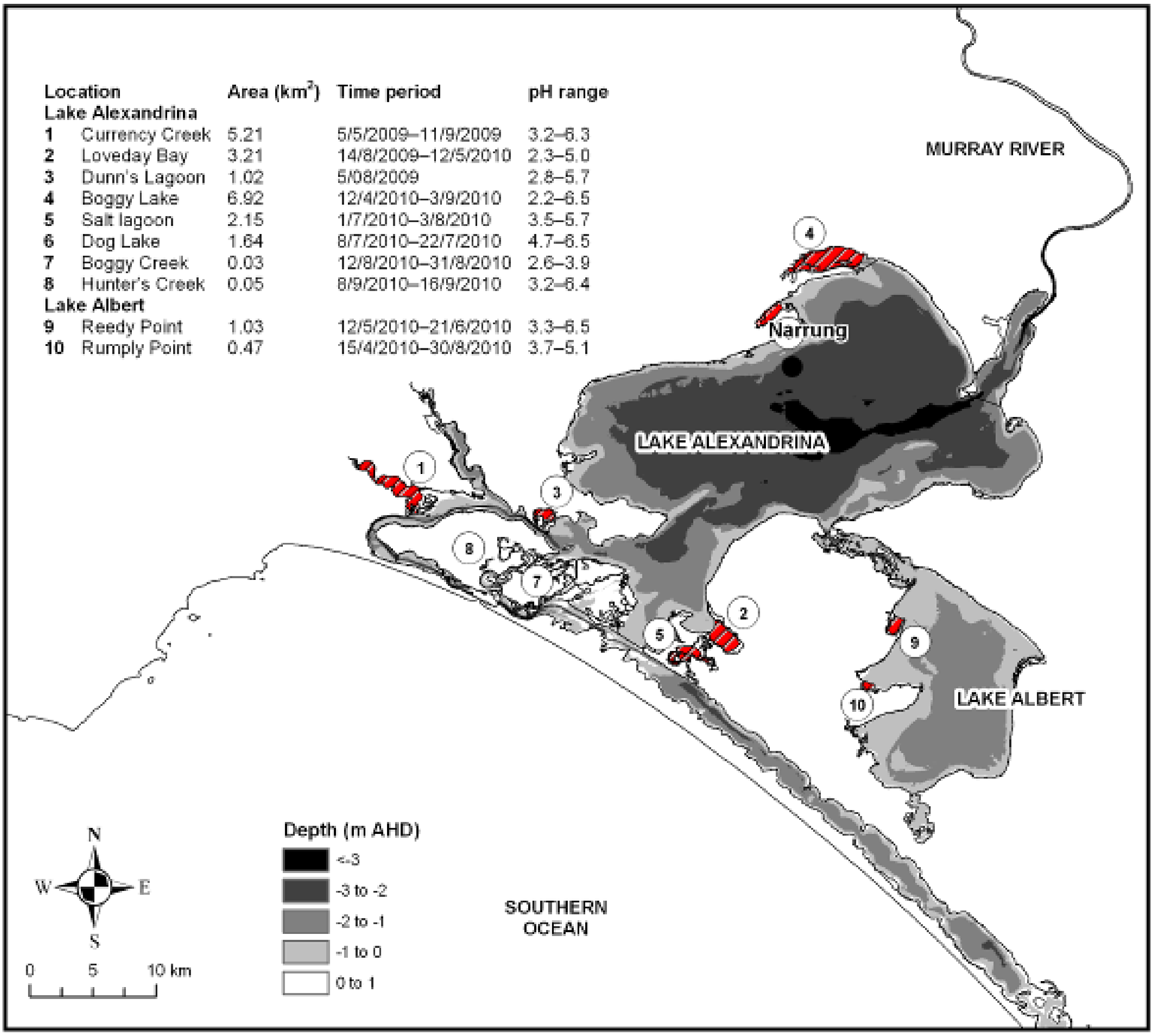


Figure 33 **Regions (red hatched areas) of the Lower Lakes that experienced surface water acidification during 2008–10. (Source: EPA, DENR data)**

Table 11 – Surface water acidification events in the Lower Lakes region during 2009–10

Acidification region	Water level (m AHD)	Acidified area (ha)[1]	Acidification period[2]	pH range[3]	Neutralisation process
Lake Alexandrina					
Currency Creek	0	521	5/5/2009–11/9/2009	3.2–6.3	Aerial limestone addition (1,000 tonnes plus 2,000 tonnes in limestone barriers), raising water levels via regulator construction and alkalinity addition via pumping
Loveday Bay	0	321	14/8/2009–12/5/2010	2.3–5.0	Dilution and alkalinity addition from lake refill
Dunn's Lagoon[4]	-0.25	102	5/08/2009	2.84– 5.68	Dilution and alkalinity addition from lake refill
Boggy Lake	0.25	692	12/4/2010–3/9/2010	2.2–6.5	Aerial limestone addition (1,000 tonnes), dilution and alkalinity addition from lake refill
Salt lagoon	0	215	1/7/2010–3/8/2010	3.5–5.7	Dilution and alkalinity addition from lake refill
Dog Lake	0.5	164	8/7/2010–22/7/2010	4.7–6.5	Dilution and alkalinity addition from lake refill
Boggy Creek	0	3	12/8/2010–31/8/2010	2.6–3.9	Dilution and alkalinity addition from lake refill
Hunter's Creek	0.4	5	8/9/2010–16/9/2010	3.2–6.4	Dilution and alkalinity addition from lake refill
Lake Albert					
Reedy Point	0	103	12/5/2010–21/6/2010	3.3–6.5	Dilution and alkalinity addition from lake refill
Rumply Point	0	47	15/4/2010–30/8/2010	3.7–5.1	Dilution and alkalinity addition from lake refill
TOTAL		**2,173**			

1 The area of acidified water is calculated using acidic surface water quality monitoring sites from 2009–10 (Source: DENR)
2 Beginning of acidification period may have preceded monitoring in some instances
3 pH range is only shown for values below ANZECC (2000) guidelines value of 6.5 (that indicates acidification).
4 Pore water monitoring sites are included in the acidified area for Dunns Lagoon (only one site was a surface water quality monitoring site).

Loveday Bay

Loveday Bay is a shallow lagoon located at the southeastern shore of Lake Alexandrina (Figures 33 and 34). When lake water levels fell below about 0 m AHD, about half of the lagoon (separated by a natural sand barrier) disconnected from Lake Alexandrina. A large area of this disconnected region dried in the summer of 2008–09 resulting in oxidation of acid sulfate soils. Following rewetting from winter rains in 2009 the area was sampled by CSIRO during a soil sampling project (Fitzpatrick et al 2010). They discovered large areas of acidic water and the water quality in the region was then sampled by the EPA over the subsequent months (Figure 34).

The disconnected area of the lagoon (sites LB1, 5 and 6) displayed large areas of very acidic water (pH <3 and high acidities) during 2009 and into the summer of 2010 when this area completely dried out (Figure 35). Iron precipitates and partially or completely dissolved mussel shells were also observed. Sites on the Lake Alexandrina side of the natural sand barrier (sites LB 8 and 9) remained neutral and connected to the main lake water body. Following the rapid rise in water levels during early 2010, the whole of Loveday Bay reconnected with Lake Alexandrina, and pH was returned to neutral level via natural dilution and neutralisation processes.

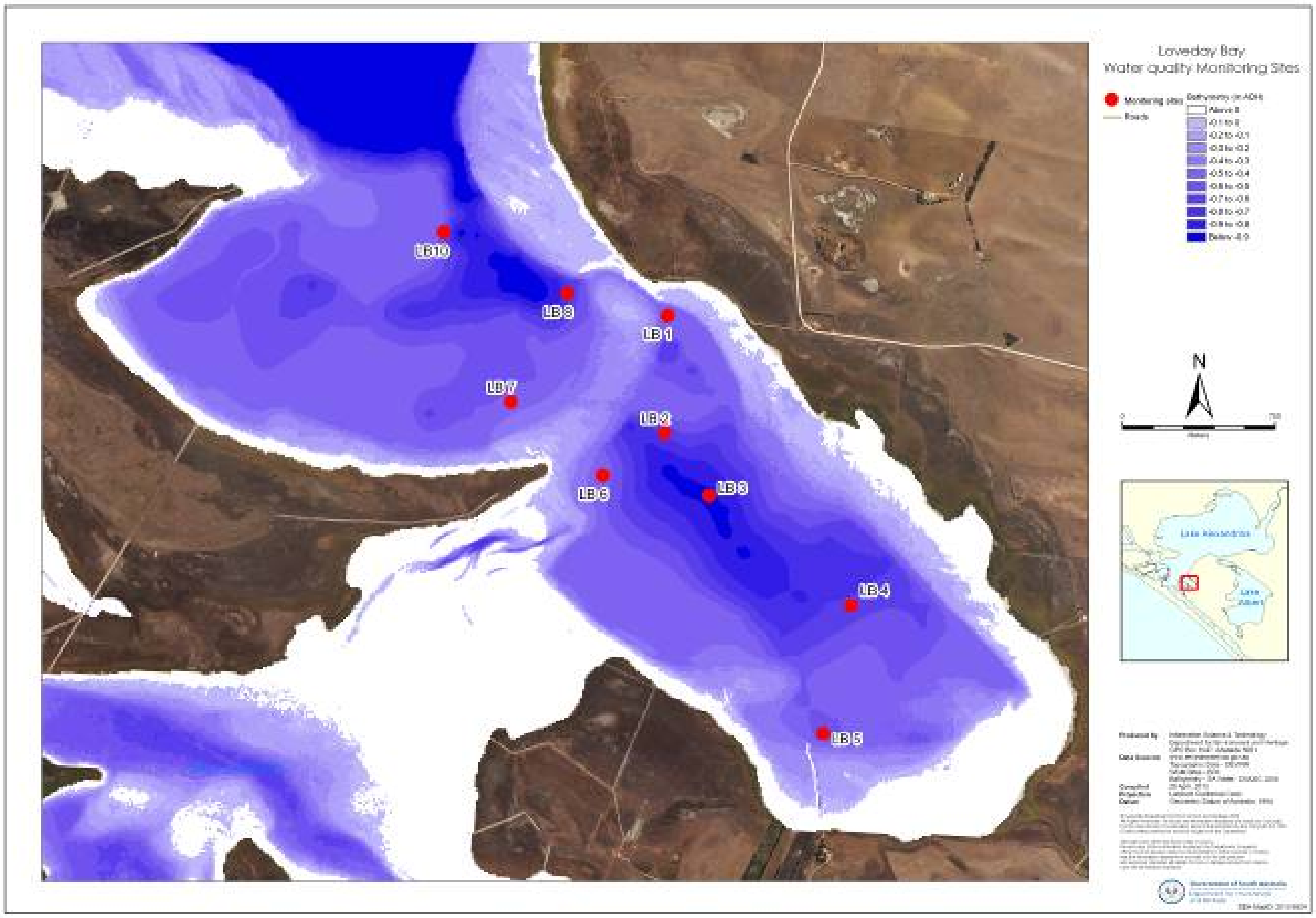


Figure 34 – Loveday Bay sample sites

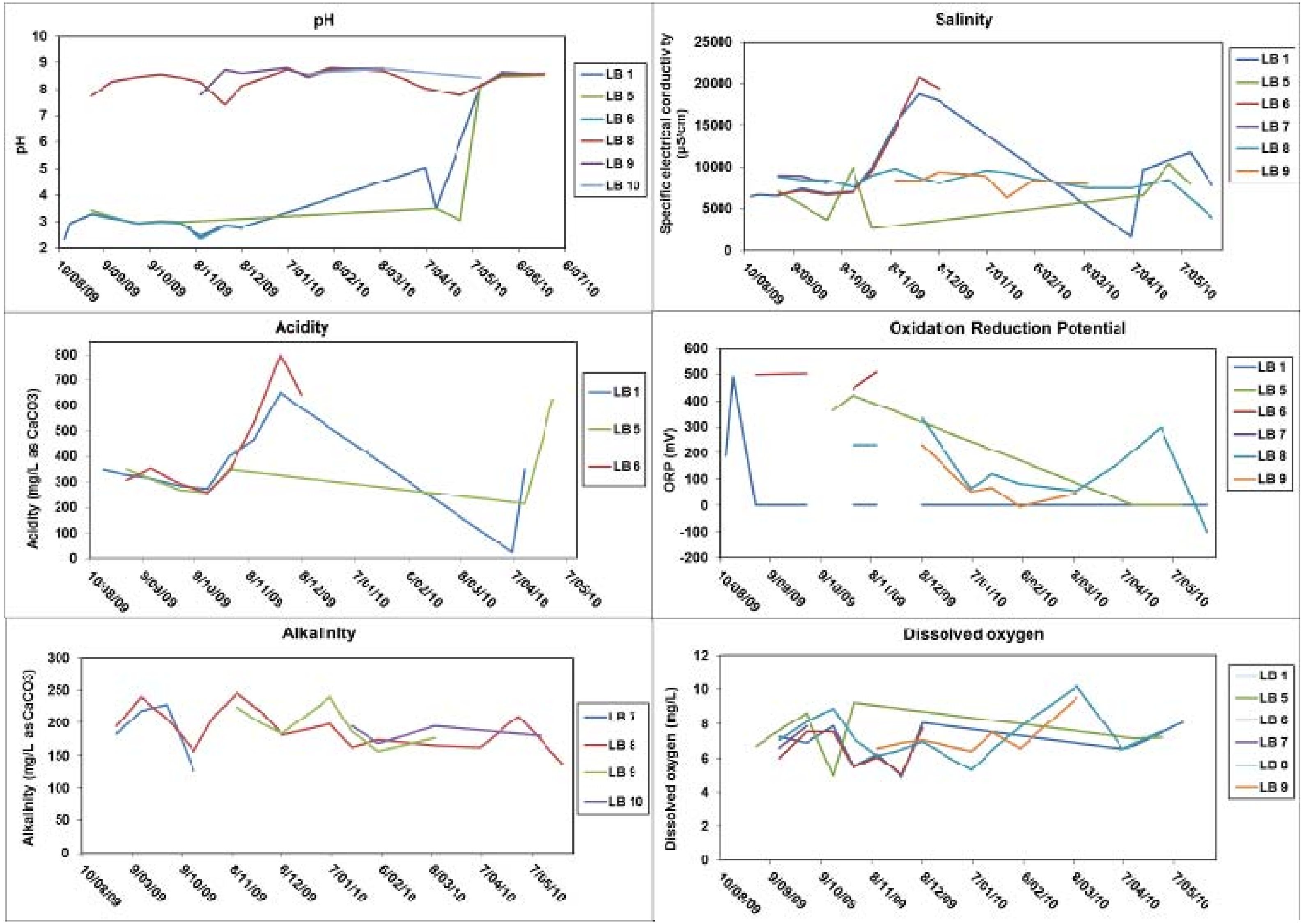


Figure 35 Loveday Bay – general water quality parameters

Boggy Lake

Boggy Lake is a shallow lagoon situated within the northwestern corner of Lake Alexandrina (Figures 33 and 36). During the water level declines from 2008–09, Boggy Lake became disconnected from the main lake water body. As a consequence large areas of acid sulfate soils (predominantly cracking clays, see front cover of this report) were exposed allowing the oxidation of pyrite to occur (Fitzpatrick 2010). During May 2010, rainfall events and water level increases in Lake Alexandrina progressively reinundated the Boggy Lake region.

Very acidic water (pH 2-3) was observed to be present over a large area, particularly in the western and northwestern margins of the lagoon that were furthest away from the main lake water body (Figure 37). The most acidic sections of the lagoon had low turbidity, very high acidity (up to 2,500 mg/L as $CaCO_3$), and very high dissolved metal (Al, Fe) concentrations. The acidified water increased in pH and reduced in acidity as they mixed with the alkaline waters of Lake Alexandrina. Orange and brown iron oxide precipitates were formed as the water was neutralised with precipitates (schwertmannite identified by CSIRO using X-ray diffraction) also found in non-acidic areas.

DENR undertook a series of aerial limestone dosing events (total of 1,000 tonnes) as shown by the dashed lines on Figure 37. Each dosing event reduced the water acidity and finally resulted in the water body becoming completely neutralised in early September 2010. Where pH was less than approximately 6.5, very large soluble aluminium levels were recorded above ANZECC guidelines for protection of aquatic organisms (Figure 38).

Figure 36 **Boggy Lake monitoring sites**

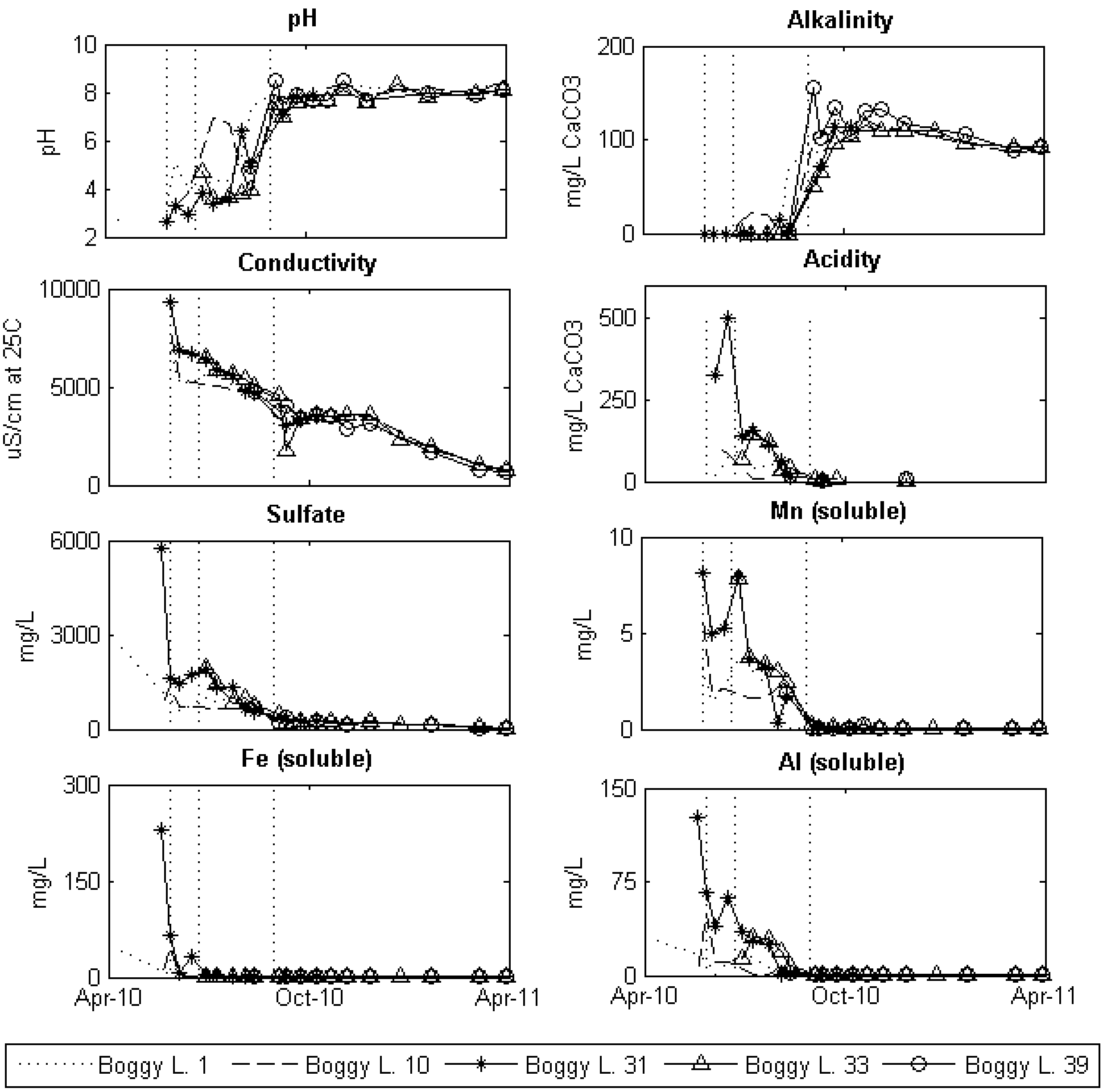


Figure 37 **Boggy Lake water quality data from selected sites (the vertical dashed lines indicate the aerial limestone dosing events)**

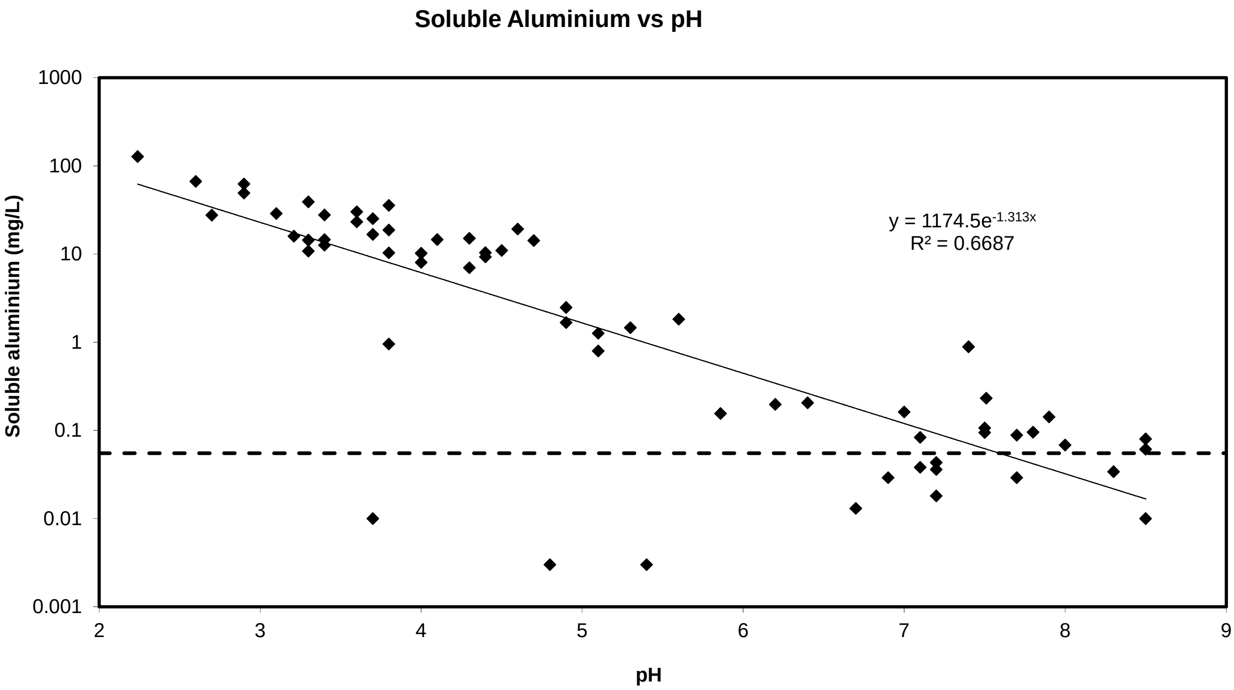


Figure 38 **Boggy Lake – Soluble Aluminium versus pH (note: log scale). The dashed line shows the ANZECC guideline of 0.055 mg/L.**

Aerial dosing of fine limestone at Currency Creek in 2009

Comparison of drought period with the long-term water quality dataset

A summary of the water quality data for the drought and reference periods is shown in Table 12(a) and (b) for three long-term monitoring sites in the Lower Lakes (Milang, Goolwa, Meningie). Time series of selected parameters (salinity, turbidity, TN, TP) are shown in Figure 39 for a selected lake site (Milang). Also shown on Figure 38 is the closest upstream monitoring site on the River Murray (Tailem Bend) which shows that, apart from minor increases in salinity, the river water quality entering the Lower Lakes during the drought period has generally improved (lower nutrient and turbidity levels).

There were large and significant ($p<0.0001$) increases in salinity/electrical conductivity at all Lower Lakes sites during the drought period, with median levels 3 to 10 times that of the reference period levels. The highest increase was at Goolwa where the median salinity of 1,801 µS/cm during the reference period rose to 17,080 µS/cm during the drought period.

Turbidity levels increased significantly in the Lower Lakes during the drought, with the exception of Goolwa. The increase was particularly large in Lake Albert, where median turbidity levels at Meningie during the drought (89 NTU) were over eight times those in the reference period (11 NTU).

No significant change in water temperature was found.

pH levels decreased slightly during the drought period at Goolwa, but there were no significant changes at Milang and Meningie.

TN levels increased significantly ($p<0.0001$) at all sites in the Lower Lakes during the drought period with median levels approximately double that of the reference period (Table 12). While apparent significant increases in NOx levels were observed during the drought period at Milang and Goolwa, the median values at all lake sites were very low (at or near the detection limit of 0.005 mg/L). The very low levels of dissolved nitrogen and high TN levels in the lakes suggest that a large amount of nitrogen is in organic form.

Similar to TN, TP increased significantly ($p<0.0001$) at all sites in the Lower Lakes during the drought period with median levels just under double that of the reference period (Table 12). In the Lower Lakes, FRP levels did not significantly change apart from at Goolwa, where concentrations were higher during the drought. At the other sites in the Lower Lakes (Milang and Meningie) all median FRP values in the lakes during the drought and reference periods were estimated to be below the detection limit (0.005 mg/L). In the Lower Lakes at Milang, all samples had TN:TP ratios above Redfield stoichiometry indicating a phosphorus limited system during both drought and reference periods (Table 12).

Chlorophyll *a* levels increased significantly during the drought period in the main areas of the Lower Lakes, particularly at Meningie where levels more than doubled. Goolwa did not show a significant change in chlorophyll *a* levels.

Power equation fits of water quality with mean lake depth (Figure 40) indicating that water level (and hence volume) changes were a good predictor of water quality change for the Lower Lakes.

The drivers of these water quality changes are briefly discussed. See Mosley et al (2012) for more detailed analysis and discussion.

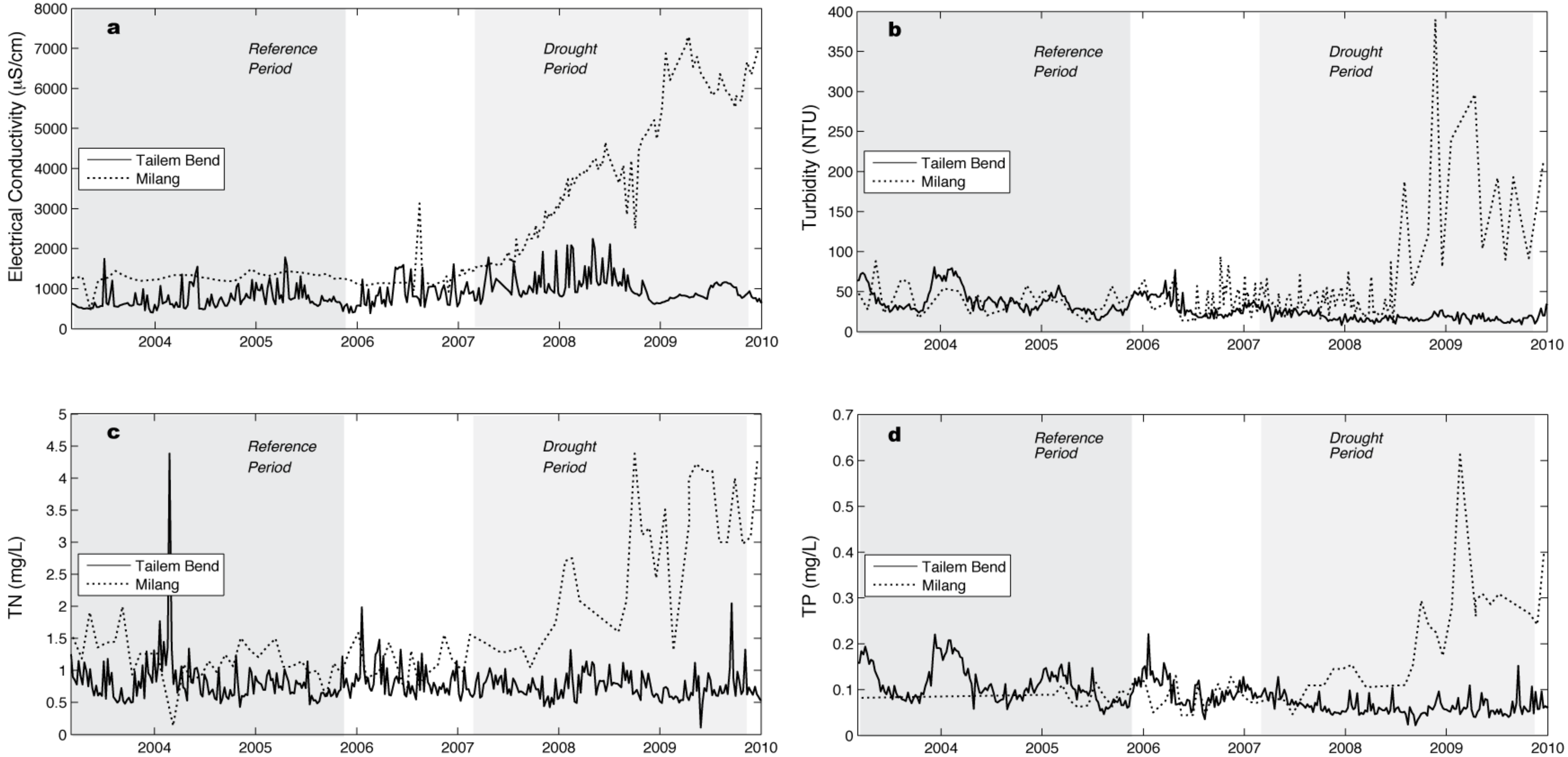


Figure 39 **Salinity (as measured by electrical conductivity), turbidity, total nitrogen and total phosphorus at Milang (Lower Lakes) and Tailem Bend (Lower River Murray) from 2003–10. The reference and drought periods used for the statistical comparisons are shown.**

Table 12 **Summary statistics (number of samples, n; median; interquartile range, IQR) and p-values (for significant differences based on Mann-Whitney U test) for (a) general water quality parameters and (b) nutrients and Chlorophyll *a* between the extreme low flow (March 2007–November 2009) and preceding reference (March 2003–November 2005) periods at Milang, Meningie, and Goolwa.**

Exceedances of water quality guidelines for 95% ecosystem protection from ANZECC (2000) are shown in bold. Where available, the guideline values used were specific ones provided for lakes in southcentral Australia. The chlorophyll *a* data was assessed against the hyper-eutrophic guideline value.

(a)

Parameter		**Milang**		**Goolwa**		**Meningie**	
		Low flow	**Ref.**	**Low flow**	**Ref.**	**Low flow**	**Ref.**
Conductivity (µS/cm)	n	97	31	44	31	67	30
	Median	3,840	1,293	21,900	2,165	7,360	2008
	IQR	2,820	125	11,058	1,392	5,170	284
	p-value	< 0.0001		< 0.0001		< 0.0001	
TDS (mg/L)	n	97	31	45	31	67	30
	Median	2,112	711	12,045	1,191	4,048	1,104
	IQR	1,551	69	6,082	766	2,844	156
	p-value	< 0.0001		< 0.0001		< 0.0001	
Water temperature (°C)	n	101	9	41	10	26	10
	Median	16.0	15.0	17.0	15.5	14.1	16.5
	IQR	7.0	8.0	7.0	5.8	6.5	4.3
	p-value	NS		NS		NS	
pH	n	108	10	44	10	69	10
	Median	8.5	8.6	8.4	8.6	8.5	8.5
	IQR	0.3	0.3	0.3	0.3	0.2	0.1
	p-value	NS		0.0015		NS	
Turbidity (NTU)	n	28	31	25	31	69	30
	Median	56	36	8	15	89	11
	IQR	88	23	9	7	56	17
	p-value	0.002		0.0002		< 0.0001	

(b)

Parameter		Milang		Goolwa		Meningie	
		Low flow	Ref.	Low flow	Ref.	Low flow	Ref.
TN (mg/L)	n	29	31	29	31	66	30
	Median	2.75	1.15	1.93	1.13	3.15	1.51
	IQR	2.18	0.39	0.98	0.30	1.45	0.57
	p-value	< 0.0001		< 0.0001		< 0.0001	
NO_x (mg/L)	n	29	31	29	31	66	30
	Median	0.005	0.002	0.009	0.001	0.006	0.001
	IQR	0.006	0.002	0.021	0.001	0.004	0.003
	p-value	< 0.0001		< 0.0001		NS	
TP (mg/L)	n	29	10	29	10	66	10
	Median	0.154	0.088	0.104	0.061	0.188	0.107
	IQR	0.157	0.028	0.095	0.062	0.068	0.046
	p-value	0.0079		0.004		0.001	
FRP (mg/L)	n	26	31	29	31	60	30
	Median	0.0025	0.0007	0.0036	0.0008	0.0047	0.0008
	IQR	0.0040	0.0033	0.0051	0.0016	0.0024	0.0025
	p-value	NS		0.0089		NS	
TN:TP ratio (molar units)	n	26	10	29	10	63	10
	Median	29.9	27.8	41.2	42.1	39.1	29.7
	IQR	5.0	9.9	13.4	5.3	44.4	7.7
	p-value	NS		NS		0.002	
Chlorophyll *a* (µg/L)	n	12	32	26	32	53	31
	Median	34.9	25.0	28.2	25.0	63.5	31.0
	IQR	8.3	10.4	35.6	7.0	44.8	21.4
	p-value	0.0236		NS		< 0.0001	

NS = not significant at 5% level (p>0.05), n/a = data not available and/or statistical test not applied

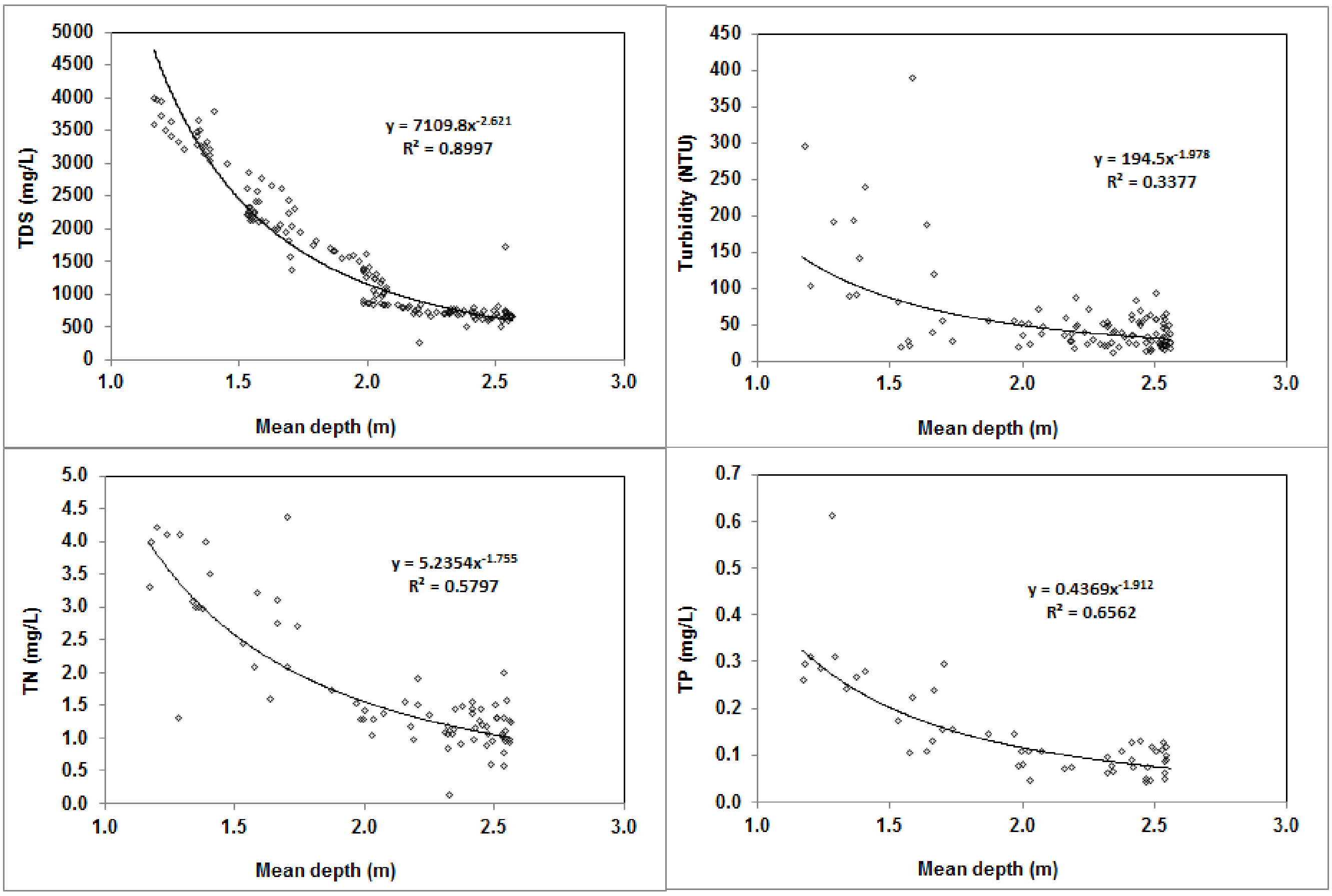


Figure 40 **Relationships between mean water depth with salinity (TDS), turbidity, TN and TP at Milang using data from 2003–10. See Mosley et al (2012) for more details.**

4 Discussion

The hydrological drought in the Lower Lakes from 2007 to late 2009 resulted in large water quality changes. These changes resulted from complex shifts in hydrological and biogeochemical processes, and were only able to be elucidated by intensive monitoring during the drought. The changing water quality dynamics before, during and after drought are represented on the conceptual model shown in Figure 41. The key processes represented on this model are discussed further below.

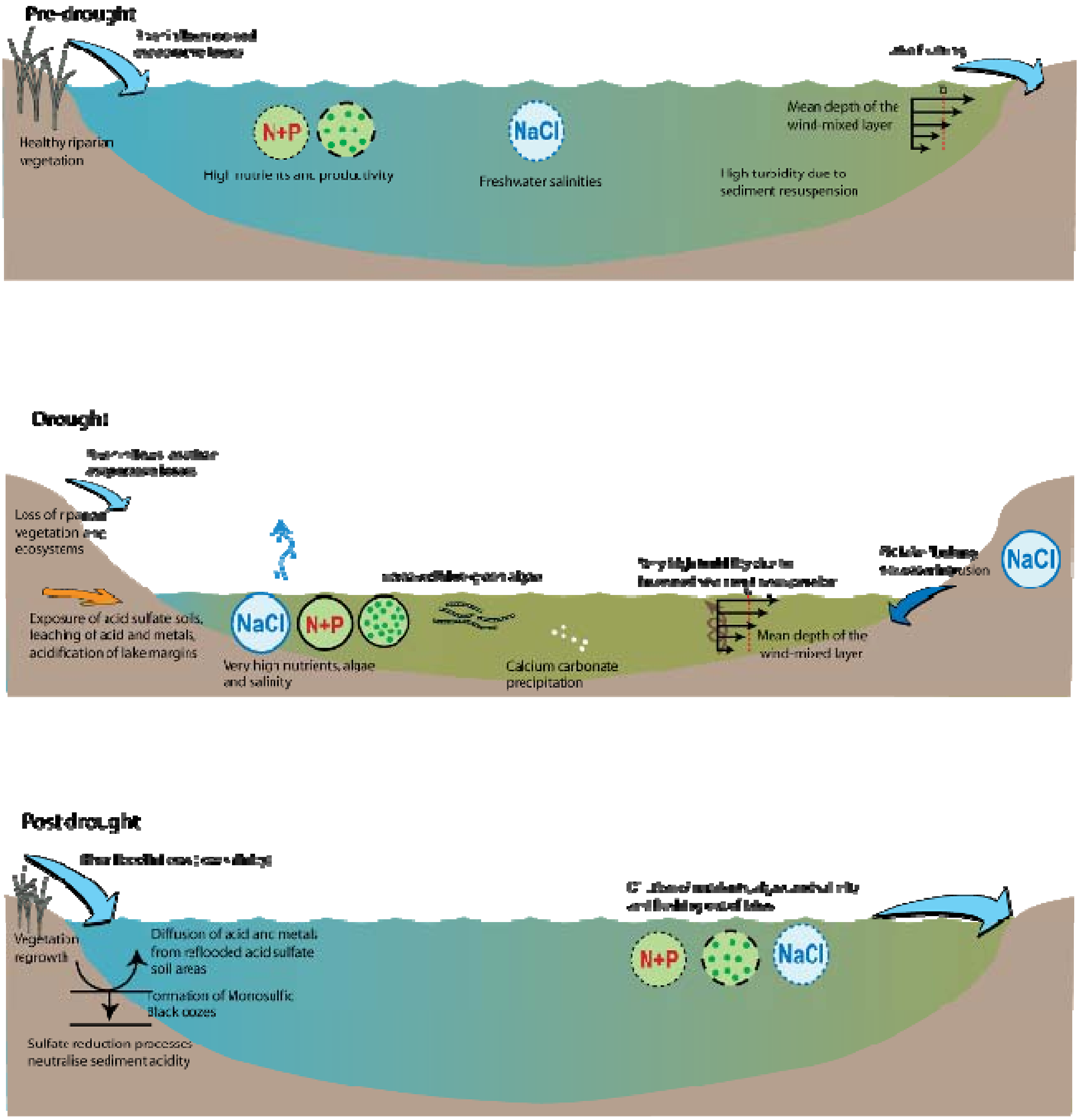


Figure 41 Conceptual model of processes leading to changing water quality pre, during, and post hydrological droughts in the Lower Lakes

River inflows and quality

The drought period from 2007–09 was characterised by extremely low River Murray inflows to the Lower Lakes. As a consequence water levels and volumes declined markedly in the Lower Lakes. This extreme hydrological outcome likely resulted from very low basin rainfall in the preceding year (279 mm in 2006) and longer term reductions in autumn rainfall in the basin, which is critical for preparing the catchment for runoff by replenishing soil moisture storages (Potter et al 2008, Timbal 2009). Recent evidence suggests the climatic and hydrological shifts occurring in the Murray–Darling Basin are associated with changing patterns in Indian Ocean temperatures (Ummenhofer et al 2010). The decisions to drawdown basin water storages in 2006 also hindered the ability of river managers to deliver regulated environmental flows the following years. A quantitative analysis of changes in the loadings of water quality constituents from the river into the Lower Lakes was not undertaken in this report. However, it is clear from the reduced river flow over Lock 1 (Figure 2) and reduced nutrient and turbidity concentrations (and only minor increase in salinity) at Tailem Bend (Figure 32) that loadings have reduced during the drought. This indicates that deteriorating water quality in the Lower Lakes during the drought is not driven by deteriorating river water quality as also discussed in more detail in Mosley et al (2012).

Influence of lake hydrology on water quality

A complete lack of lake flushing occurred from 2007–09 as no discharge over the barrages to the Coorong and Murray Mouth occurred. This resulted in a concentration of dissolved and particulate material in the lakes driven by evaporation and the associated large reductions in lake volume. Salinity increases were very large, particularly in the southern regions of the lake furthest from the river inflow and closest to the barrages, which leaked seawater into the lakes (due to sea levels being higher than the lakes for much of drought period). As a consequence of these salinity increases, major losses of freshwater species occurred (Nielsen 2003[1], EPA 2010, AWQC 2012) and the water became unsuitable for irrigation (ANZECC 2000). Despite the dilutions during 2010, salinity levels still exceed guidelines for maintenance of healthy freshwater ecosystems (Nielsen et al 2003). Lake Albert will take some time (years) to recover as being a terminal lake system with a narrow and shallow entrance, it is difficult to flush.

Increases in the major ion concentrations during the drought were generally consistent with the changes in the water balance (river and rainfall inflows – evaporation) as illustrated by linear relationships with chloride concentration. The exception to this was for bicarbonate and to a less extent calcium. Modelling calculations (PHREEQC version 2, using typical inorganic chemical composition) indicated saturation of the lake waters during the drought period with respect to calcium carbonate ($CaCO_3$, calcite and aragonite) and hydroxyapatite ($Ca_5(PO_4)_3OH$). This suggests these minerals may be precipitating in the lake, resulting in a decoupling of calcium and bicarbonate from the behaviour of the other major ions. The possible precipitation of hydroxyapatite could also help maintain low soluble phosphorus levels however the kinetics of this reaction are slow and may be inhibited in natural waters (Inskeep and Silvertooth 1988) and algal uptake of soluble P is likely to be more important. The influence of acidification events on major ion chemistry in localised areas is discussed below.

The lack of lake flushing during the drought period also likely resulted in the observed very high concentration of nutrients and algae. This effect has been observed in other temperature lake locations (Dillion 1975, Schindler et al 1996, Schindler 1997). In the Lower Lakes, soluble nutrients remained very low during the drought, and the high TN:TP ratio and dominance of cyanobacteria suggest that the lakes were phosphorus limited (Schindler et al 1998). Any soluble nutrients that become available appear to be rapidly taken up by algae and the lakes were classed as hyper-eutrophic under the ANZECC (2000) classification. It is uncertain whether any of the nutrient increases relate also to fertiliser additions to the sediment margins as was conducted in the Lower Lakes revegetation program.

In most regions of the Lower Lakes during the drought the phytoplankton community has been dominated by cyanobacteria (predominantly non-toxic Planktolyngbya, Aphanocapsa, Synechocystis species although a large toxic Nodulariaspumigena bloom occurred in Lake Albert during the winter–spring of 2009). This cyanobacterial dominance in the lakes is a distinct shift from the green algae (Planctonemalauterbornii) dominated phytoplankton community reported

[1] Few freshwater species are predicted to remain above 8,000 µS/cm electrical conductivity (EC), and the diversity of freshwater ecosystems decreases rapidly above 5,000 EC.

by Geddes (1984) during a period of higher flow. Increased eutrophication leads to increased cyanobacteria biomass and dominance in temperature lake systems (Pick and Lean 1987).

In general our results indicate there is increased cyanobacterial dominance in the Lower Lakes during hydrological droughts. The exception to this general trend was the presence of high levels of green algae (Chlorella) over much of the sampling period at Goolwa. The reasons for this are unclear but may relate to the increased salinity and marine influences, and the associated low turbidity in the Goolwa Channel relative to other sites. The blue-green algal species (Synechocystis and Synechococcus) that became more dominant during 2010 in the Goolwa Channel were known salt-tolerant species and this differed from the blue-green algal species composition seen at other sites. Water temperature did not increase during the drought so this does not appear to be a factor in driving increased productivity during hydrological droughts in the Lower Lakes.

Dissolved organic carbon, and to a less clear extent colour, follow seasonal patterns with highest levels in summer and lowest levels in winter. This is likely due to increased algal productivity and breakdown of particular organic matter in the higher water temperatures of summer months. Dissolved oxygen is maintained near saturation throughout the Lower Lakes which is likely due to rapid replenishment from the atmosphere via wind mixing (regularly turning over the entire water column) on the shallow lakes. However depth profiling undertaken by Aldridge et al (2009) found some localised low dissolved oxygen levels in deeper waters of the Goolwa channel.

Suspended sediment dynamics

Turbidity increased during the drought in the Lower Lakes, particularly in Lake Albert, which became very shallow (<1 m deep on average) for much of the drought period. This increase is likely due in part to the dominance of the colloidal fraction in the Murray system which stays in suspension (Douglas et al 1993) and can be concentrated during the lake volume decline. Turbidity levels in the Lower Lakes during the drought have also been found to correlate with the depth of the wave mixed layer as controlled by wind speed and fetch (Skinner 2010). As the lakes have become much shallower during the drought, the wave mixed layer has been able to reach a much greater area of bottom sediment (Mosley et al 2012). This has likely increased the amount of sediment resuspension during the drought and led to the elevated turbidity levels. In addition, finer clay sediments are predominantly found towards the middle of the lakes (Barnett 1993), so there was likely more mobilisation of finer sediment materials as water levels declined.

Interestingly the ambient metal (Fe and Al) levels were well correlated with each other but not well correlated with turbidity. This could suggest, at least at certain times, the turbidity is comprised of large amounts of organic material (eg living or dead algal cells) and/or an additional source of Al and Fe (possible acid sulfate soil related) that is not directly correlated to resuspended material. As noted earlier, increased algal productivity occurred during the drought despite higher turbidities which would have reduced light penetration. The resuspension of chlorophyll in dead algal biomass which has settled out of the water column may be giving a misleading impression of increased productivity. The lower turbidity levels at Goolwa compared with the other sites are likely due to dilution from the seawater intrusion and salt-induced flocculation of clay colloids (Mosley et al 2003). Further research during water level decline is required to separate out the relative importance and dynamics of these sediment processes.

Acidification on lake margins

The very low water levels during the drought resulted in exposure of large areas of sediments containing acid sulfate materials (Fitzpatrick et al 2008, 2010). The rewetting of these sediments via rainfall events or lake refill resulted in quite substantial (3%) areas of the Lower Lakes turning acidic. Metals, most notably aluminium which is highly toxic to aquatic organisms, major ions and nutrients were released at the same time. The Lower Lakes Acid Sulfate Soil Research Program (DENR 2010) had predicted in advance acidification of marginal areas based on soil surveys (Fitzpatrick et al 2010), acid and metal mobilisation experiments (Simpson et al 2010, Sullivan et al 2010, Hicks et al 2010), and lake geochemical modelling (Hipsey et al 2010). This information enabled targeted and effective monitoring and management using limestone dosing in Currency Creek and Boggy Lake. The other acidified areas neutralised naturally following the rapid refill of the lakes in 2010 and subsequent dilution and inflow of alkalinity. The sulfate:chloride ratio was a good indicator of acid sulfate soil impacts. The reduction in this ratio, as occurred when Lake Albert was refilled, also indicated sulfate reduction processes as these acidic soils were reinundated.

The very acidic waters had low turbidity. This could indicate either dissolution of the clay minerals comprising the turbidity and/or flocculation of the turbidity due to very high soluble aluminium and sulfate concentrations.

Following neutralisation, metal precipitates were observed in many areas due to hydrolysis and subsequent precipitation of the dissolved metals. Acidic precipitates were also observed but were likely to be transient and persist only while low pH conditions are present. The long-term fate of these metal precipitates is currently unclear but they are known to be aquatic organisms (Stauber et al 2008). The overall ecological impacts of these acidification events are uncertain and difficult to determine as they were preceded by drying and salinisation which caused their own severe impacts. The sediment may remain toxic for some time after the water column is neutralised and further research is required to assess risks to benthic organisms.

Management implications

Along with many other arid and semi-arid river systems, median river flows in the southern Murray–Darling basin are predicted to decline further over the next 20 years (13% decrease by 2030) due to climate change (CSIRO 2008). Hence extreme low flow periods will likely become more frequent and intense in these vulnerable systems. Careful water resource planning and management will be required in arid systems to prevent water quality deteriorating to the point where socio-economic and environmental values are threatened. The findings in this report strongly support that a substantial increase in environmental flows to maintain system flushing, water levels and quality in the lower reaches of the system during low flow conditions.

5 Conclusion

The results of this monitoring study demonstrate that water quality in the Lower Lakes at the end of the Murray–Darling Basin deteriorated substantially during the hydrological drought from 2007–09. There were dynamic and complex interactions between hydrology and bio-geochemical processes leading to the observed water quality outcomes during the drought. A marked shift to a more saline, turbid and eutrophic system occurred during the drought. These water quality changes were attributed to a lack of flushing, which coupled with lake volume reductions, resulted in concentration of dissolved and suspended material and increased wind-driven resuspension of sediments as the lakes became much shallower.

Cyanobacterial species became more dominant with one large toxic bloom recorded. Rewetting of exposed acid sulfate soils on the lake margins also resulted in severe surface water acidification and very high soluble metal levels in over 2,000 ha of surface water. The poorer water quality during the drought has had substantial negative impacts on the aquatic ecosystems and associated socio-economic values in the region. Droughts and water security problems are projected to intensify in the future in southern Australia. Improved basin-wide water management will be required to prevent future water quality impacts similar to that which occurred in the Lower Lakes during the current drought.

Recommendations

- Further research and monitoring of acid fluxes from acidified sediments that are now submerged.
- Further assessment of water quality during future low flow events is recommended in Lower Lakes region, as well as the time period for recovery from the recent event.
- Further research is undertaken on mechanisms of nutrient supply and demand in the Lower Lakes, including possible phosphorus fluxes from suspended and benthic sediment and algal nutrient requirements, and influence of zooplankton dynamics.
- Further research on dynamics of concentration and resuspension of sediment and algal material during low water levels.
- Linkages of water quality and algal dynamics with zooplankton and higher trophic level dynamics.

6 Acknowledgements

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Appendix 1 Limestone treatment amounts (approximate) and dates

Table A1 Boggy Lake Limestone treatment dates and amounts

Limestone treatment stage	Date	Tonnes of calcium carbonate	Hectares treated
1	28 May, 1–3 June 2010	420	332
2	22 – 24 June 2010	400	341
3	29 – 30 August 2010	175	370
Total		995	1,043

Table A2 Timeline of 2009 limestone dosing program in Currency Creek and the Finniss River

<table>
<tr><th>Region</th><th>Month</th><th>Location</th><th>Method</th><th>Amount (approximate tonnage)</th></tr>
<tr><td rowspan="12">Currency Creek</td><td colspan="4">Stage 1</td></tr>
<tr><td>April -May</td><td>Upper Currency Creek</td><td>Barriers</td><td>305</td></tr>
<tr><td>April -May</td><td>Currency Creek Hill</td><td>Mounded barriers</td><td>251</td></tr>
<tr><td colspan="4">Stage 2</td></tr>
<tr><td>May–July</td><td>Lower Currency Creek</td><td>Barriers</td><td>831</td></tr>
<tr><td>June–July</td><td>South of Currency Creek Hill</td><td>Barriers</td><td>230</td></tr>
<tr><td>June</td><td>Middle of lower Currency Creek</td><td>Slurry dosing</td><td>43</td></tr>
<tr><td>June</td><td>Upper Currency Creek</td><td>Dry aerial dosing</td><td>120</td></tr>
<tr><td>June</td><td>Lower Currency Creek</td><td>Dry aerial dosing</td><td>271</td></tr>
<tr><td>July</td><td>Lower Currency Creek</td><td>Dry aerial dosing</td><td>600</td></tr>
<tr><td>July</td><td>Lower Currency Creek</td><td>Slurry aerial dosing</td><td>9</td></tr>
<tr><td colspan="3">Subtotal</td><td>2,660</td></tr>
<tr><td rowspan="3">Finniss River</td><td colspan="4">Stage 1</td></tr>
<tr><td>April</td><td>Upper Finniss River</td><td>Mounded barriers</td><td>312</td></tr>
<tr><td colspan="3">Subtotal</td><td>312</td></tr>
<tr><td>Combined</td><td colspan="3">Total</td><td>2,972</td></tr>
</table>