Draft Coastal Zone Management Plan for Wooloweyah Lagoon

PART 2: APPENDICES

Prepared by:

Dr Nicole White

Clarence Valley Council

2009

Wooloweyah Lagoon, from Radial No. 1

Locked Bag 23
GRAFTON NSW 2460

Phone: (02) 6643 0200
Fax: (02) 6642 3108
E-mail: council@clarence.nsw.gov.au

Funded by:

clarence valley COUNCIL

Department of Environment, Climate Change and Water NSW

December 2009

Appendix A

Wooloweyah Lagoon

Condition Assessment

Clarence Valley Council

Department of Environment, Climate Change and Water NSW

Prepared by:

Nicole White

November 2009

Clarence Valley Council
Locked Bag 23
GRAFTON NSW 2460

Phone: (02) 6643 0200
Fax: (02) 6642 3108
E-mail: council@clarence.nsw.gov.au

Funded 1:1 by Clarence Valley Council, and the Department of Environment, Climate Change and Water NSW through the Estuary Management Program.

Acknowledgements

The Steering Committee established to oversee the progress of the Wooloweyah Lagoon Condition Assessment was comprised of representatives from Clarence Valley Council, Department of Environment, Climate Change and Water, Industry and Investments NSW, Land and Property Management Authority and the Northern Rivers Catchment Management Authority.

Thankyou to John Harrison from the Professional Fishermen's Association for organising the initial boat trips to the lagoon for reconnaissance, and to the fishermen who were the guides. Also thankyou to the landholders for allowing access through their property.

Executive Summary

Wooloweyah Lagoon catchment is an ecologically and economically important area on the Clarence River floodplain. The lagoon is listed as a wetland of national importance and provides significant shorebird habitat. Within the catchment are a number of habitats listed as Endangered Ecological Communities and much of the eastern area is national park. The two major industries within the catchment are the estuary prawn trawl and sugarcane.

The aim of the Wooloweyah Lagoon Condition Assessment was to provide information on the current health of the lagoon and identify potential management issues within the catchment. Land use immediately adjacent to the lagoon and channels includes Yuraygir National Park to the southeast, urban development to the east and northeast (Wooloweyah village and Yamba), rural-residential development in the south (Gulmarrad), and agriculture (predominantly sugar cane and grazing) to the west and south. Associated with the agriculture is the extensive Taloumbi drainage network.

The condition assessment was conducted over a 12-month period to capture seasonal changes in water and sediment quality, monitor runoff water quality from different land uses within the catchment, and provide a broad overview of catchment processes, health and pressures. Turbidity and nutrients have been identified by a range of earlier studies as water quality issues within the Wooloweyah Lagoon catchment.

Turbidity within the lagoon was a function of wind speed, wind direction, duration of wind speed and direction, and the turbidity of runoff water entering the lagoon. Lagoon turbidity was often above the trigger value recommended by the Healthy Rivers Commission (1999) due to these (primarily) natural processes. No long-term influence of trawling on lagoon turbidity could be determined from the data collected, however, short-term increases in turbidity were apparent immediately behind trawlers. The turbidity of runoff water was generally highest from areas under sugarcane, although during non-rainfall periods the national park sites had higher turbidity than those under agriculture, suggesting that the sediments within the catchment may have an elevated erosion potential.

Nutrient concentrations were highest in Palmers Channel and the drains which discharge into it (Middle Road and Carrs Drains). Concentrations within the Taloumbi Drain were also higher than in the lagoon. Accordingly, chlorophyll-*a* concentrations were also relatively high through the monitored waterways, although no algal blooms were observed. The bottom sediments of Wooloweyah Lagoon were also identified as a potential source of total phosphorous due to the high concentrations and resuspension of sediments by wind-waves. Sedimentation within the lagoon was highest in the calmer southern region, while the northern region had the lowest accretion rate and is subject to sediment movement from tidal flows. Increased drainage of the catchment may be contributing some sediments to the system, along with erosion of channel banks. This is primarily an issue in Palmers Channel and Micalo Channel.

While the condition assessment identified cane drains (Middle Road and Carrs Drain) as contributing high loads of nutrients and sediments to Palmers Channel, further studies are required to quantify the amount. Carrs Drain appeared to have a low flow rate, so the contribution of this drain is questionable. The trigger value for turbidity within Wooloweyah Lagoon should be increased to 35 NTU due to the significant impact of wind on sediment resuspension. For other waterways within the catchment, the trigger value could remain at 25 NTU. It is recommended that the condition assessment be repeated every 2-3 years to monitor the implementation of actions from the Coastal Zone Management Plan for Wooloweyah Lagoon, and also to help build knowledge of baseline conditions within the catchment. However, the frequency and scale of monitoring will ultimately be dependent on available funding.

Table of Contents

Executive Summary ... iv
Table of Contents ... v
List of Figures ... vi
List of Tables ... vii
1. Introduction ... 8
1.1. What is a condition assessment? ... 8
1.2. Site description ... 8
1.2.1. Geomorphology and soils ... 10
1.2.2. Climate ... 11
1.2.3. Flora and fauna ... 11
1.3. Catchment pressures and issues ... 12
1.3.1. Water clarity ... 12
1.3.2. Nutrients ... 12
1.3.3. Sedimentation ... 12
2. Methodology ... 13
2.1. Regular water quality monitoring ... 14
2.2. Event-based water quality monitoring ... 15
2.3. Sediments ... 16
2.4. Catchment and habitat assessment ... 17
2.5. Data analysis ... 17
3. Results ... 18
3.1. Climate ... 18
3.1.1. Air temperature ... 18
3.1.2. Rainfall ... 18
3.1.3. Wind ... 20
3.2. Water quality ... 21
3.2.1. Turbidity ... 21
3.2.2. Baseline conditions for 2008/2009 ... 24
3.2.3. Event sampling ... 30
3.3. Sediment quality ... 37
3.4. Sedimentation within the Lagoon ... 40
3.5. Catchment and habitat assessment ... 41
4. Discussion ... 43
4.1. Turbidity ... 43
4.2. Nutrients ... 45
4.3. Other water quality parameters ... 47
4.4. Sedimentation ... 48
4.5. Catchment assessment ... 50
5. Conclusions ... 52
6. References ... 53
Appendix A1 – Description of Sites and Access ... 56
Appendix A2 – Sample Site Coordinates (WGS84) ... 57
Appendix A3 – Water Quality Data ... 58
Appendix A4 – ANSTO Report on Sediment Cores at Wooloweyah Lagoon ... 71
APPENDIX B – SUMMARY OF MANAGEMENT OPTIONS FROM FOLEY AND WHITE (2007) ... 87

List of Figures

Figure 1: Location of Wooloweyah Lagoon and its catchment on the Lower Clarence River floodplain... 9
Figure 2: Wooloweyah Lagoon catchment area. Drainage lines are indicating, and include natural and artificial drainage. 10
Figure 3: Relict shorelines of Wooloweyah Lagoon, indicated by the concentric ridges on the western flats. 13
Figure 4: Locations of water quality and sediment monitoring sites, and where sediment cores were collected in the Wooloweyah Lagoon catchment. 15
Figure 5: The sediment sampling device, showing some sediment collected from one of the drains..... 16
Figure 6: Total monthly rainfall, mean daily maximum and minimum daily temperature for the period August 2008 to July 2009. Long-term (1877-2009) mean monthly rainfall is also shown........ 18
Figure 7: Daily rainfall recorded at Yamba Pilot Station, August 2008 to July 2007........ 19
Figure 8: Frequency of wind direction at Wooloweyah Lagoon during each month over the condition assessment period. CA = total condition assessment period. 20
Figure 9: Range of wind speed associated with each wind direction during the condition assessment period. The lower boundary of the box indicates the 25^{th} percentile, the upper boundary the 75^{th} percentile and the line within the box the median. Whiskers above and below the box indicate the 90^{th} and 10^{th} percentile, respectively. Filled circles represent outliers........ 21
Figure 10: Turbidity within Wooloweyah Lagoon, August 2008 to July 2009. The HRC (1999) maximum trigger value of 25 NTU is indicated by 22
Figure 11: Correlation between lagoon turbidity and wind speed........ 22
Figure 12: Turbidity of Wooloweyah Lagoon in relation to wind direction. The lower boundary of the box indicates the 25^{th} percentile, the upper boundary the 75^{th} percentile and the line within the box the median. Whiskers above and below the box indicate the 90^{th} and 10^{th} percentile, respectively. Filled circles represent outliers. 23
Figure 13: Average turbidity within each zone for regular monitoring (including the May 2009 flood).... 23
Figure 14: Turbidity of event-based sites, with the average NTU per sample period also shown. 24
Figure 15: Average pH of regular monitoring zones at Wooloweyah Lagoon. The decrease in pH during April and May 2009 corresponded with high rainfall. 25
Figure 16: Average salinity of regular monitoring zones at Wooloweyah Lagoon. Taloumbi and Palmers Channel generally had the lowest salinity throughout the assessment period. 26
Figure 17: Salinity and dissolved oxygen concentrations in the Wooloweyah Lagoon study area. The lower boundary of the box indicates the 25^{th} percentile, the upper boundary the 75^{th} percentile and the line within the box the median. Whiskers above and below the box indicate the 90^{th} and 10^{th} percentile, respectively. Filled circles represent outliers. 26
Figure 18: Average concentrations of total phosphorus at Wooloweyah Lagoon. The trigger value (HRC 1999) of 0.05 mg L^{-1} is indicated by the dashed line. 27
Figure 19: Average concentrations of orthophosphate at Wooloweyah Lagoon regular monitoring zones. The trigger value (HRC 1999) of 0.005 mg L^{-1} is indicated by the dashed line. 28
Figure 20: Average total nitrogen concentrations at regular monitoring zones. Most sites were above the trigger value (HRC 1999) of 0.4 mg L^{-1}, as indicated by the dashed line. 28
Figure 21: Average nitrate concentrations at regular monitoring zones. The trigger value (HRC 1999) of 0.015 mg L^{-1} is indicated by the dashed line. 29
Figure 22: Average concentrations of ammonia at regular monitoring zones. The majority of sites were above the trigger value (HRC 1999) of 0.015 mg L^{-1}, as indicated by the dashed line........ 29
Figure 23: Average concentrations of chl-*a* at the regular monitoring zones. The majority of zones were above the HRC guideline (1999) of 0.004 mg L^{-1}, as indicated by the dashed line. 30
Figure 24: Total phosphorus concentrations of runoff from event-based sample sites. 31
Figure 25: Orthophosphate concentrations of runoff from event-based sample sites. 32

Figure 26: Total nitrogen concentrations of runoff from event-based sample sites. 32
Figure 27: Nitrate concentrations of runoff from event-based sample sites. 33
Figure 28: Nitrite concentrations of runoff from event-based sample sites.. 33
Figure 29: Ammonia concentrations of runoff from event-based sample sites. 34
Figure 30: Average DO concentration at each event-based monitoring zone for each event captured. The average of all sites for each event is also shown. 35
Figure 31: Average salinity at each event-based monitoring zone, with the average of all sites for each event also shown. Salinity was generally lowest in Carrs Drain and highest in the National Park (NP). 35
Figure 32: Average pH at event-based monitoring zones. There was a considerable decrease in pH during the April, May and June 2009 events, from the baseline values recorded in August 2008.......... 36
Figure 33: Chl-*a* concentrations of runoff water from event-based sample sites. 36
Figure 34: Average sediment total phosphorous concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were generally highest within the drains and during October 2008.. 37
Figure 35: Average sediment phosphate concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were generally highest in July 2009. 38
Figure 36: Average sediment nitrate concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were generally highest in July 2009. 38
Figure 37: Average sediment ammonia concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were highest in October 2008 and January 2009. 39
Figure 38: Average sediment total nitrogen concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were highest in the Taloumbi drain and Carrs Drain. N.B. to convert %N to ppm, multiply by 10,000. 39
Figure 39: X-rays of sediment cores collected from Wooloweyah Lagoon (ANSTO 2009). 40
Figure 40: Acid sulfate soils risk map of the Wooloweyah area (MHL 2000)... 42
Figure 41: Location of seagrass, saltmarsh and mangrove within the Wooloweyah Lagoon catchment (mapped by NSW DPI 2006). Mangroves are also present along sections of Palmers, Micalo and Oyster Channels. 43
Figure 42: Sediment transport in a coastal lagoon (sourced from OzCoasts 2009). 49

List of Tables

Table 1: Water quality indicators and trigger values, as defined by the HRC (1999). 14
Table 2: Erosion classification table (Burns *et al.* 2007)... 17
Table 3: Average water quality values for regular sites over the 12-month condition assessment period. 25
Table 4: Mean water quality values for event-based monitoring sites, calculated from 7 events (not including August 2008)... 31
Table 5: Bank condition of monitoring sites, August 2008. See Table 2 for erosion classifications........ 42

1. Introduction

The aim of the Wooloweyah Lagoon Condition Assessment was to provide information on the current health of the lagoon and identify potential management issues within the catchment. The previous management strategy (Woodhouse 2001) listed a number of actions to be implemented over the short- and long-term. One of those actions was to improve water quality monitoring in the lagoon and connecting drains and channels. The condition assessment of Wooloweyah Lagoon is the resultant outcome, which not only provides data on baseline conditions, but also sets a monitoring protocol for future water quality studies within the catchment. The results of the assessment were used to support, and have been incorporated into, the *Coastal Zone Management Plan for Wooloweyah Lagoon* (White 2009a).

1.1. What is a condition assessment?

There are a number of wetland assessment programs which have been designed for a variety of purposes, including assessing wetland function, habitat quality and distribution, and catchment and wetland integrity (DSE 2006). Due to the variety of wetland assessments, the definition for a condition assessment is often ambiguous. Butcher (2003) defines wetland condition as the “state or ecological condition of a wetland”. Ecological character, which is the sum and interactions of the biological, physical and chemical components of the wetland ecosystem (Phillips *et al.* 2002 cited in Butcher 2003), can be used as a measure of wetland condition. A wetland assessment, as defined by Finlayson and Eliot (2002 cited in Butcher 2003), is:

> “the identification of the status of, and threats to, wetlands as a basis for the collection of more specific information through monitoring activities.”

In the *Australia State of the Environment Report 2001 Theme Report* (Lennon *et al.* 2001), a condition assessment is defined as:

> “a record of the state of the critical aspects of the place at a given time. This should be suitable for developing options for future action and, as a record against which to judge change.”

Based on these definitions, for the purpose of this project a wetland condition assessment is defined as a method to determine the current state of a wetland using biological, chemical and physical indicators. Condition indicators may be used as monitoring tools to identify changes in wetland condition due to natural and/or human disturbances. The results of the assessment may provide information to improve the management model, and the assessment program can also be used for ongoing monitoring to determine the success of implemented management actions.

1.2. Site description

Wooloweyah Lagoon is a tidal barrier estuarine lagoon on the Clarence River floodplain, north coast of New South Wales (latitudes 29° 27’ S to 29° 32’ S and longitudes 153° 16’ E to 153° 21’ E). The lagoon is approximately 12 km from the mouth of the Clarence River and is connected to the main estuary by three channels: Palmers, Micalo/Shallow and Oyster Channels (Fig. 1). Land use immediately adjacent to the lagoon and channels includes Yuraygir National Park to the southeast, urban development to the east (Wooloweyah village) and northeast (Yamba), and agriculture (predominantly sugar cane and grazing) to the west and south.

Wooloweyah Lagoon has a depth range of 0-2 m (average approximately 1.3 m), a surface area of 24 km^2, a volume of 32.5 million m^3, a length of approximately 9 km and a width of 1-4.5 km (Lancaster

1990; MHL 2000). The catchment has an area of 206 km^2 (Foley & White 2007), including the lagoon and an area of 32 km^2 which drains into Palmers Channel, Micalo/Shallow Channel and Oyster Channel. The catchment is bounded by several ranges along the southern border, including The Coast, Bees Nest and Shark Creek ranges. The catchment extends mostly west and south from the lagoon (Fig. 1) and these areas are, therefore, the dominant source of land drainage (Lancaster 1990). It is estimated that more than 70% of runoff enters the lagoon through the Taloumbi Ring and Radial Drainage system due to the extensive drainage network on the western flats (Foley & White 2007; Fig. 2). Eighty-five percent of the Wooloweyah Lagoon tidal prism is supplied by Oyster Channel and 15% by Palmers Channel (Soros-Longworth & McKenzie Pty Ltd 1978). The lagoon is flushed predominantly via Oyster Channel, although the longer ebb tide of Palmers Channel is an important means of water release and thus flushing of the lagoon (Winders, Barlow & Morrison Pty Ltd 1987; Lancaster 1990).

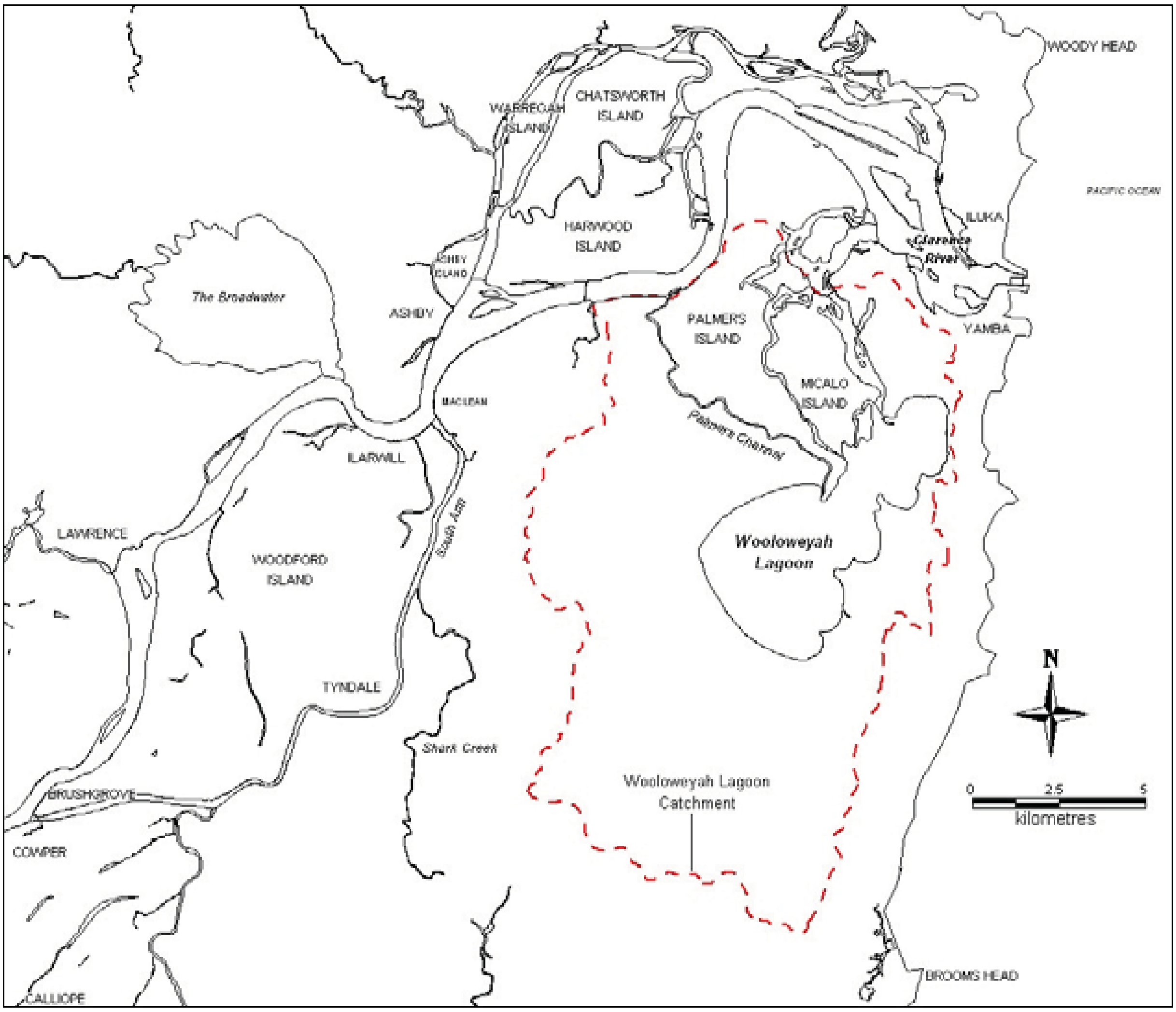

Figure 1: Location of Wooloweyah Lagoon and its catchment on the Lower Clarence River floodplain.

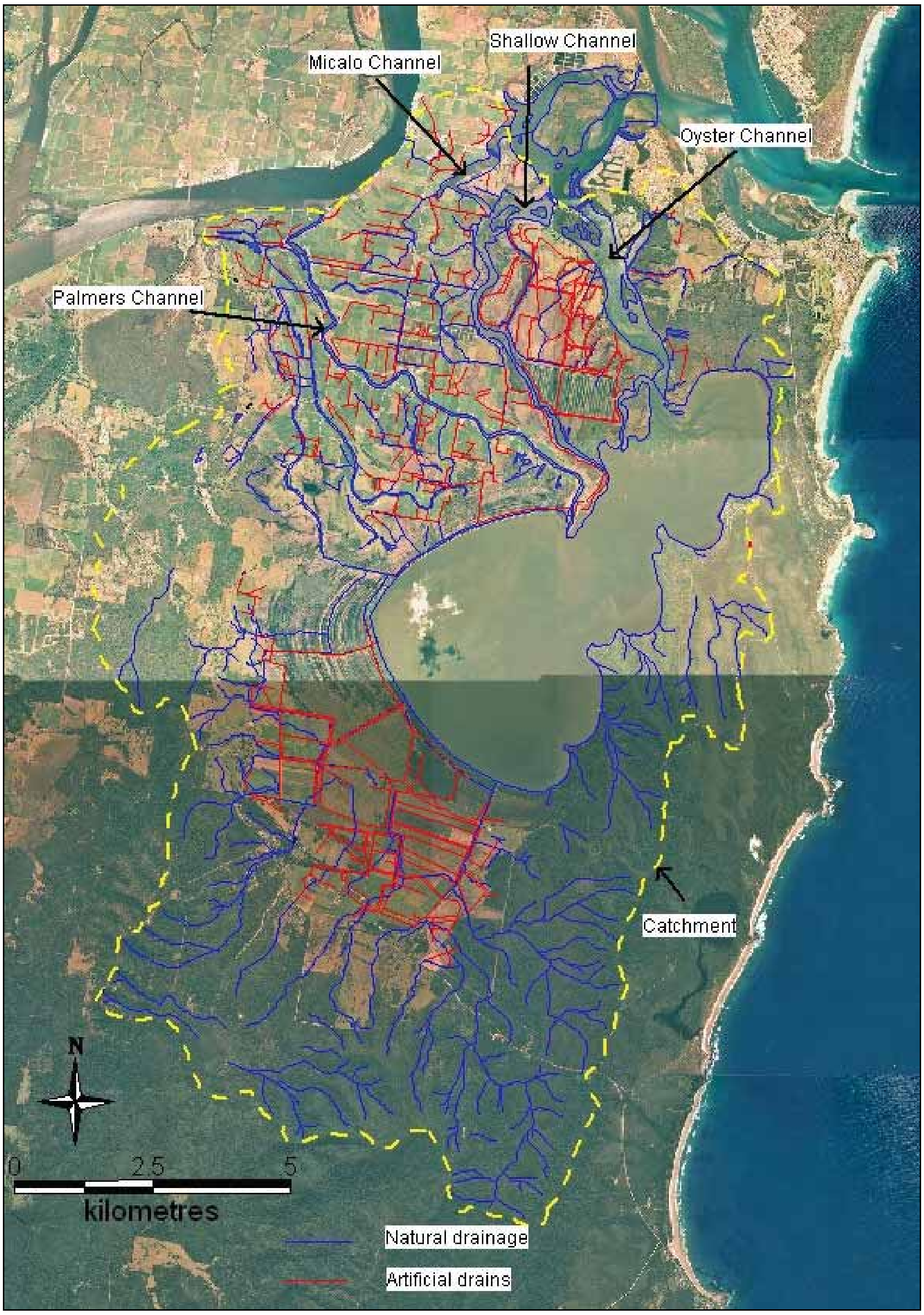

Figure 2: Wooloweyah Lagoon catchment area. Drainage lines are indicating, and include natural and artificial drainage.

1.2.1. Geomorphology and soils

The lagoon developed due to infilling of a deeper river valley which formed during periods of lower sea level, and formation of a barrier dune against the eastern bedrock exposures separated the lagoon from the coast (Woodhouse 2001). The lagoon then became separated from the main river channel due to continual infilling of the lower floodplain by land drainage. Wooloweyah Lagoon is a sediment settling basin, with marine sand continuing to be deposited as a flood-tide delta in the northern end of the lagoon, and sediments and fine silts deposited during floods are trapped (Hashimoto & Hudson 1999; Woodhouse 2001).

Soils in the drainage basin are predominantly yellow and grey-brown podzolics, with the eastern and southern shores mainly sands and sandy lithosols (Lancaster 1990). Acid sulfate soils (ASS), which formed during the last sea level rise less than 10,000 years ago (Dent 1986; Sammut *et al.* 1996), have been identified in the area. The lower estuary floodplain and islands of the Clarence River (which includes Wooloweyah Lagoon, Oyster Channel, Palmers Channel and Micalo/Shallow Channel) has been identified as an ASS priority management area (Tulau 1999).

Groundwater quality is reasonable in the upper 10 m of alluvium due to the extensive unconsolidated deposits of the floodplain (Woodhouse 2001). Below 10 m are black muds and silt with groundwater quality ranging from brackish to highly saline. The groundwater contribution to Wooloweyah Lagoon is approximately 50 m^3 day^{-1} (Woodhouse 2001). The hydraulic conductivity of the silty sand aquifer to the north-east of the lagoon ranges from 1.1-11 m day^{-1}, with an average of approximately 3 m day^{-1} (MHL 1999).

1.2.2. Climate

The region has a coastal subtropical climate with warm, wet summers and cool, dry winters (Woodhouse 2001). The climate is influenced by the subtropical high pressure belt during winter and spring, and easterly monsoonal trade winds and northern tropical cyclones during summer and autumn (MHL 2000). The warmest month is February with a mean daily temperature range of 20.3-26.7 °C and the coldest month is July with a mean daily range of 9.7-19.0 °C (ABM 2008). Mean annual rainfall at Yamba is 1454 mm, although Wooloweyah Lagoon and its catchment may receive a higher annual precipitation due to orographic rainfall caused by the range to the southwest of the lagoon and moist sea air (Lancaster 1990). The dry season is from August to November and the wet period from January to May. On average September is the driest month and March is the wettest (59 mm and 183 mm, respectively).

Winds are variable, with summer months dominated by northeasterlies and southeasterlies, and south to southeasterlies predominant during autumn. Winter months are characterised by west to southwesterlies strongest in the morning (Lancaster 1990), becoming more northerly during early spring (see Section 3.1). Strong winds (greater than 15 knots) are mainly onshore and from the south and southeast (Woodhouse 2001). See Section 3.1 for climatic data during the condition assessment period.

1.2.3. Flora and fauna

The Wooloweyah Lagoon catchment contains a number of habitats listed as Endangered Ecological Communities (EECs) under the *Threatened Species Conservation Act 1995*. This includes saltmarsh, swamp oak floodplain forest, swamp sclerophyll forest on coastal floodplains, freshwater wetlands on coastal floodplains, lowland rainforest, and coastal vine thickets of Eastern Australia. Seagrass (protected under the *Fisheries Management Act 1994*) and mangroves (protected under the *Coastal Protection Act 1979*) also occur within the catchment. Refer to Section 3.5 for mapped locations of saltmarsh, seagrass and mangrove.

The Lower Clarence River estuary is significant waterbird habitat, it is the third most important wader habitat in NSW and has the highest known species diversity (Australian Heritage Commission 1999; Woodhouse 2001). Priority roost and foraging sites within the Wooloweyah Lagoon catchment are Joss Island, Oyster Channel and the Micalo Island prawn farm (Rohweder 2006). A number of species listed on the *Threatened Species Conservation Act 1995* and under international bilateral Migratory Bird Agreements (JAMBA, CAMBA and RoKAMBA) have been recorded within the Wooloweyah Lagoon catchment (Environment Australia 2001). Due to these high ecological values, Wooloweyah Lagoon is listed on the 'Directory of Important Wetlands in Australia' (Environment Australia 2001).

1.3. Catchment pressures and issues

A number of catchment pressures have been identified through the *Wooloweyah Lagoon Management Strategy* (Woodhouse 2001) and the *Coastal Zone Management Plan for Wooloweyah Lagoon* (White 2009), and include:

- Agriculture (sugarcane and grazing) – land clearing, fertilisers, drainage.
- Rural-residential, urban and tourism development – runoff, septic leakages, sewage discharge, land clearing, construction of roads and causeways.
- Trawling – disturbance of sediments.
- Acid sulfate soils – potential effects, including acidic discharge.

While a range of issues have been identified by previous studies (Williams 1987; Lancaster 1990; HRC 1999; Woodhouse 2001), the predominant recurring issues relate to water clarity (turbidity) and nutrient concentrations. More recently, sedimentation of the channels has become another major issue in terms of navigation for the commercial trawlers and potentially flushing of the lagoon (Section 1.2). As such, the Wooloweyah Lagoon condition assessment was designed with these three main issues in mind.

1.3.1. Water clarity

Turbid water reduces the infiltration of light, thereby affecting seagrass distribution, and suspended solids may also smother seagrass upon settlement. Poor water clarity in Wooloweyah Lagoon has often been attributed to resuspension of sediments by wind due to the shallowness of the lagoon and long fetch (Williams 1987; Lancaster 1990; HRC 1999; Woodhouse 2001). Trawling has also been cited as a possible source of increased turbidity, however, there have been no studies on Wooloweyah Lagoon to quantify this statement.

1.3.2. Nutrients

Increased nutrient concentrations in the lagoon may be from a number of sources, including land use, overflow from the Yamba STP and release from suspended sediments. Lancaster (1990) noted that nutrients were flushed from the catchment after heavy rainfall. During low and medium flows nutrients were flushed into the lagoon but not out of the system, thus increasing the chance of an algal bloom. However, the quantity of nutrients entering the lagoon from runoff during a rainfall event is highly dependent on antecedent conditions. Sediments within the drains and lagoon may also be a potential source of nutrient inputs to the water column, as these are generally fine sediment which have an increased capacity to bind elements (including nutrients), which may then be released into the water column through mixing and resuspension. The Yamba STP is another potential source of nutrients to the lagoon system. Currently, the majority of recycled water is discharged into a woodland/wetland, which during periods of high rainfall may overflow into the northern end of Wooloweyah Lagoon (NSW PWD 1991; NSW DPWS 1998). Completion of the Yamba STP augmentation will cease the discharge of treated sewage into the woodland/wetland, as recycled water will be used for irrigation and recycled water which cannot be used will be release through ebb tide discharge into the Clarence River (Sinclair Knight Merz 2005).

1.3.3. Sedimentation

There is a large amount of anecdotal evidence to suggest that Wooloweyah Lagoon is infilling, with sediments and fine silts deposited during floods trapped in the system and marine sand continuously deposited as a flood-tide delta at the northern end of the lagoon (Woodhouse 2001).It has been suggested that the lagoon is becoming smaller rather than shallower (Hashimoto pers. comm. 6/10/00 cited in Woodhouse 2001). Air photos of the flats west of the lagoon reveal relict shorelines, consisting of a series of at least 50 closely spaced concentric ridges (Fig. 3) which extend inland by more than

2 km in some areas (Tulau 1999) indicating the previous varying extents of the lagoon system (Woodhouse 2001). The main issues associated with sedimentation of the lagoon are reduced navigability for trawlers through the Palmers Channel delta, and also potentially reduced environmental flows and flushing of the lagoon due to sedimentation of the lagoon entrances to Palmers Channel and Oyster Channel.

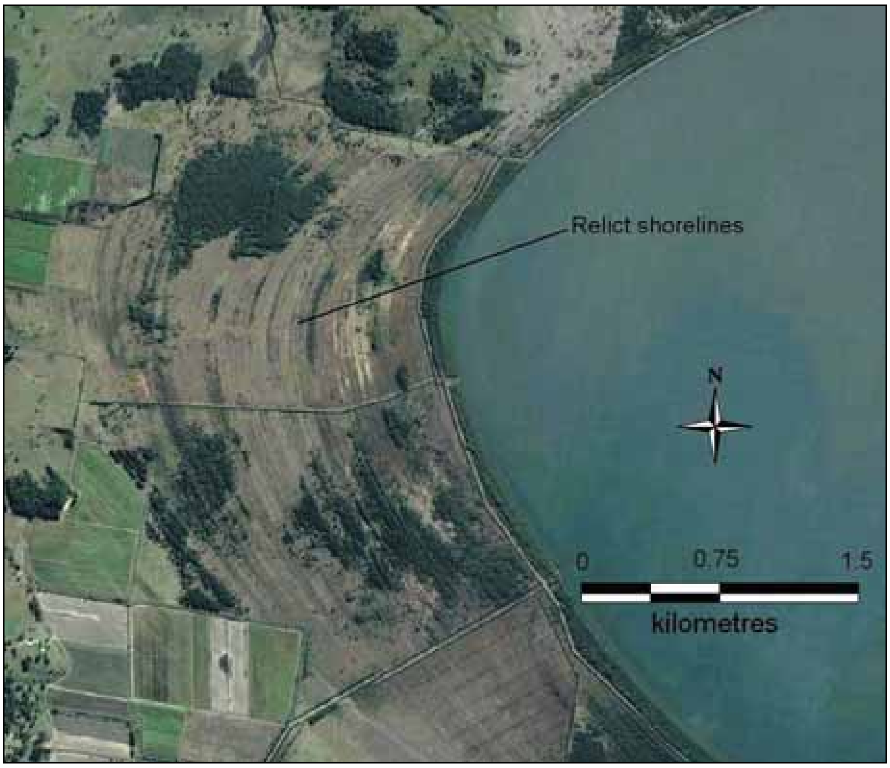

Figure 3: Relict shorelines of Wooloweyah Lagoon, indicated by the concentric ridges on the western flats.

2. Methodology

The condition assessment was conducted over a 12-month period (August 2008 to July 2009) and consisted of three main components – water quality, sediments and catchment/habitat assessment. Water quality monitoring was conducted through regular monthly sampling and event-based sampling. The regular monitoring was designed to provide baseline data on water quality within the lagoon and connecting channels, while the event-based monitoring was designed to determine the quality of water entering the lagoon and channels from the catchment. Site descriptions and coordinates are provided in Appendices A and B. Sediment sampling was conducted quarterly, with the purpose to identify potential nutrient stores. Sediment cores were also collected from the lagoon for determining sedimentation rates. Indicators of water quality and sediment quality are listed in Table 1, along with the trigger values determined by the HRC (1999). The trigger value for each indicator is used to assess the risk to protection of the aquatic ecosystem (an environmental value) (DECC 2009), and is only applicable during dry periods (i.e. non-rainfall event sampling periods). If the water quality values are below the trigger value (or within the trigger value range, as for pH; see Table 1), then there is determined to be a low risk to the environmental value. Values above the trigger value (or outside the range) may indicate that there is a possible risk to the environmental value and that there is a need for further action to investigate and/or repair the cause (DECC 2009).

Table 1: Water quality indicators and trigger values, as defined by the HRC (1999).

Indicator	Trigger value/range
pH	7-8.5
DO	6 mg L^{-1} (80-110 %saturation)
Turbidity	5-25 NTU
TN	0.4 mg L^{-1}
TP	0.05 mg L^{-1}
Nitrate, nitrite, ammonia	0.015 mg L^{-1}
Phosphorus	0.005 mg L^{-1}
Chlorophyll-*a*	0.004 mg L^{-1}

Continuous monitoring of turbidity within Wooloweyah Lagoon was performed with a Greenspan Turbidity Logger (model no. TS300). Turbidity measurements were recorded every half-hour from mid-August 2008 to mid-February 2009. The logger was removed for maintenance in mid-February 2009 and was not returned to the Lagoon until late April 2009. This was due to increased biofouling of the equipment during the warmer months, and therefore viable data could not be collected. Once the logger was re-installed, the frequency of turbidity measurements was reduced to hourly, until the end of the assessment period (mid-July 2009). The logger was located at site R15 (Fig. 4) in the western region of the lagoon.

The catchment assessment was performed with desktop applications, while a visual assessment of bank condition was conducted during the first monthly sampling period (August 2008). The spatial design of the condition assessment was developed to compare the effect of different catchment land uses (i.e. urban, agricultural and undisturbed/national park) on the lagoon. The temporal aspect of the condition assessment was designed to capture seasonal changes in rainfall and wind patterns, and waterway use (i.e. trawling versus non-trawling periods).

Climatic data was sourced from the Australian Bureau of Meteorology, Yamba Pilot Station. Data included hourly measurements of wind speed and direction, and cumulative rainfall. Daily rainfall was calculated to 9 am.

2.1. Regular water quality monitoring

Fifteen sites were established within the lagoon and Palmers, Micalo, Shallow and Oyster Channels (Fig. 4, sites R1-R15), and another site was also established in the Taloumbi Ring Drain near the confluence with Radial Drain No. 2 (Fig. 4, site R16/E2) to provide background data on water quality within the drain. Water quality monitoring was conducted each month from August 2008 to July 2009, and at some regular sites (R9, R11, R12, R14 and R15) during the event-based round in late-May 2009 (see Section 2.2), following a major flood. During each sample period, sites were accessed by car and boat.

At each site, *in situ* measurements of pH, salinity and water temperature were recorded with a TPS 90FL Field Lab, and dissolved oxygen (DO) with a Hach LDO probe. A 1 litre sample of water was collected in a polyethylene bottle (pre-rinsed three times with sample water) which was sealed and kept in cool and dark conditions until delivered to the Environmental Analysis Laboratory (EAL) at Southern

Cross University, Lismore. Water samples were analysed at the EAL for nutrient concentrations (total phosphorous (TP), total nitrogen (TN), nitrate, nitrate and phosphate), turbidity, chlorophyll-*a* concentrations (chl-*a*) and algal biomass (a multiplication factor of 100 of chl-*a*; not reported here).

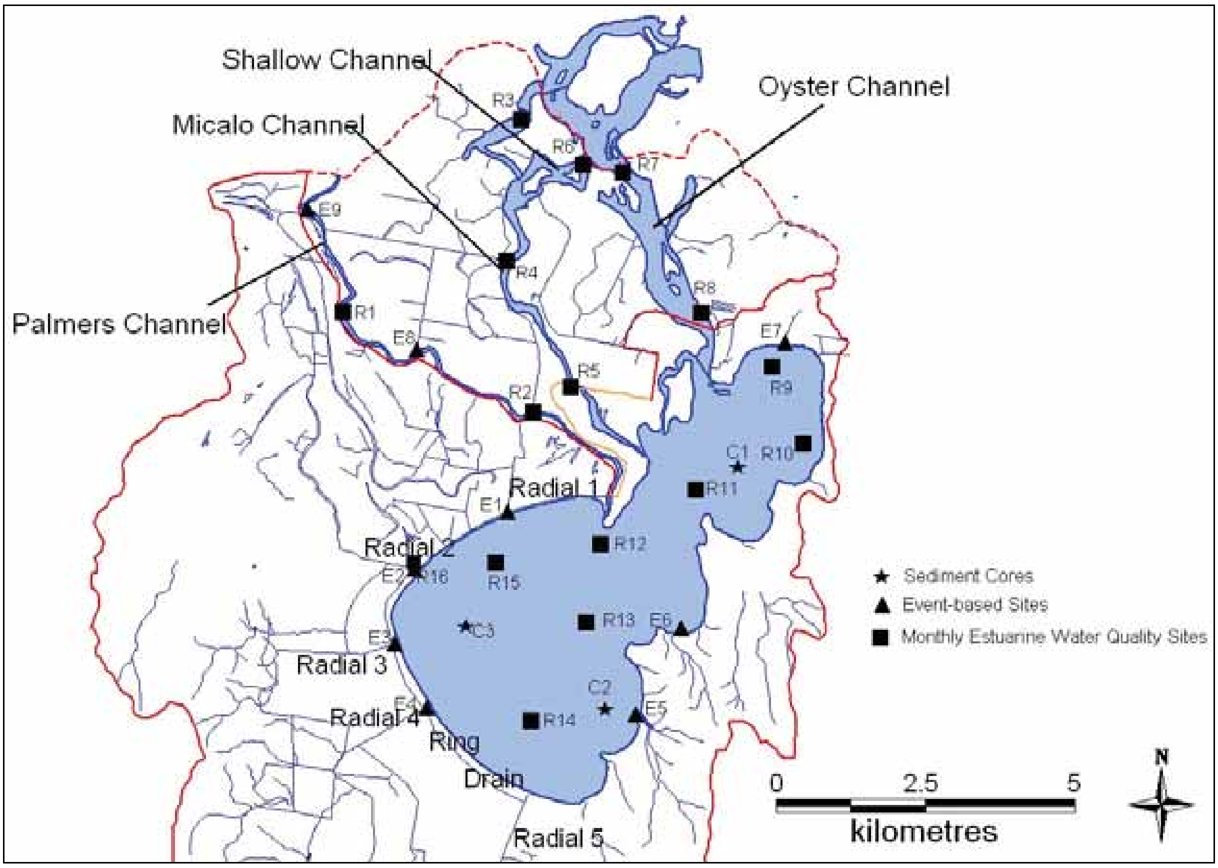

Figure 4: Locations of water quality and sediment monitoring sites, and where sediment cores were collected in the Wooloweyah Lagoon catchment.

2.2. Event-based water quality monitoring

Event-based monitoring sites were established in the Taloumbi Ring Drain at the confluence of Radial Drains No. 1, 2, 3 and 4 (sites E1, R16/E2, E3 and E4, respectively), creeks draining from Yuraygir National Park (sites E5 and E6), a creek which was indicated as being a major source of surface water overflow from the Yamba STP (E7), Middle Road Drain (E8) and Carrs Drain (E9) (Fig. 4). The techniques for collection and analysis of the water samples, and monitoring of *in situ* parameters were the same as those described in Section 2.1 for the regular water quality monitoring.

The amount of rainfall required over a 24-hour period to trigger event-based monitoring was defined as 25 mm or more from July to November, and 50 mm or more from December to June. The amount and intensity of rainfall prior to each event sample was variable over the study period, and therefore influenced the amount of runoff from the catchment. Antecedent conditions also played an important role in the amount of runoff from the catchment with each rainfall event.

A total of 8 monitoring rounds were conducted at the event-based sites: 27th August 2008, 5th September 2008, 18th November 2008, 15th February 2009, 1st and 15th April 2009, 29th May 2009, and 23rd June 2009. The first event sample in August 2008 was conducted to establish baseline data for the event sites, to which future event based samples could be compared. The third event sample in November 2008 did not meet the trigger value for rainfall; however, prolonged dry conditions prompted the need for an event sample on the occasion that dry conditions prevailed during the condition assessment period. Similarly, the event samples in February 2009 and mid-April 2009 also did not meet the rainfall trigger values originally defined. However, on the latter occasion the sampling was preceded by two weeks of consistent rainfall following sampling at the start of April. The event monitoring conducted in late-May 2009 followed a major flood event in the Clarence River catchment. Due to the extent of flooding and road closures, staff were unable to access the lagoon until nearly a week after the flood peak.

2.3. Sediments

Sediments were collected quarterly (October 2008, January 2009, April 2009 and July 2009) and analysed for total and soluble nutrients at the EAL. Sediments were collected from all regular and event-based water quality monitoring sites (Fig. 4). Sediment samples were also collected from some sites in late-May, after the major flood event (sites R9, R11, R12, R14, R15, R16/E2 and E4-E9).

Collection of sediments involved scooping a sample from the top 10 cm of the sediment using a plastic beaker (pre-rinsed in the surface water) attached to a sample pole (Fig. 5). The full beaker was carefully lifted out of the water and excess water drained off, before placing the sediment into a sealable plastic sample bag. Sediment samples were kept in cool, dark conditions until delivery to the EAL.

To determine sedimentation rates within Wooloweyah Lagoon, the Australian Nuclear Science and Technology Organisation (ANSTO) was contracted to collect and date sediment cores. Three cores were collected in October 2008, and the locations are indicated in Fig. 4. All sediment ages reported within this report are according to the CRS (constant rate of lead-210 supply) model. Refer to Appendix A4 for sediment dating methodology and the report on the sediment core analysis.

Figure 5: The sediment sampling device, showing some sediment collected from one of the drains.

2.4. Catchment and habitat assessment

A bank condition assessment was conducted during the first round of regular monthly water quality monitoring. At each applicable site, notes on vegetation type, erosion, pugging, presence of structures, substrate type and adjacent land use were taken. Bank erosion was classified as stable, good moderate or unstable (Table 2; Burns *et al.* 2007).

Natural drainage density was calculated by dividing the number of kilometres of natural drainage within the Wooloweyah Lagoon catchment with the area of the catchment (less waterway area), to give a length per area value. The length of constructed drainage was added to the natural drainage for current drainage density.

Table 2: Erosion classification table (Burns *et al.* 2007).

Classification	Description
Stable	No signs of erosion, and the bank is protected by healthy ground cover plants and/or a well developed litter layer (fallen leaves, twigs, bark etc.).
Good	Minor spot erosion occurring in some places, however most of the bank is protected by healthy ground cover plants and/or a well-developed litter layer.
Moderate	Spot erosion linked causing damage to vegetation and bare spots. There may be rill erosion causing some scouring, and there is damage to the ground cover vegetation and/or the litter layer.
Unstable	Extensive erosion with bare spots, rills and scouring common. There may also be gully erosion. There is considerable damage to the ground cover vegetation and/or the litter layer.

2.5. Data analysis

Monitoring results have been summarised into eleven zones, based on the waterway, for easier presentation and explanation of the results. Water quality data for individual sites is provided in Appendix A3. The average (mean for all parameters, except pH which uses the median value) of all sites within each zone is presented for each sampling round. The median value of pH was used instead of the mean as pH is measured on a logarithmic scale. The zones for the monthly sampling are labelled as: Palmers Channel (R1 and R2); Micalo Channel (R3-R5); Shallow Channel (R6); Oyster Channel (R7 and R8); Lagoon North (R9-R11); Lagoon South (R12-R15); and Taloumbi (R16/E2). For event-based sampling, the zones are defined as: Taloumbi (E1, R16/E2, E3, E4); National Park (E5 and E6); STP (E7); Middle Rd Drain (E8); and Carrs Drain (E9). Results for sediment nutrient analysis are presented in a similar way, with all the above zones used (sites contributing to Taloumbi were the same as those for the event-based zones). Results of monitoring immediately after the May 2009 flood, where applicable, have been included in the graphs of the regular sites.

For samples where concentrations were below the detection limit (BDL), values of half the detection limit were inserted. Although this presents some form of bias in analysis of the data, there is no standard technique for accounting for samples BDL. All other techniques (i.e. replacement with zero or value of detection limit, or leave as a missing value) also result in bias in the data analysis. Therefore, replacement with a value of half the detection limit is used for this study, as recommended by ANZECC (2000).

3. Results

3.1. Climate

3.1.1. Air temperature

The warmest months during the condition assessment period were January to March, while the coolest months were June to August (Fig. 6). During August 2008 the mean daily air temperature range was 8.7-20.2 °C, and during February 2009 was 21.2-27.7 °C.

3.1.2. Rainfall

Total monthly rainfall was below average during August to October 2008, December 2008 to February 2009, and July 2009 (Fig. 6). In November 2008 total monthly rainfall was more than twice the long-term average (191 mm and 92 mm, respectively). Nearly 80% of the total monthly rainfall occurred as two separate rainfall events: the first occurred from 17-20 November (68 mm), and the second from 26-27 November (83 mm; Fig. 7). Total monthly rainfall in March and April 2009 (243 mm and 245 mm, respectively) was also considerably higher than the long-term average (Fig. 6). However, 60% of the total rainfall in March occurred within a 24-hour period at the end of the month (146 mm; Fig. 7). In contrast, rainfall was generally consistent throughout April, with the maximum rainfall in a 24-hour period only accounting for 21% of the total month's rainfall (36 mm on 22nd April 2009; Fig. 7).

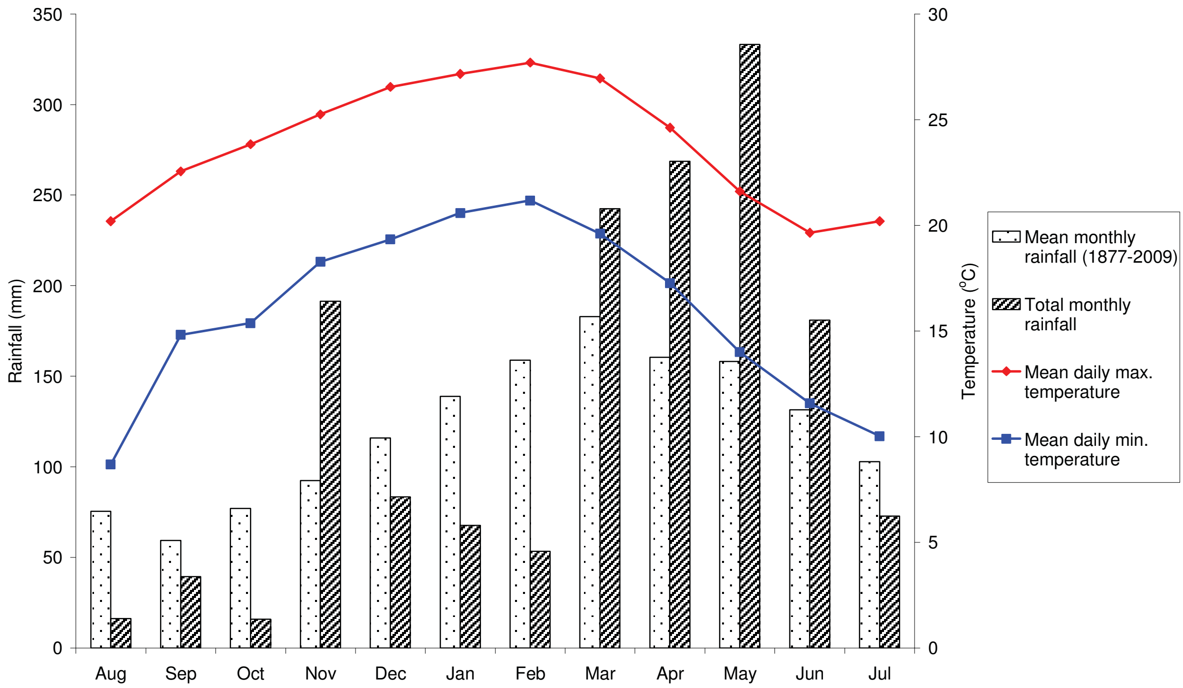

Figure 6: Total monthly rainfall, mean daily maximum and minimum daily temperature for the period August 2008 to July 2009. Long-term (1877-2009) mean monthly rainfall is also shown.

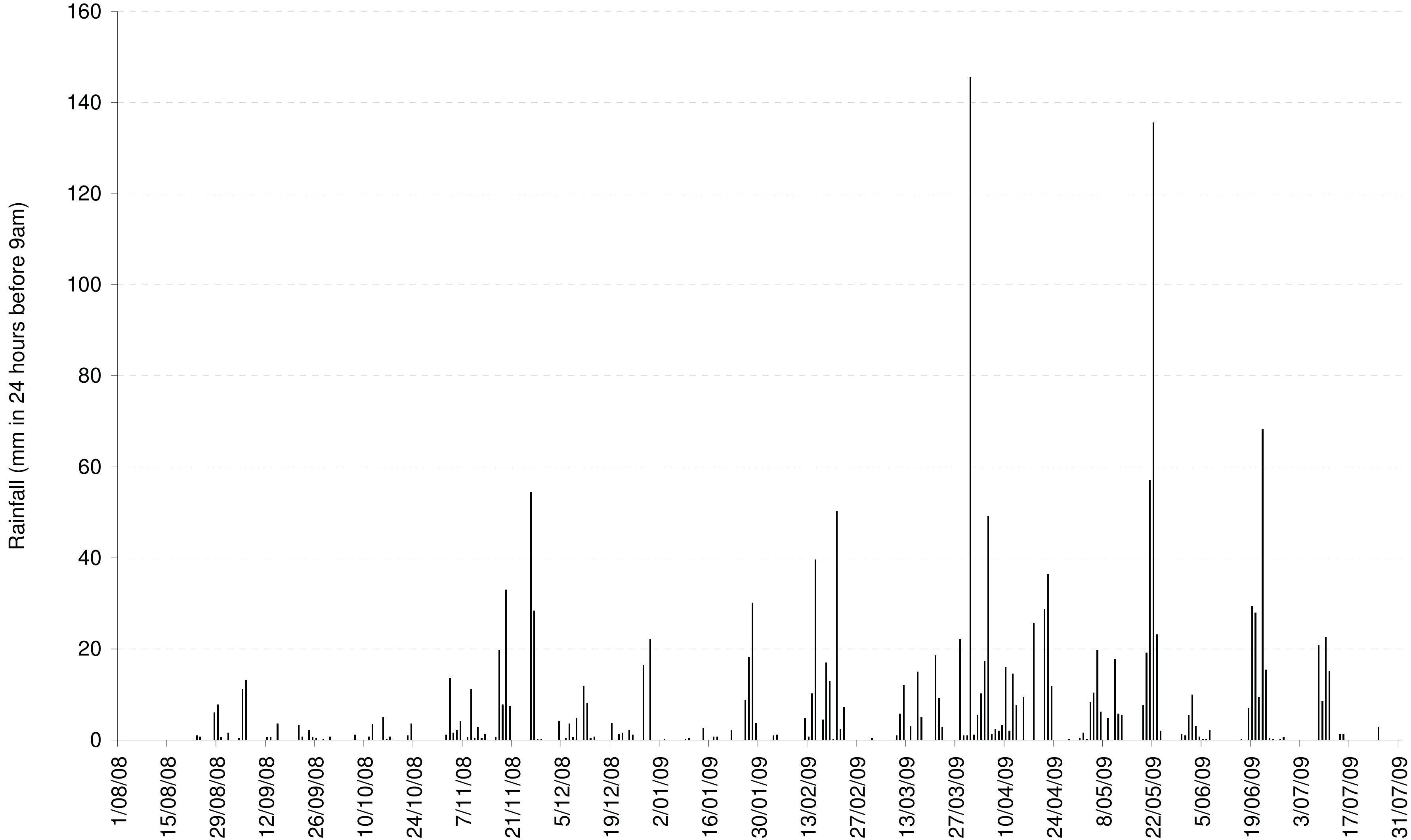

Figure 7: Daily rainfall recorded at Yamba Pilot Station, August 2008 to July 2007.

Total monthly rainfall in May was more than twice the long-term average (333 mm compared to 158 mm, respectively; Fig. 6). The majority of the monthly rainfall was over the 24-hour period prior to 9 am on 22nd May, with 136 mm recorded (Fig. 7), accounting for 41% of the total months rainfall. Over the 5-day period from the 19th to 23rd May there was a total of 244 mm (55% total months rainfall). Further upstream in the Clarence catchment, Grafton received 173 mm in the 24 hours before 9 am on 22nd May, and Dorrigo received 449 mm. A total of 917 mm was recorded at Dorrigo over the period 19th-25th May, and 319 mm was recorded at Grafton. While the rainfall received at Yamba on the 22nd May was similar to that on the 31st March 2009 (146 mm; Fig. 7), the rainfall in the upper catchment of the Clarence River was not as high during the March event, and therefore there was only minor flooding in the Wooloweyah catchment at that time. Storm surge and spring tides contributed to the major flooding of the lower Clarence floodplain.

Rainfall in June 2009 was above the long-term average (Fig. 6), although the majority of rainfall was near the end of the month (18th to 23rd June; Fig. 7). A total of 158 mm was recorded over this 6-day period, accounting for 87% of the total month's rainfall. Due to the major flooding only one month prior to this, and the time of year (i.e. lower evaporation rates), the significance and impact of this event on water quality and the environment was greatly increased.

3.1.3. Wind

Wind direction varied seasonally, with westerlies and southwesterlies dominating over winter (Fig. 8). During spring northerly winds were predominant, changing to east-southeasterlies during summer and autumn. Over late autumn winds were variable, ranging from southeasterlies to southwesterlies (Fig. 8). Westerlies, northerlies, southeasterlies and southerlies were the predominant winds over the condition assessment period (Fig. 8). Strong winds were associated with southeasterlies and southerlies, while the weakest winds were generally from the southwest (Fig. 9).

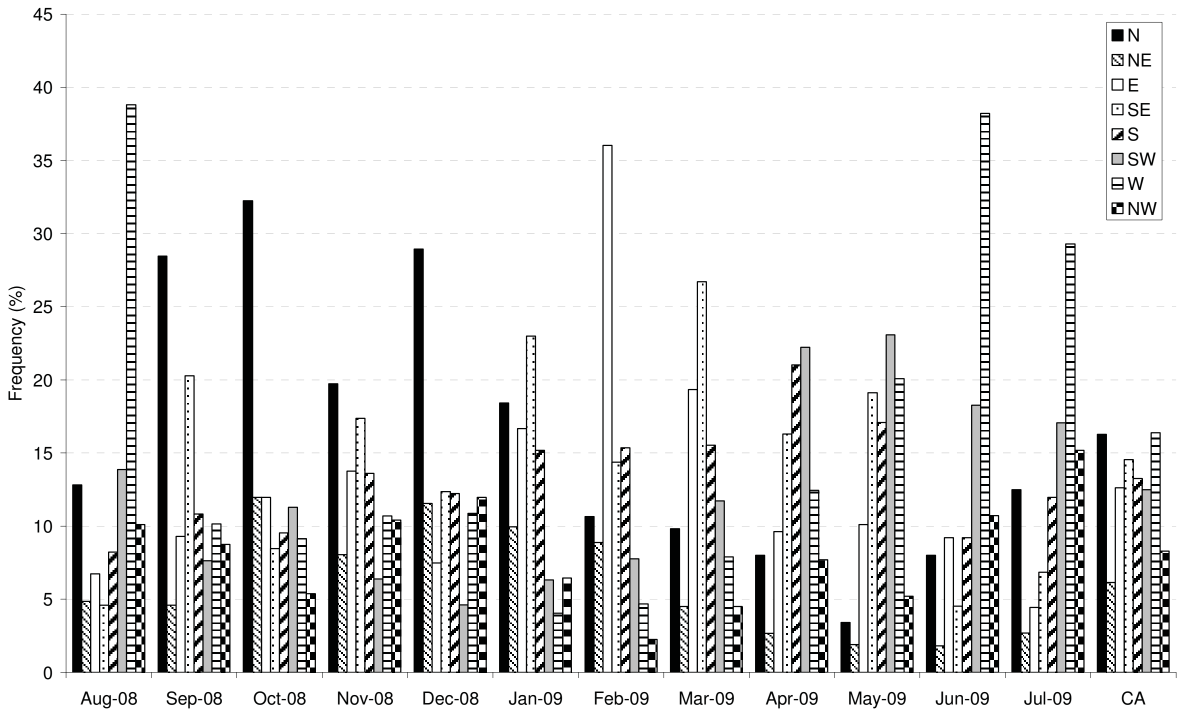

Figure 8: Frequency of wind direction at Wooloweyah Lagoon during each month over the condition assessment period. CA = total condition assessment period.

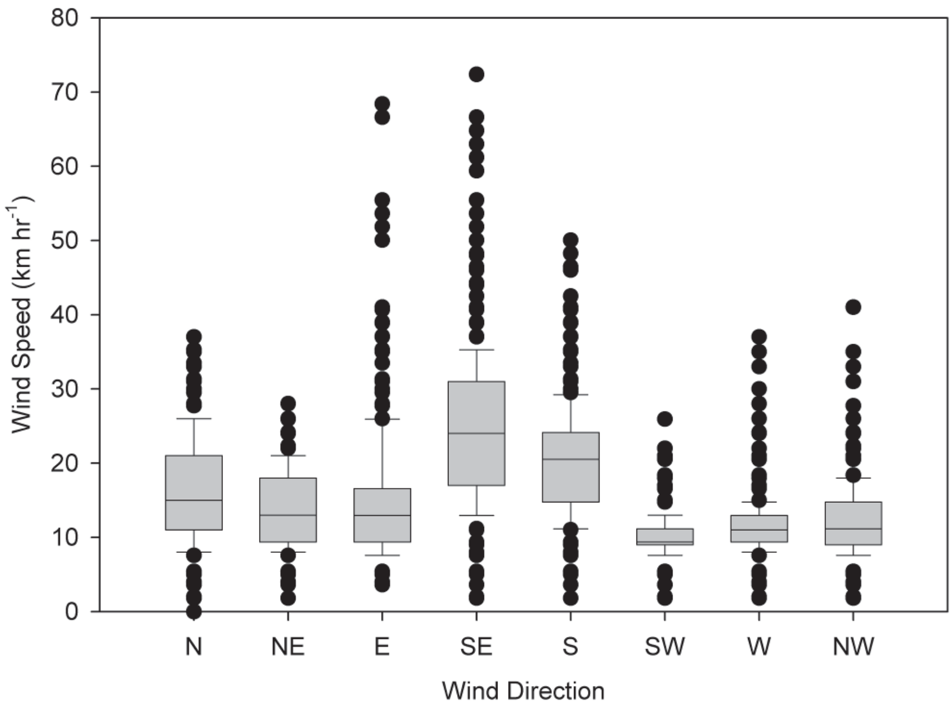

Figure 9: Range of wind speed associated with each wind direction during the condition assessment period. The lower boundary of the box indicates the 25th percentile, the upper boundary the 75th percentile and the line within the box the median. Whiskers above and below the box indicate the 90th and 10th percentile, respectively. Filled circles represent outliers.

3.2. Water quality

3.2.1. Turbidity

Turbidity within the lagoon was often above the trigger value recommended by the HRC (1999) of 25 NTU (Fig. 10). The average (mean) turbidity was 45 NTU, and 58% of the values were above 25 NTU. There was a weak correlation between wind speed and turbidity within the lagoon (Fig. 11). Turbidity was generally highest when winds were from the south and southeast (median turbidity of 47-48 NTU; Fig. 12), when winds were also generally strongest (Fig. 9). Median turbidity values were lowest in relation to southwesterly and westerly winds; however, high turbidity corresponded with winds from all directions (Fig. 12). Rainfall, and therefore increased turbidity in runoff water, may have also affected turbidity within the lagoon (see below). The two-fold effect of wind and rainfall was exemplified in May 2009 during the major flooding. Two peaks in turbidity were captured by the logger (Fig. 10) – the first corresponded with 100 km hr^{-1} wind gusts (average wind speed of 65-73 km hr^{-1}), and the second increase in turbidity coincided with the main flood peak arriving from upriver.

During the regular monitoring of the lagoon, zone averages were primarily below the HRC (1999) trigger value of 25 NTU, with the exception of Lagoon North during December and late-May, Taloumbi in late-May, and Oyster Channel and Shallow Channel during July (Fig. 13). Within all zones, there was an increase in turbidity between October and November, which remained at an elevated level during December. Potential causes of increased turbidity over this period were trawling, a change in wind direction, and/or increased rainfall. A sample collected from behind a trawler in November had a turbidity value of 170 NTU, whereas other nearby sites within the lagoon had turbidity only ranging from 19 NTU to 36 NTU (see Appendix A3). Increased turbidity over the November/December period (Fig.

13) may have also been due to the change in wind direction from westerlies to northerlies (Fig. 8). The turbidity of discharge water to the lagoon was also elevated during November (Fig. 14) and corresponded to increased rainfall (Fig. 7).

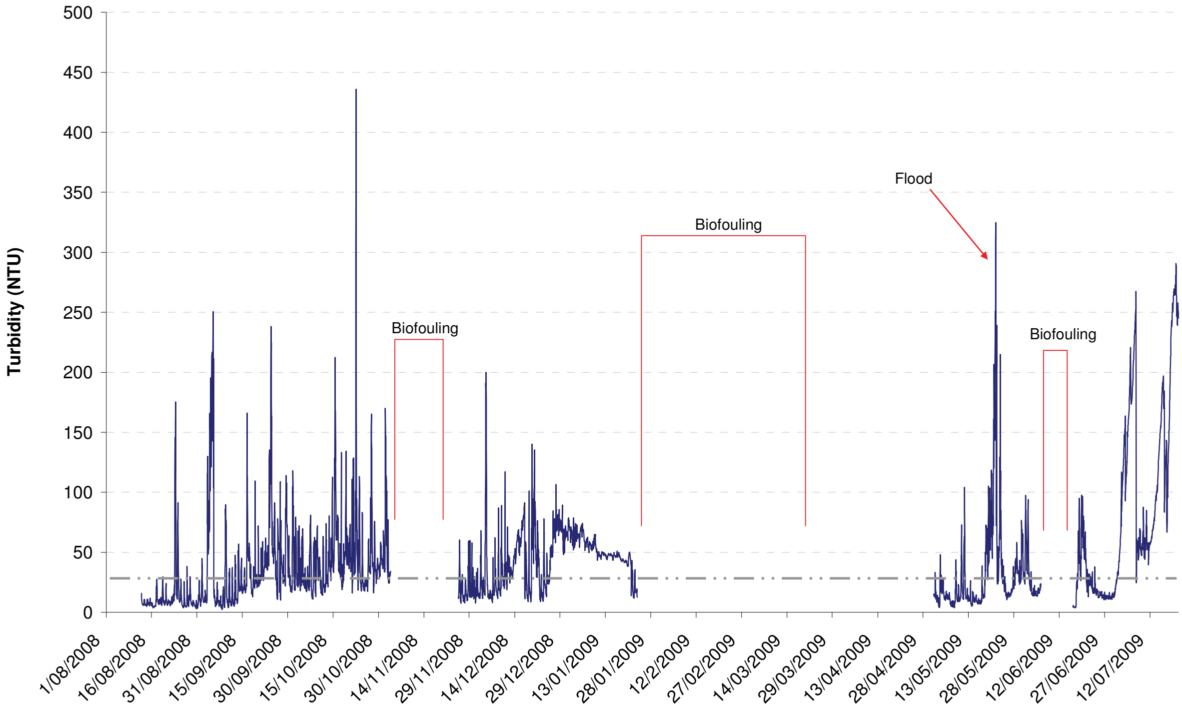

Figure 10: Turbidity within Wooloweyah Lagoon, August 2008 to July 2009. The HRC (1999) maximum trigger value of 25 NTU is indicated by — · · — · ·.

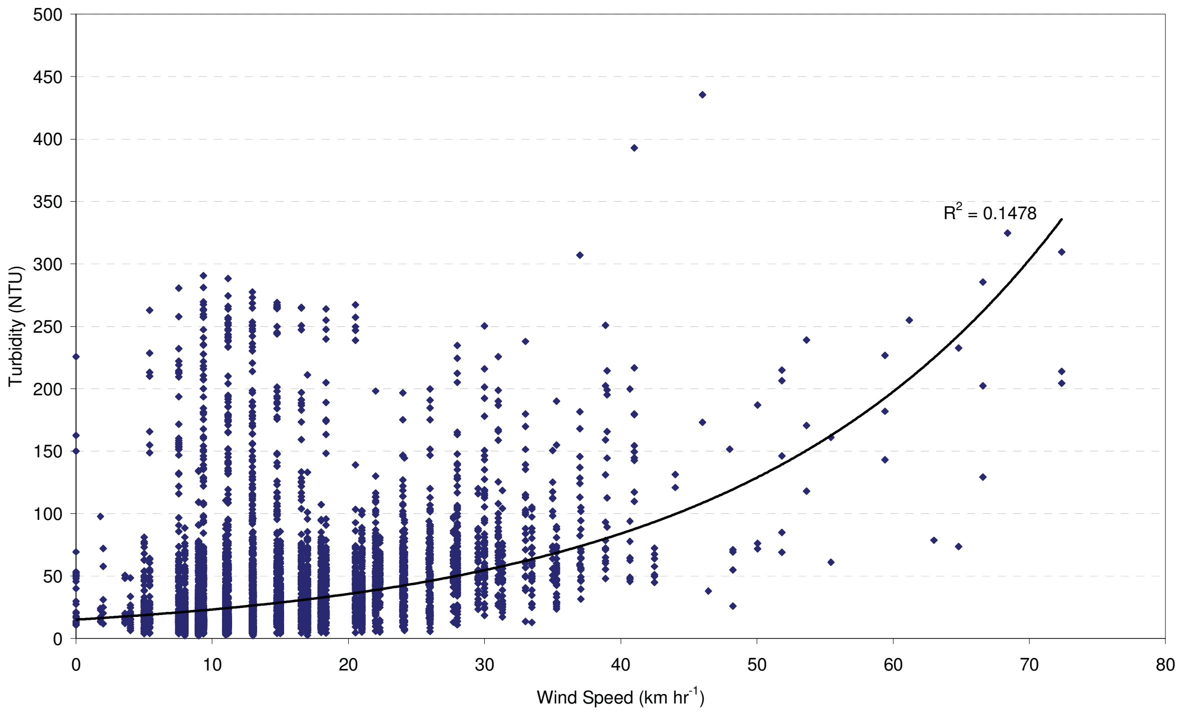

Figure 11: Correlation between lagoon turbidity and wind speed.

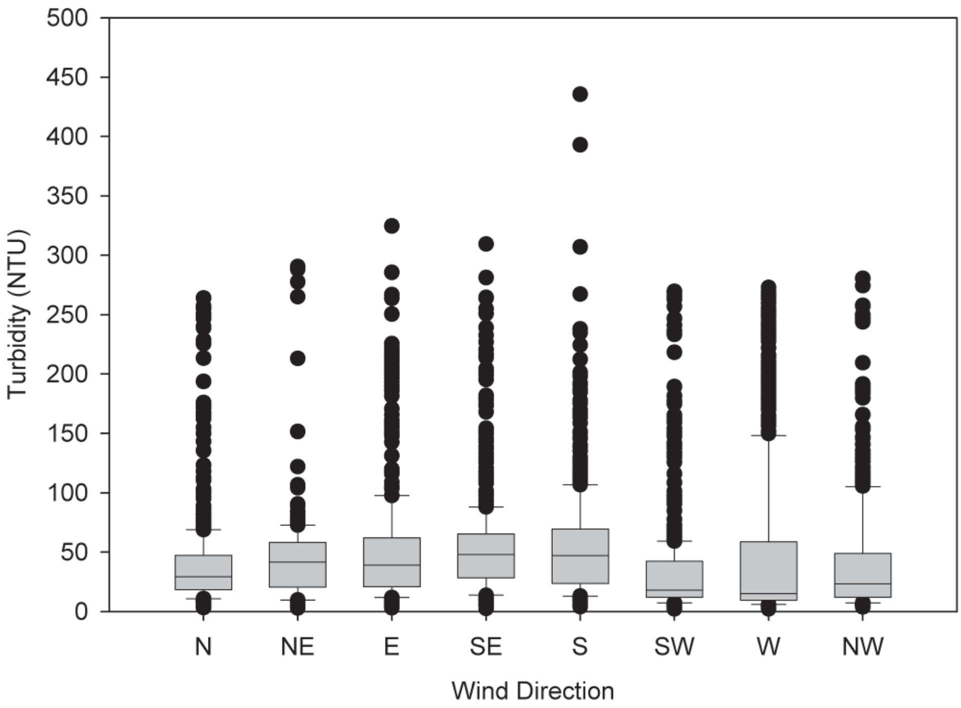

Figure 12: Turbidity of Wooloweyah Lagoon in relation to wind direction. The lower boundary of the box indicates the 25th percentile, the upper boundary the 75th percentile and the line within the box the median. Whiskers above and below the box indicate the 90th and 10th percentile, respectively. Filled circles represent outliers.

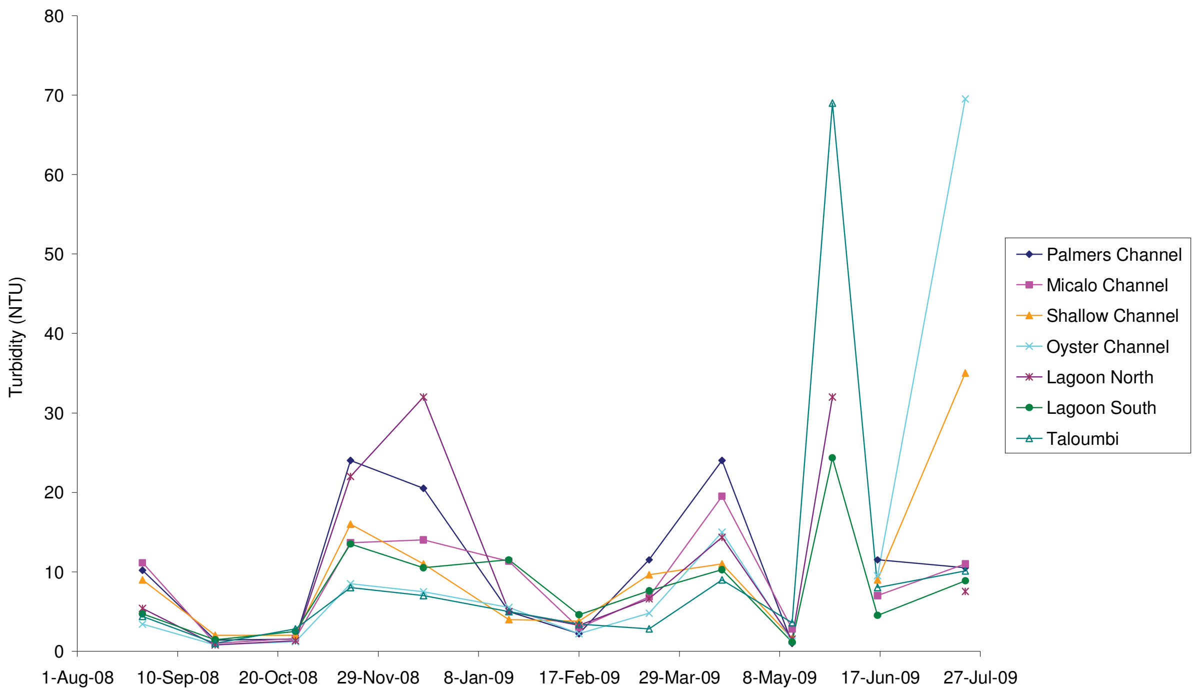

Figure 13: Average turbidity within each zone for regular monitoring (including the May 2009 flood).

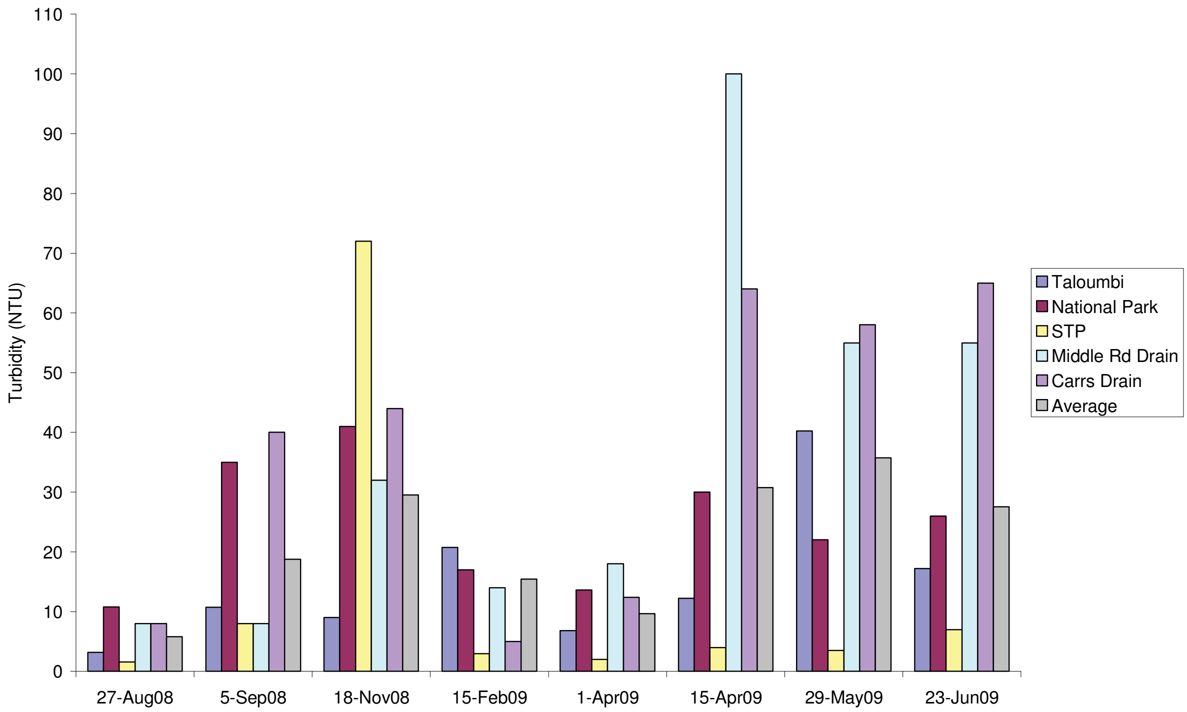

Figure 14: Turbidity of event-based sites, with the average NTU per sample period also shown.

Increased turbidity across all zones in April and late-May was directly related to rainfall events (Fig. 7), with both regular sites and event-based sites showing an increase in turbidity (Fig. 13 and Fig. 14). Turbidity was highest in Palmers Channel, Middle Rd Drain, Carrs Drain and Micalo Channel during mid-April, and all the drains during late-May. In terms of comparisons between land use, turbidity of runoff was generally highest at Middle Rd Drain, Carrs Drain and National Park (average of 36 NTU, 37 NTU and 24 NTU, respectively) (Fig. 13).

3.2.2. Baseline conditions for 2008/2009

Average pH for each zone over the whole assessment period and during most sample periods was above 7 (Table 3), and did not fall below 6 at any individual site. A decrease in pH was recorded at all sites between March and April, and at sites monitored during late-May (post-flood), both corresponding with increased rainfall (Fig. 15). The pH in all zones, at some stage during April to May, fell below the lower trigger value range (HRC 1999) of 7-8.5 (Table 1).

Average salinity was generally lowest at Taloumbi and Palmers Channel, but was also most variable in these zones (Fig. 16 and Fig. 17). Average salinity within the lagoon was similar between the northern and southern regions, however, it was more variable in the Lagoon South zone (Fig. 17).The rapid decrease in salinity at all sites between March and April was due to increased rainfall over this period (Fig. 7). The second decrease in salinity at all sites between May and June was also due to high rainfall when major flooding occurred.

Dissolved oxygen concentrations within the lagoon and channels were predominantly above the trigger value (HRC 1999) of 6 mg L^{-1} (Fig. 17), with the exception of Palmers Channel in April 2009 (2.8 mg L^{-1} at site R1 and 4.4 mg L^{-1} at site R2). Similarly, in the Taloumbi drain DO was only 0.6 mg L^{-1} during the April 2009 period. While the average DO was lower in the Taloumbi drain in comparison to the other regular monitoring sites, it was also the most variable (Fig. 17). Dissolved oxygen concentrations greater than 10 mg L^{-1} were recorded on several occasions within the Taloumbi drain.

Table 3: Average water quality values for regular sites over the 12-month condition assessment period.

Parameter	Palmers Channel	Micalo Channel	Shallow Channel	Oyster Channel	Lagoon North	Lagoon South	Taloumbi
pH	7.6	7.6	7.7	7.8	7.9	7.9	7.1
Salinity (ppm)	17876	26801	26015	24670	25119	22796	15155
DO (mg L^{-1})	7.3	8.2	8.3	8.3	7.9	8.3	7.0
Turbidity (NTU)	10	8	10	11	10	8	10
TP (mg L^{-1})	0.05	0.03	0.03	0.03	0.03	0.04	0.09
Orthophosphate (mg L^{-1})	0.014	0.004	0.006	0.005	0.004	0.004	0.022
TN (mg L^{-1})	0.56	0.42	0.39	0.38	0.41	0.54	1.03
Nitrate (mg L^{-1})	0.036	0.013	0.017	0.016	0.011	0.008	0.007
Nitrite (mg L^{-1})	0.004	0.003	0.003	0.003	0.002	0.002	0.007
Ammonia (mg L^{-1})	0.057	0.067	0.039	0.047	0.041	0.036	0.060
Chl-*a* (mg L^{-1})	0.008	0.007	0.006	0.005	0.008	0.011	0.013

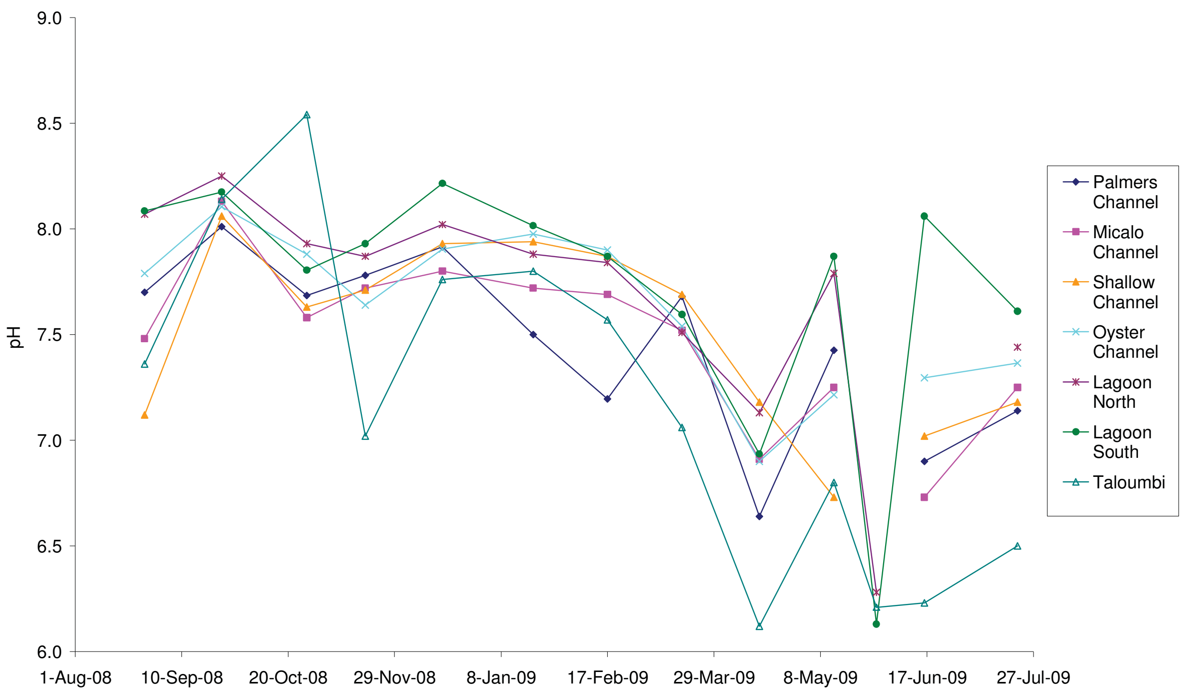

Figure 15: Average pH of regular monitoring zones at Wooloweyah Lagoon. The decrease in pH during April and May 2009 corresponded with high rainfall.

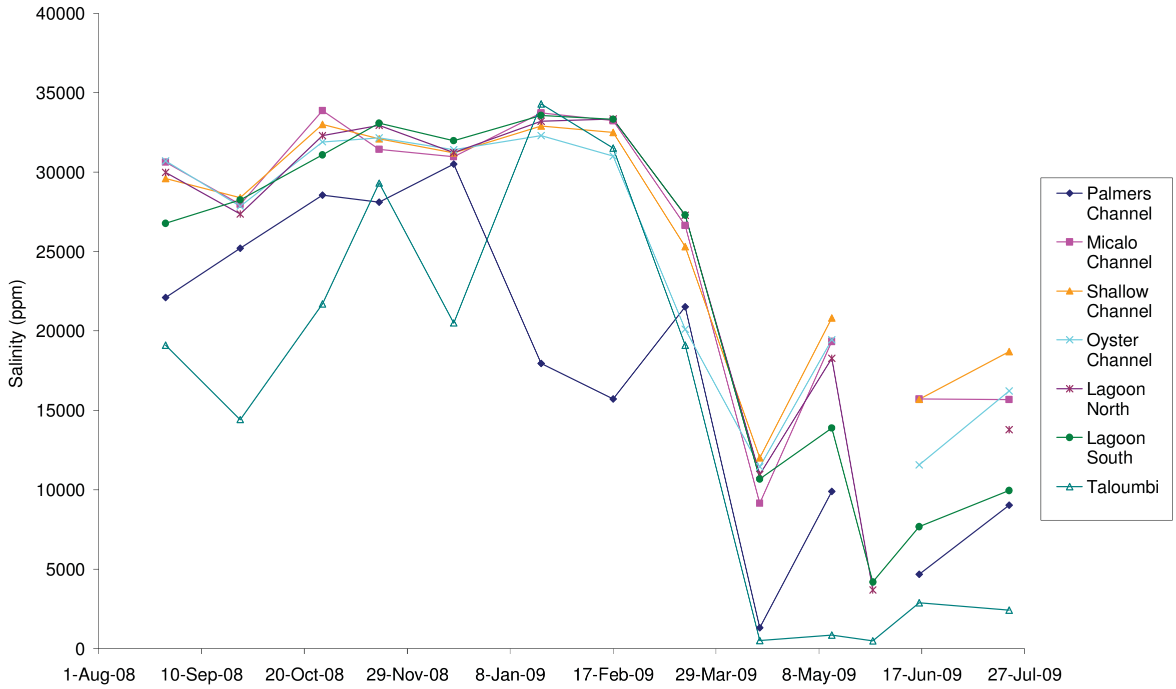

Figure 16: Average salinity of regular monitoring zones at Wooloweyah Lagoon. Taloumbi and Palmers Channel generally had the lowest salinity throughout the assessment period.

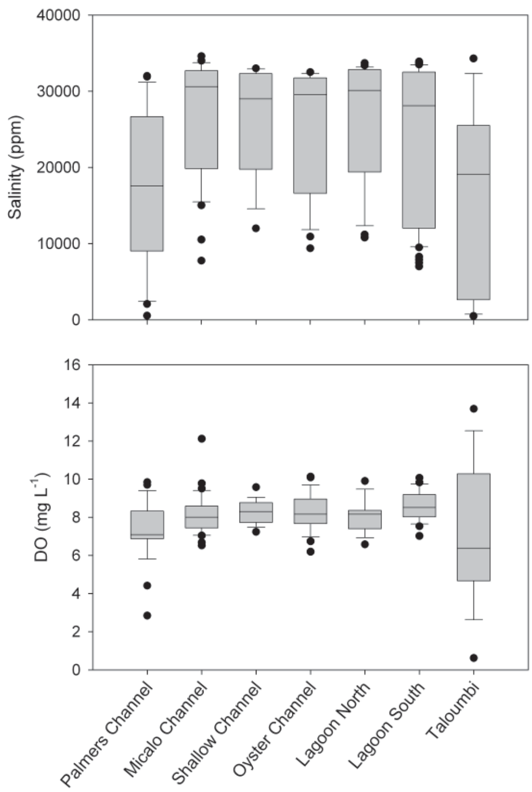

Figure 17: Salinity and dissolved oxygen concentrations in the Wooloweyah Lagoon study area. The lower boundary of the box indicates the 25th percentile, the upper boundary the 75th percentile and the line within the box the median. Whiskers above and below the box indicate the 90th and 10th percentile, respectively. Filled circles represent outliers.

Concentrations of TP were generally below the trigger value (HRC 1999) of 0.05 mg L^{-1} (Fig. 18), with the exception of Taloumbi over the majority of the study (average of 0.09 mg L^{-1}; Table 3). Palmers Channel was occasionally above the trigger value, specifically in September, November, March, April and May. However, these periods coincided with increased rainfall and high TP concentrations in discharge water from Middle Rd Drain and Carrs Drain (see Section 3.2.3). A large number of samples were below the detection limit for orthophosphate (0.005 mg L^{-1}). However, higher concentrations above the trigger value (HRC 1999) of 0.005 mg L^{-1} within Taloumbi and Palmers Channel were apparent (Fig. 19), as was the increased concentrations of orthophosphate at all sites following significant rainfall (Fig. 7) in April.

The variation in concentrations of TN corresponded to rainfall patterns, with increases at all sites in September, November, March and April (Fig. 20). In contrast to TP, TN concentrations remained high after the flooding in May 2009 (Fig. 18 and Fig. 20, respectively). Taloumbi consistently had the highest concentration of TN (average 1.03 mg L^{-1}; Table 3), with the exception of September when Lagoon South had the highest average at regular monitoring zones, and was above the HRC (1999) trigger value of 0.4 mg L^{-1}. In contrast, concentrations of nitrate and ammonia were relatively low in Taloumbi when compared to the other zones (Fig. 21 and Fig. 22, respectively). Palmers Channel had the highest average concentration of nitrate (0.036 mg L^{-1}) and Micalo Channel had the highest average concentration of ammonia (0.067 mg L^{-1}; Table 3), above the HRC (1999) trigger value of 0.015 mg L^{-1}. Nitrite concentrations were predominantly below detection limits (0.005 mg L^{-1}), although an increase in concentrations occurred at all sites in April 2009, and Taloumbi had very high concentration of nitrite during April and May (0.030 mg L^{-1} and 0.037 mg L^{-1}, respectively).

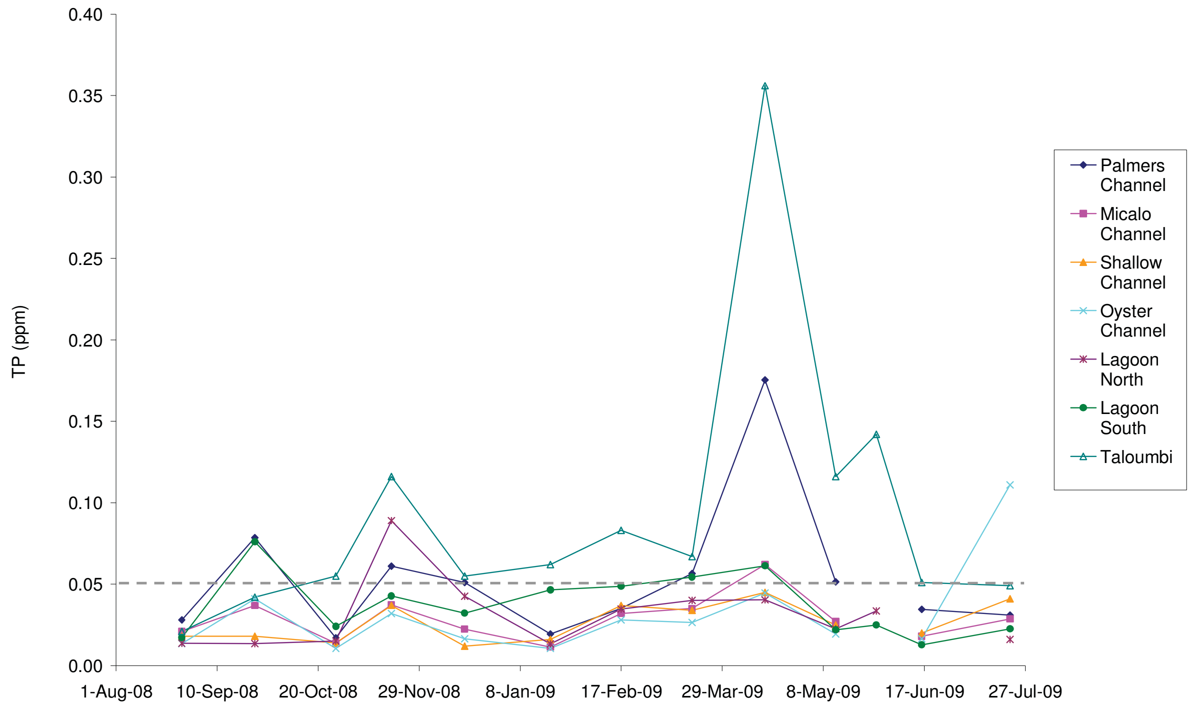

Figure 18: Average concentrations of total phosphorus at Wooloweyah Lagoon. The trigger value (HRC 1999) of 0.05 mg L^{-1} is indicated by the dashed line.

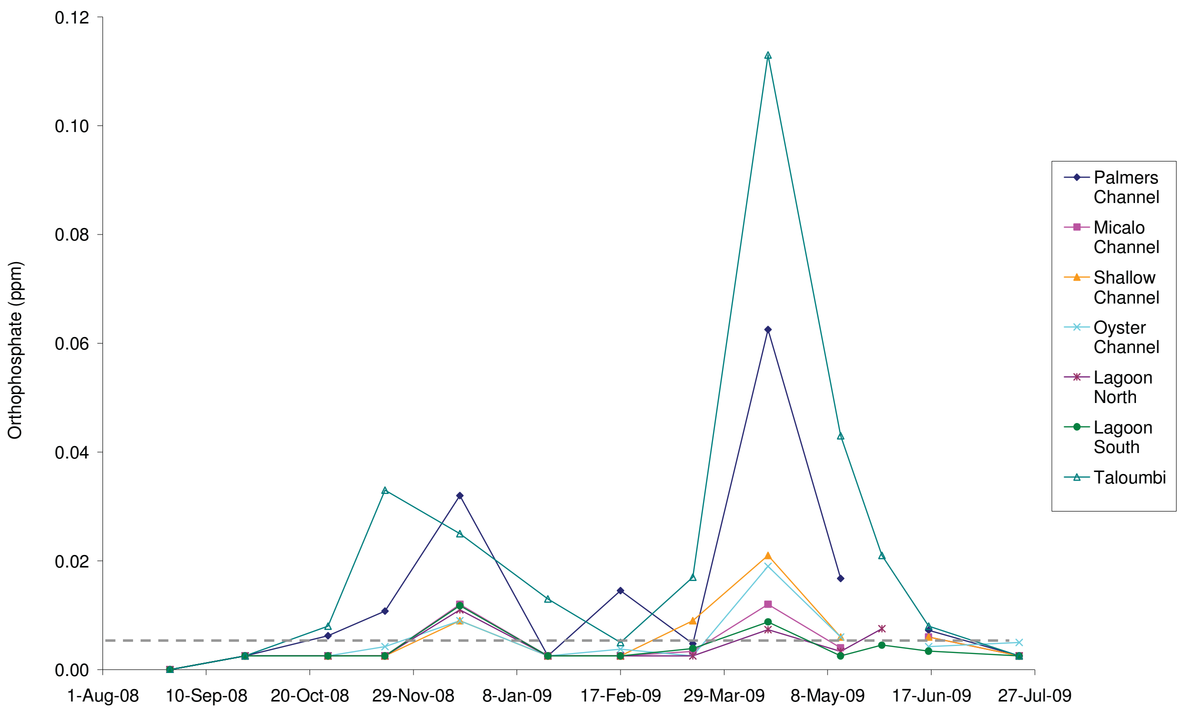

Figure 19: Average concentrations of orthophosphate at Wooloweyah Lagoon regular monitoring zones. The trigger value (HRC 1999) of 0.005 mg L^{-1} is indicated by the dashed line.

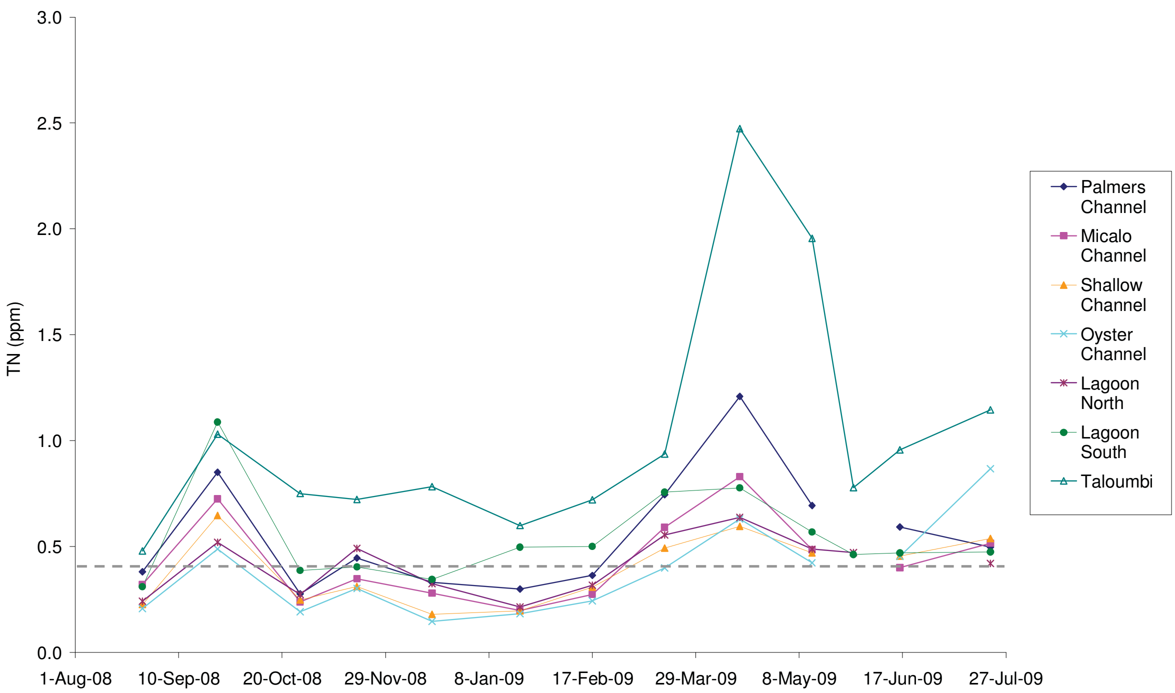

Figure 20: Average total nitrogen concentrations at regular monitoring zones. Most sites were above the trigger value (HRC 1999) of 0.4 mg L^{-1}, as indicated by the dashed line.

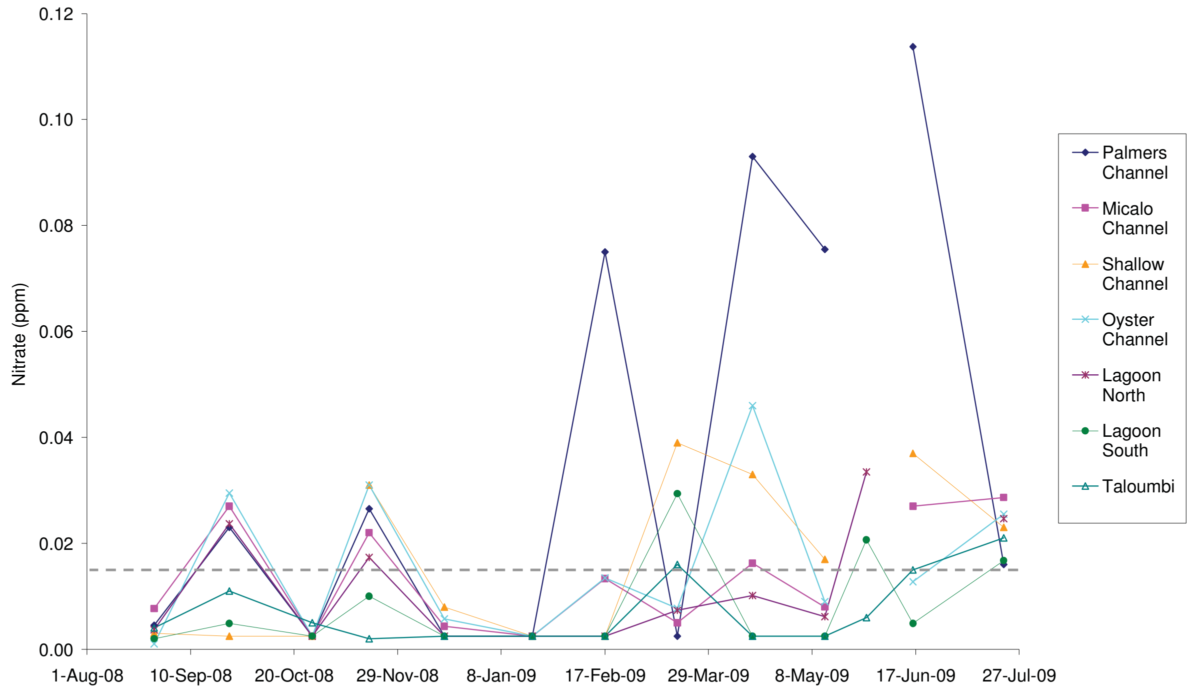

Figure 21: Average nitrate concentrations at regular monitoring zones. The trigger value (HRC 1999) of 0.015 mg L^{-1} is indicated by the dashed line.

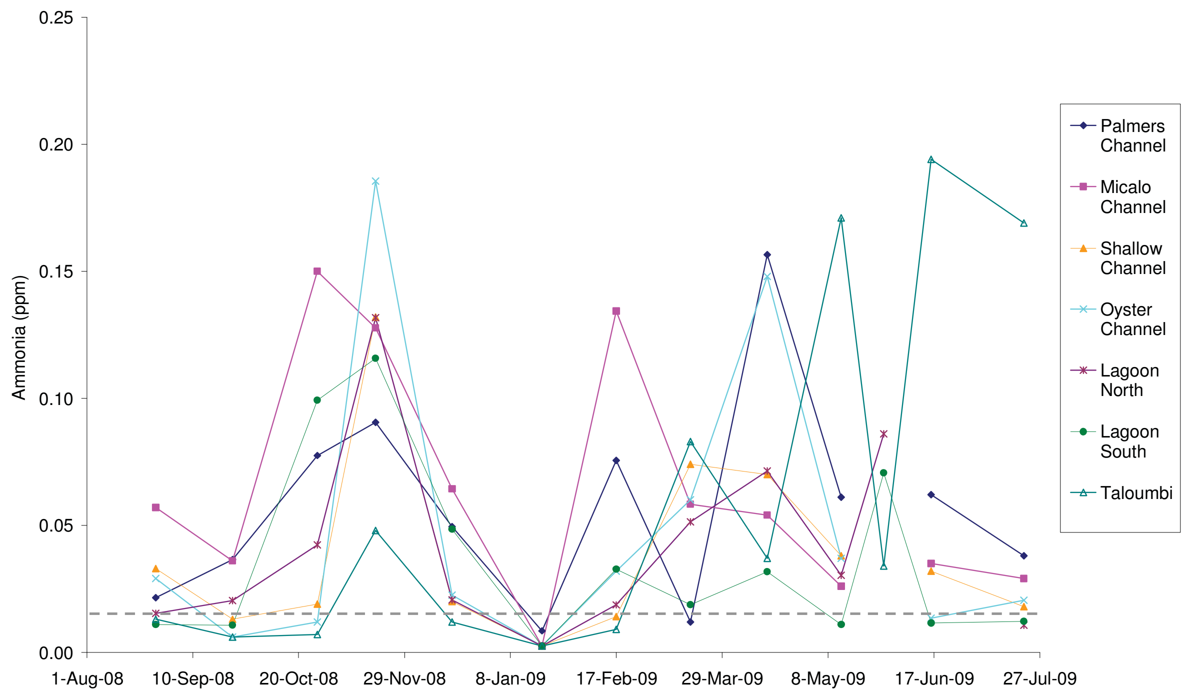

Figure 22: Average concentrations of ammonia at regular monitoring zones. The majority of sites were above the trigger value (HRC 1999) of 0.015 mg L^{-1}, as indicated by the dashed line.

Chl-*a* concentrations were above the trigger value (HRC 1999) of 0.004 mg L^{-1} for the majority of sites and sample periods (Fig. 23). Prior to increased rainfall in March/April 2009, Lagoon South and/or Taloumbi generally had the highest concentrations of chl-*a*. However, from April to the end of the assessment period in July, there was no consistent pattern of chl-*a* concentrations between sites.

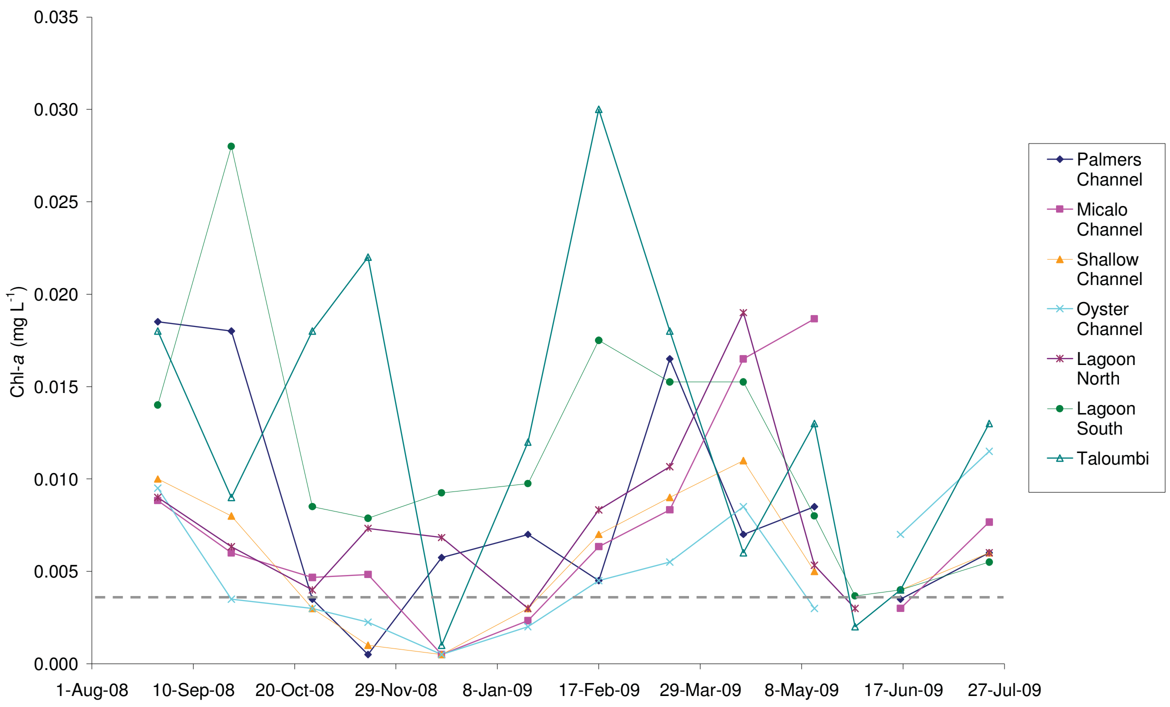

Figure 23: Average concentrations of chl-*a* at the regular monitoring zones. The majority of zones were above the HRC guideline (1999) of 0.004 mg L^{-1}, as indicated by the dashed line.

3.2.3. Event sampling

The most significant event sampling rounds, in terms of both rainfall and change in water quality, were those conducted in April, May and June 2009 (Section 2.2). The event sampling on 1st April was preceded by 146 mm of rainfall recorded over the 30th/31st March, and event sampling on the 15th April was preceded by two weeks of consistent rainfall (142 mm; Fig. 7). Water was observed flowing out of the creeks and drains on these two occasions, whereas during previous event samples there was no observable discharge. The event sampling conducted on the 29th May was highly important, as it followed a major flood throughout the Clarence River which occurred on the 23rd/24th May. The flood peak at Palmers Channel and Oyster Channel was on the 23rd May 2009, reaching 1.6 mAHD in both channels. The final event sample was conducted on the 23rd June, after 158 mm was recorded over 6 days. Therefore, while the water quality results of all event sample rounds are presented and discussed, the most significant were the last four events.

Discharge water quality was generally poorest at Carrs Drain, with an average DO of 3.7 mg L^{-1}, and higher turbidity and nutrients (Table 4, Fig. 14 and Figs 24-29). Very high concentrations of nutrients were recorded during November 2008 and April 2009, particularly nitrates (Fig. 27) and nitrites (Fig. 28). Concentrations of nutrients in the runoff water from the National Park creeks, and also the creek near the Yamba STP, were variable. However, the STP creek was generally higher than the National Park (Figs 24-29).

Table 4: Mean water quality values for event-based monitoring sites, calculated from 7 events (not including August 2008).

Parameter	Taloumbi	National Park	STP	Middle Rd Drain	Carrs Drain
pH	6.2	6.9	6.6	6.8	6.2
Salinity (ppm)	11540	14757	10574	12536	5575
Temp. (°C)	22	21	19	23	22
DO (mg L^{-1})	4.8	6.0	3.6	5.8	3.7
Turbidity (NTU)	16.7	26.4	14.2	40.3	41.2
TP (mg L^{-1})	0.11	0.05	0.17	0.14	0.43
Orthophosphate (mg L^{-1})	0.034	0.002	0.103	0.045	0.208
TN (mg L^{-1})	1.00	0.82	1.32	1.12	2.12
Nitrate (mg L^{-1})	0.018	0.009	0.011	0.329	0.819
Nitrite (mg L^{-1})	0.007	0.006	0.006	0.010	0.048
Ammonia (mg L^{-1})	0.070	0.077	0.128	0.092	0.218
Chl-*a* (mg L^{-1})	0.011	0.010	0.004	0.009	0.010

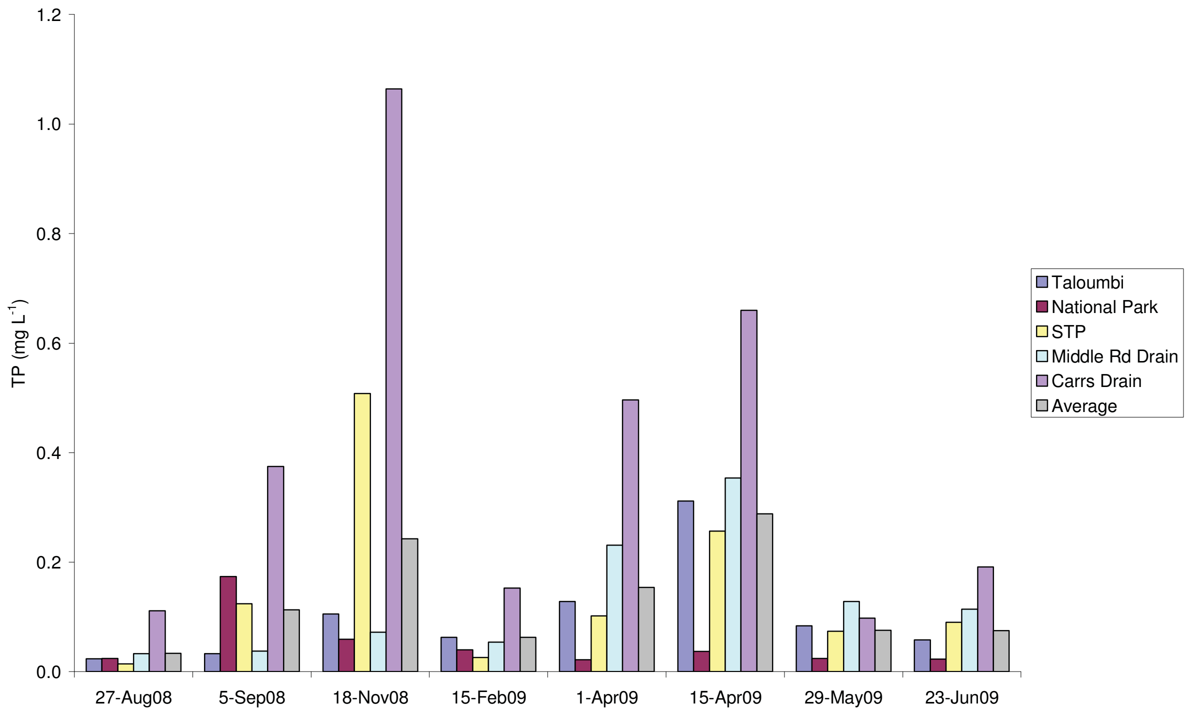

Figure 24: Total phosphorus concentrations of runoff from event-based sample sites.

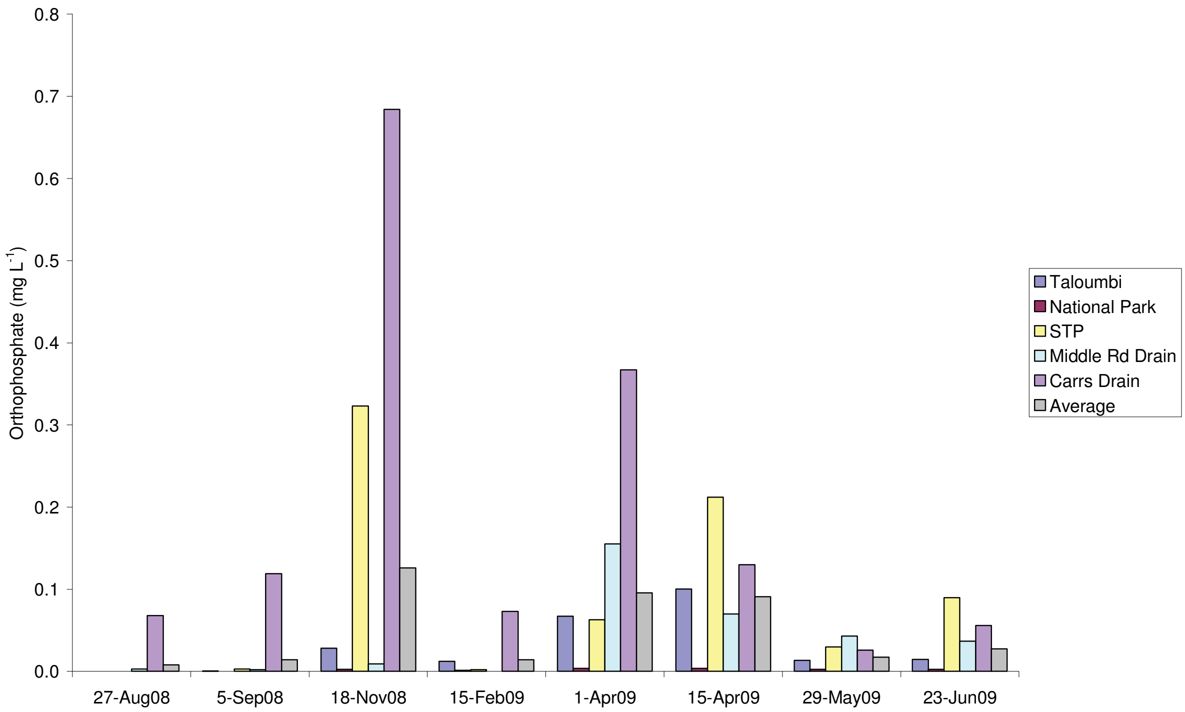

Figure 25: Orthophosphate concentrations of runoff from event-based sample sites.

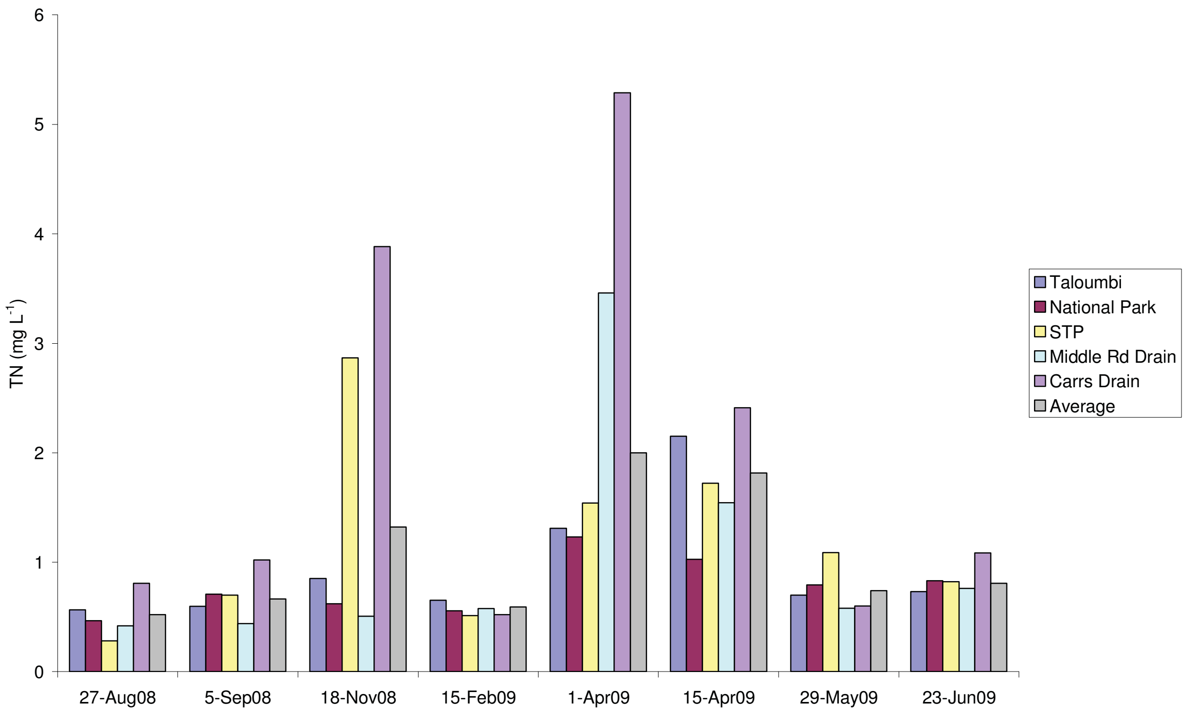

Figure 26: Total nitrogen concentrations of runoff from event-based sample sites.

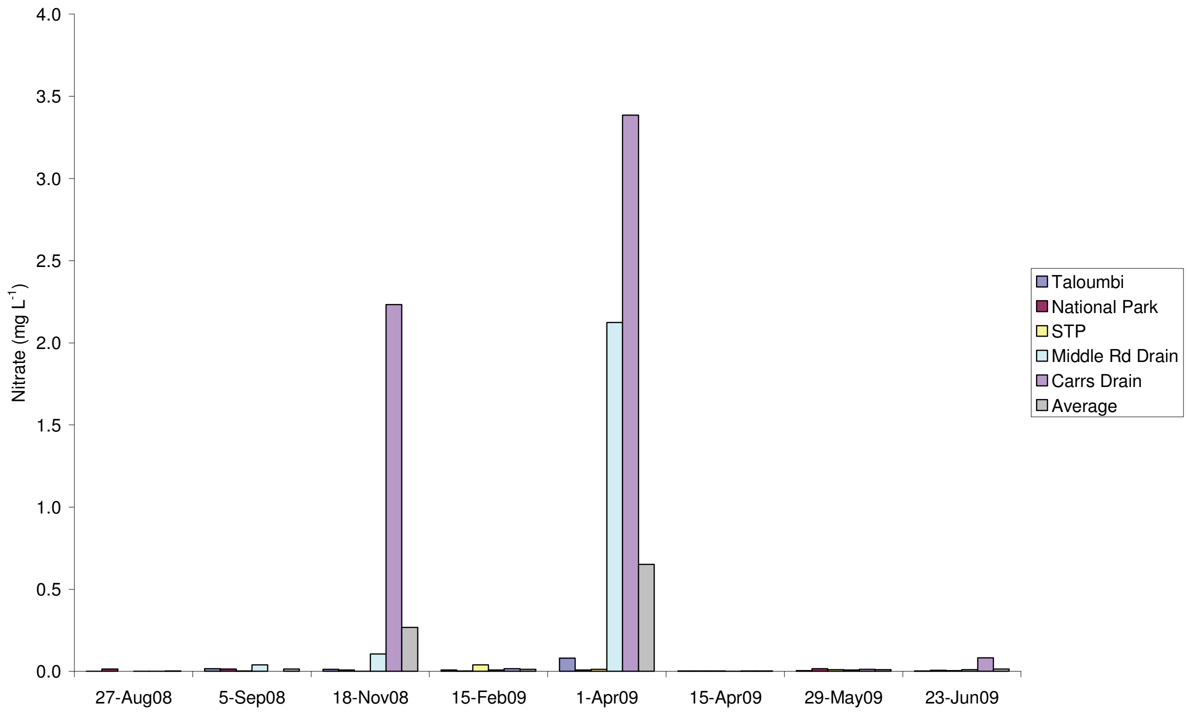

Figure 27: Nitrate concentrations of runoff from event-based sample sites.

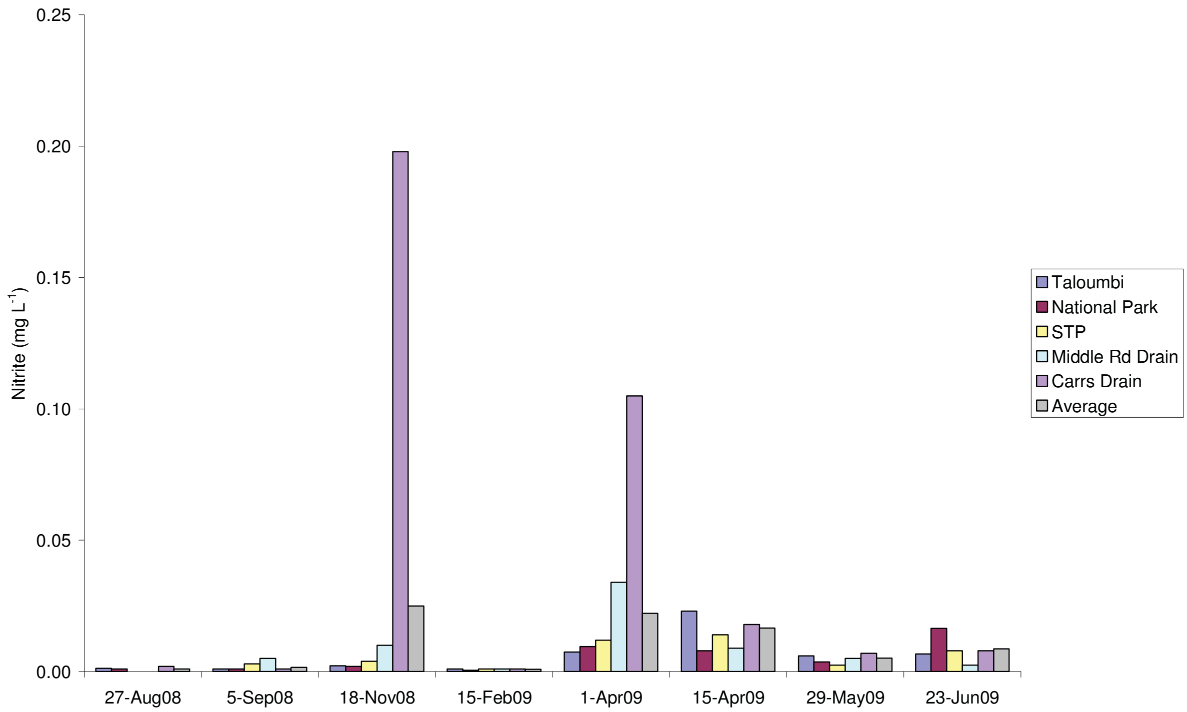

Figure 28: Nitrite concentrations of runoff from event-based sample sites.

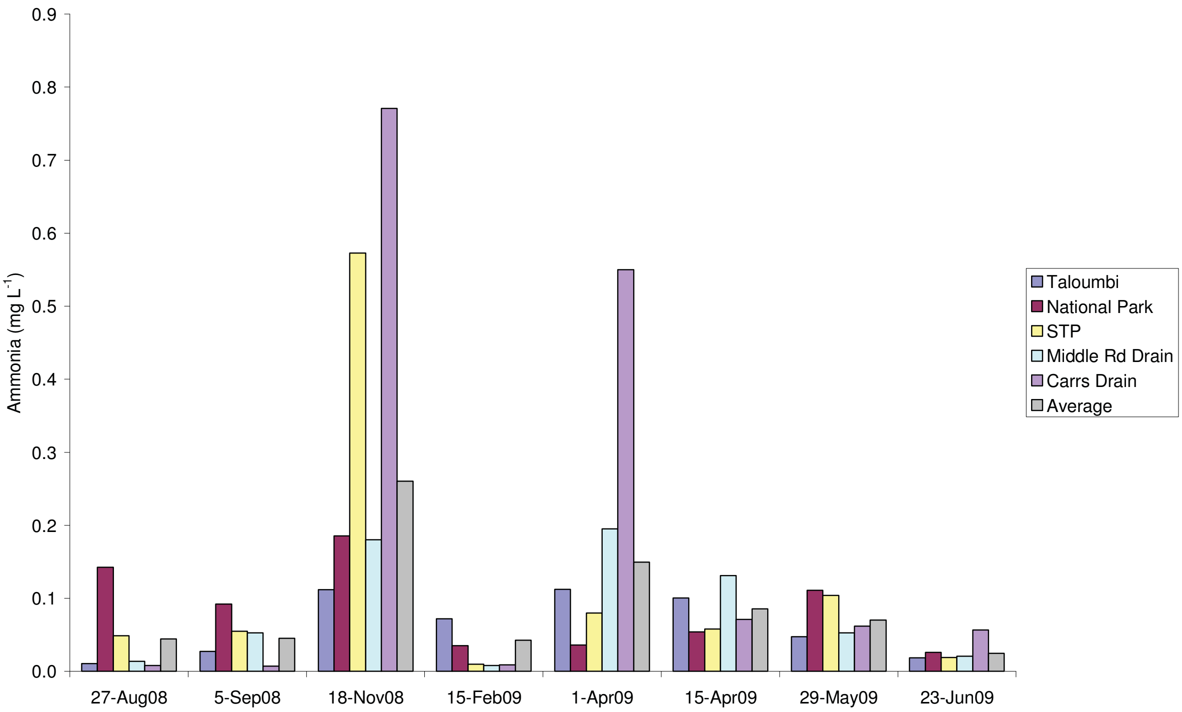

Figure 29: Ammonia concentrations of runoff from event-based sample sites.

Dissolved oxygen concentrations were variable between sites within each event captured (Fig. 30). No trend was observed in the data, with some sites decreasing in DO while other sites increased in response to the same rainfall event. Dissolved oxygen concentrations of less than 4 mg L^{-1} were recorded at each site during the assessment period (Fig. 30), although during different event sampling rounds.

Salinity was much lower at Carrs Drain in comparison to Middle Rd Drain and Taloumbi Drain (Table 4, Fig. 31). The National Park zone often had the highest salinity (Fig. 31). The significance of rainfall events in April, May and June on salinity, in comparison to the first 3 events captured, is clearly seen in Fig. 31. Similarly, all sites had a considerable decrease in pH during the last four events captured, in comparison to the baseline values in August 2008 (Fig. 32). pH remained above 5 at all event sites throughout the assessment period.

Chlorophyll-*a* concentrations were variable within and between sites during the assessment period (Fig. 33), and were generally lower from April 2009 onwards, corresponding with increased rainfall. There was no direct correlation between chl-*a* concentrations and other water quality parameters.

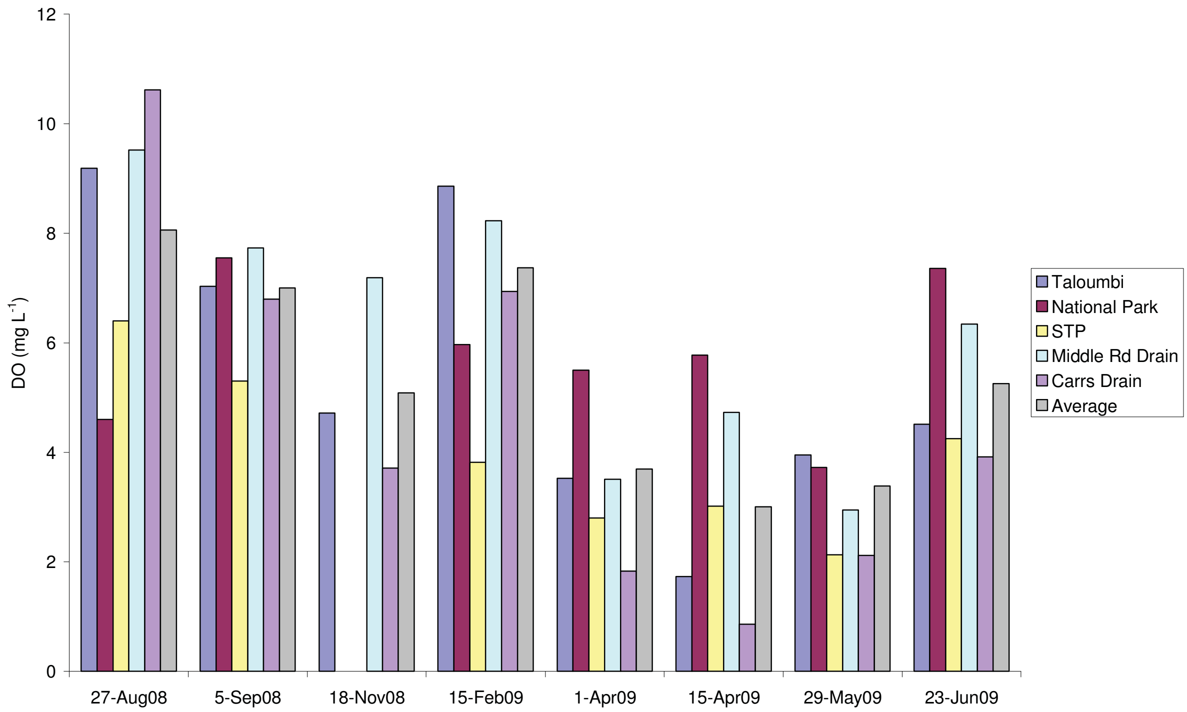

Figure 30: Average DO concentration at each event-based monitoring zone for each event captured. The average of all sites for each event is also shown.

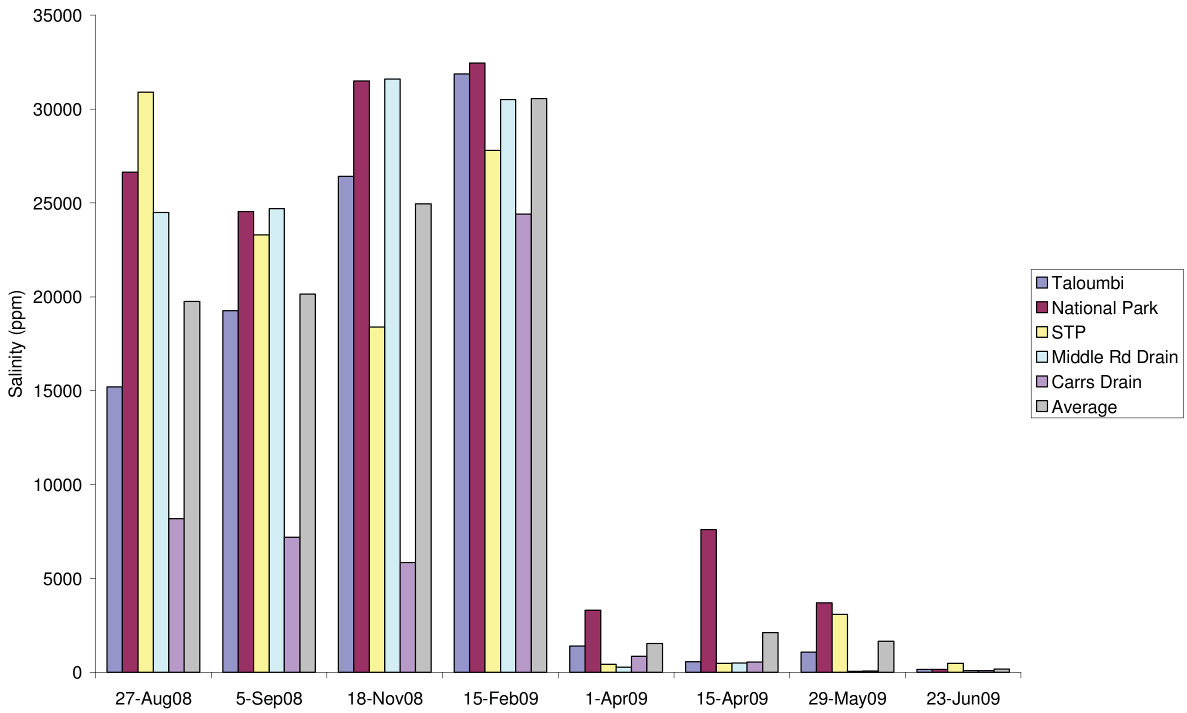

Figure 31: Average salinity at each event-based monitoring zone, with the average of all sites for each event also shown. Salinity was generally lowest in Carrs Drain and highest in the National Park (NP).

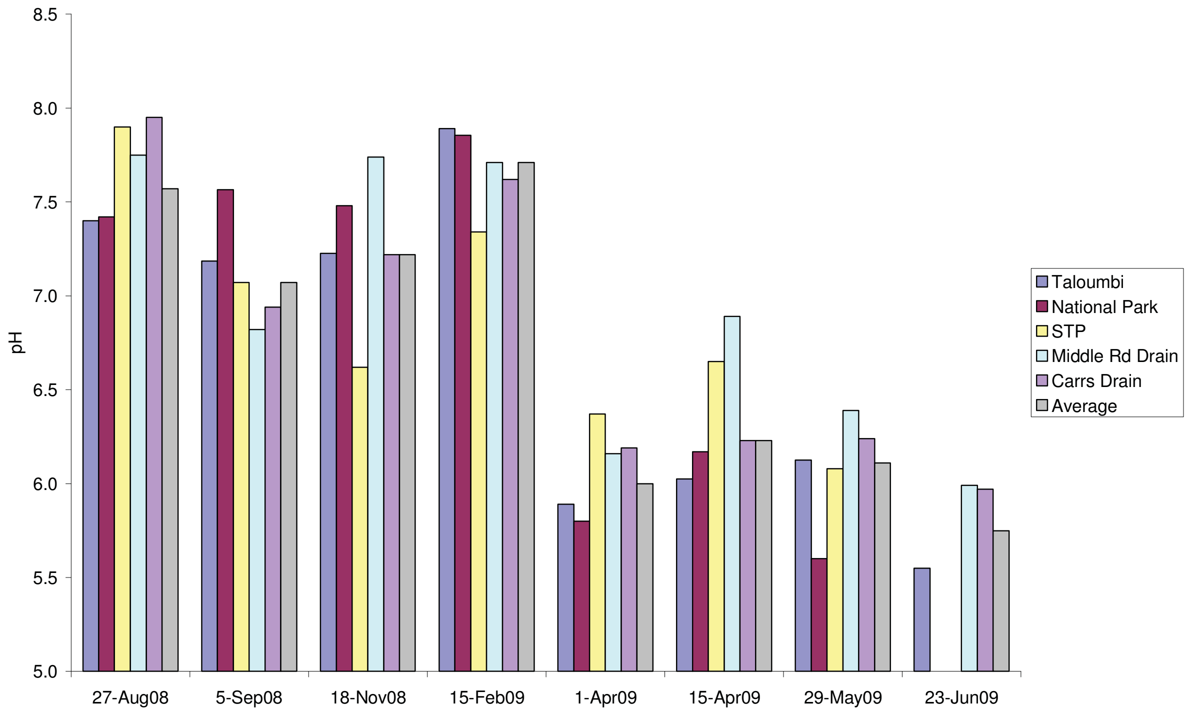

Figure 32: Average pH at event-based monitoring zones. There was a considerable decrease in pH during the April, May and June 2009 events, from the baseline values recorded in August 2008.

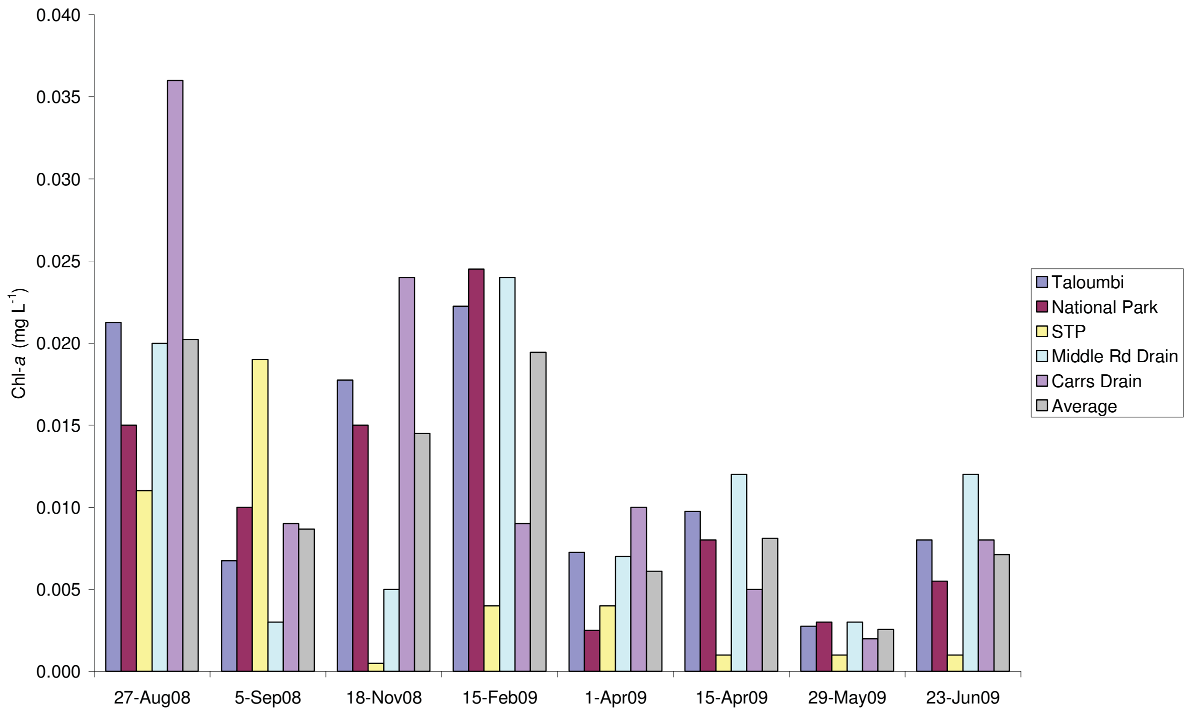

Figure 33: Chl-*a* concentrations of runoff water from event-based sample sites.

3.3. Sediment quality

Average TP concentrations were generally highest during October 2008 (Fig. 34), in contrast to phosphate which was highest during July 2009 (Fig. 35). Similarly, average sediment nitrate concentrations were also highest during July 2009 (Fig. 36). Sediment ammonia concentrations were highest during October 2008 and January 2009 (Fig. 37).

In terms of comparisons between zones, TP was highest in the Taloumbi drain, Carrs Drain and Middle Rd Drain (Fig. 34). Average ammonia and TN was highest in Carrs Drain and Middle Rd Drain (Fig. 37 and Fig. 38, respectively).

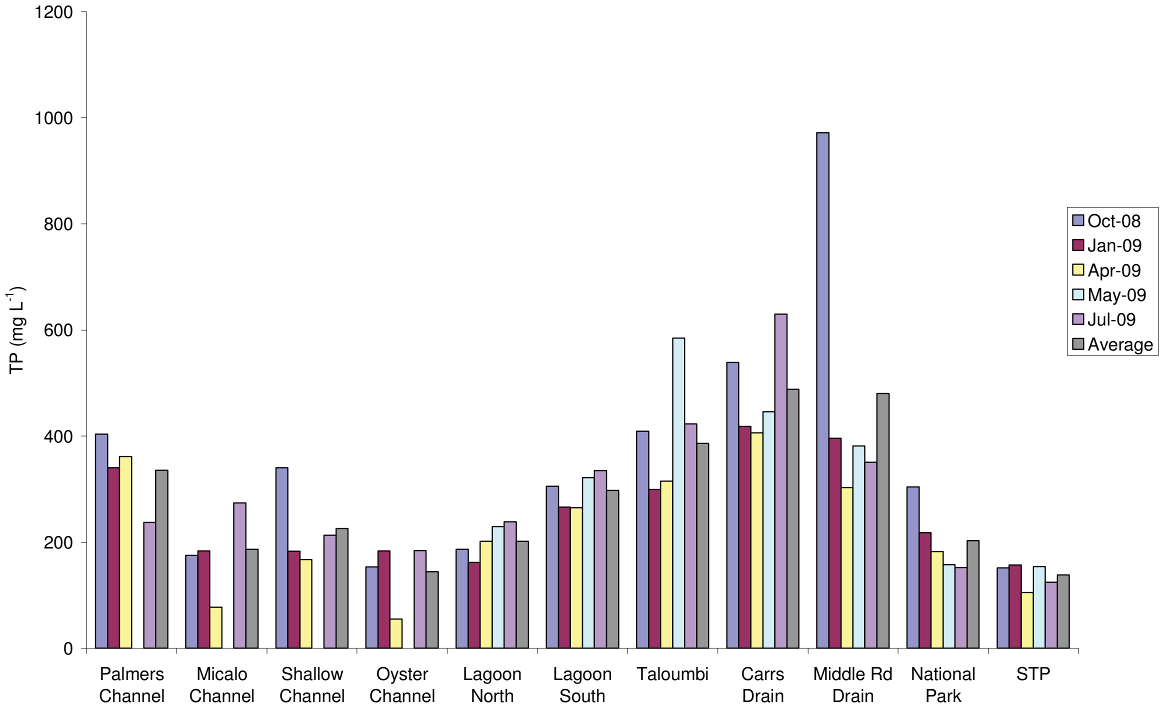

Figure 34: Average sediment total phosphorous concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were generally highest within the drains and during October 2008.

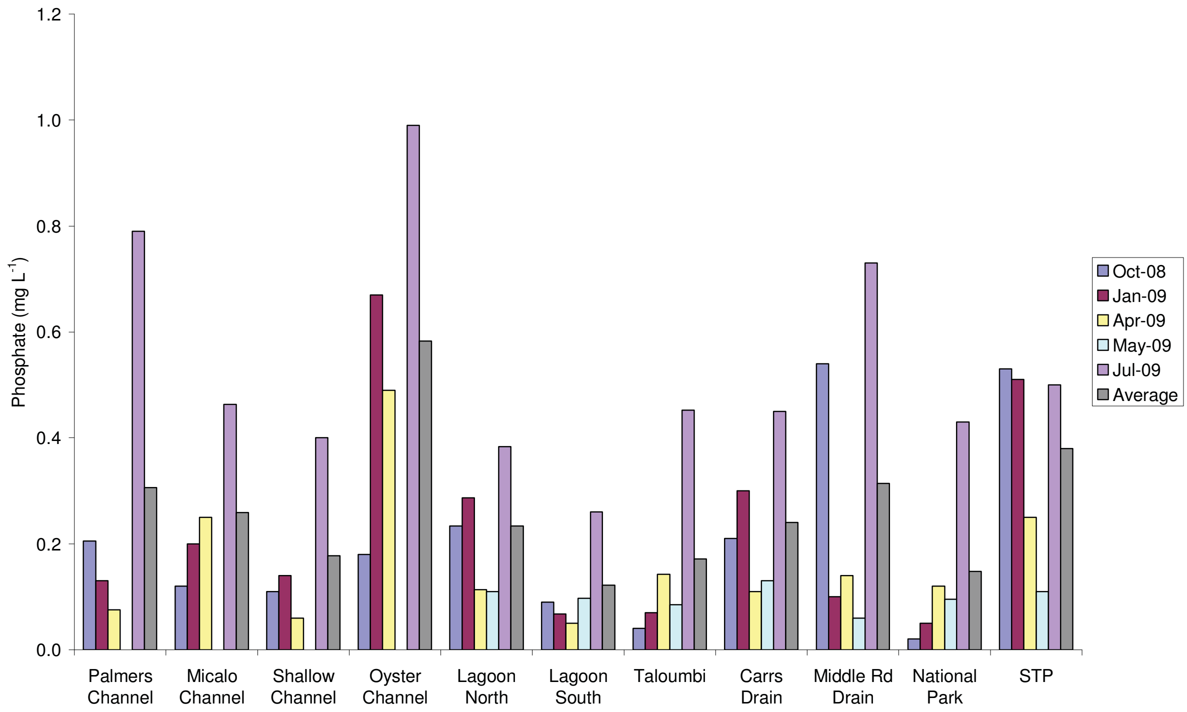

Figure 35: Average sediment phosphate concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were generally highest in July 2009.

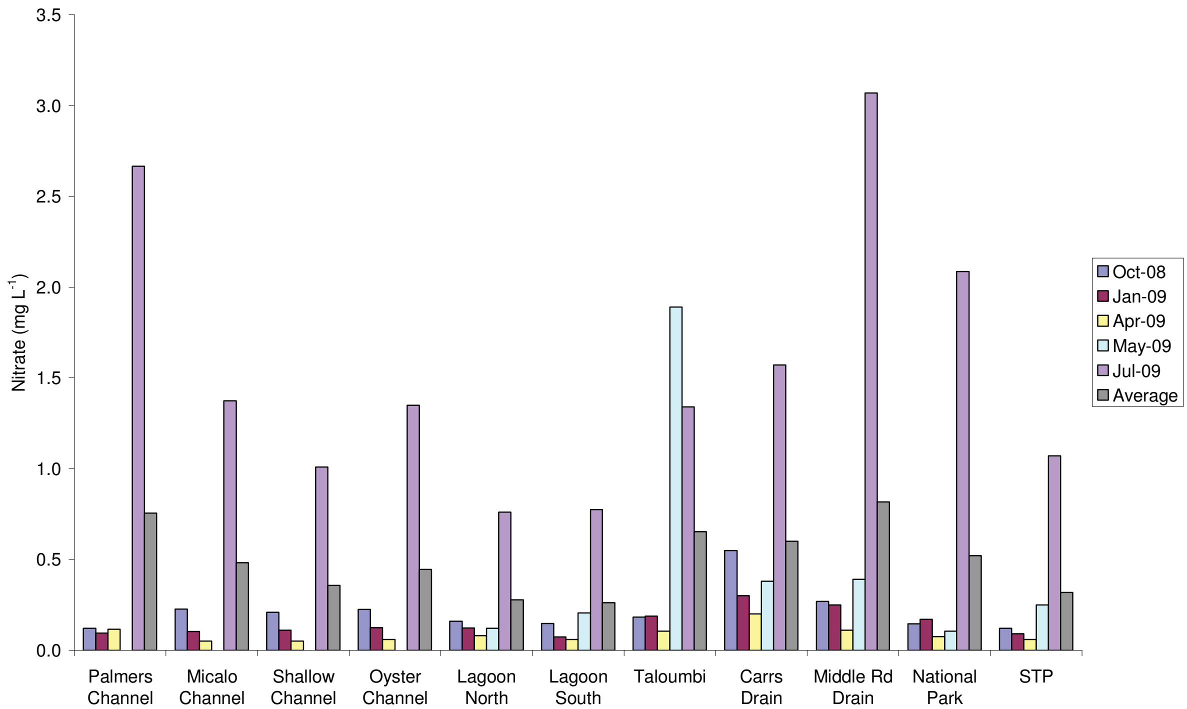

Figure 36: Average sediment nitrate concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were generally highest in July 2009.

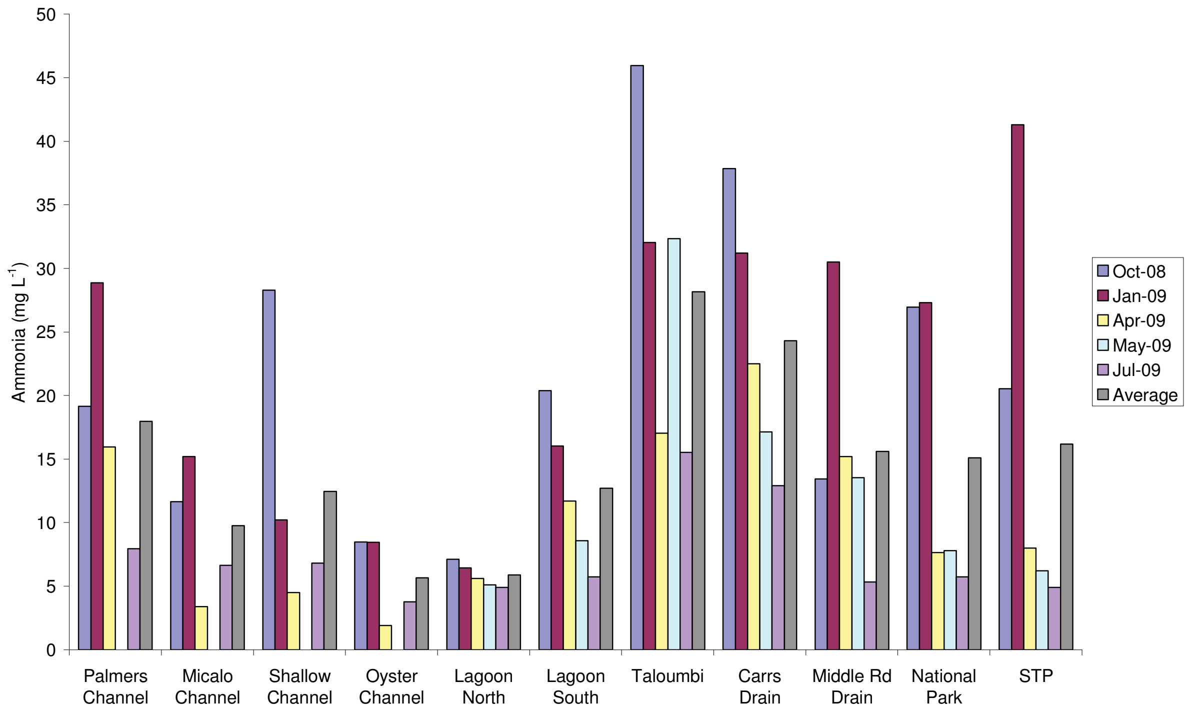

Figure 37: Average sediment ammonia concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were highest in October 2008 and January 2009.

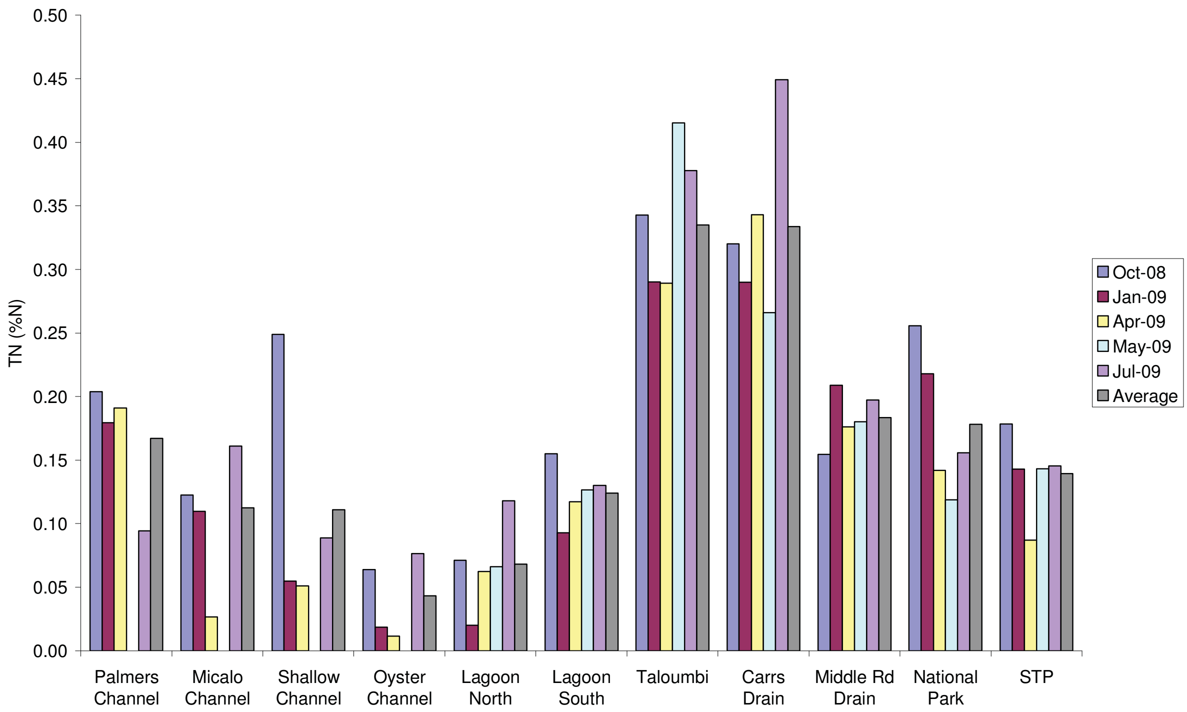

Figure 38: Average sediment total nitrogen concentrations within each monitoring zone. The average for each site over the assessment period is also given. Concentrations were highest in the Taloumbi drain and Carrs Drain. N.B. to convert %N to ppm, multiply by 10,000.

3.4. Sedimentation within the Lagoon

Sediment cores collected and analysed by ANSTO indicated the there was a difference in sediment type and sedimentation rates between the northeastern and southern areas of the Lagoon. Sediments in the northeastern part of the Lagoon were sandier than the southern area. The core from the northeastern area of the Lagoon indicated a change in sediment type (to less sandy sediment) and a decrease in mass accumulation rate at 6 cm depth. Between 4 and 6 cm depth there was disturbance (or mixing) of sediment layers, corresponding with a sediment age of between 7-10 years.

Sedimentation rates for the northeastern section were calculated as 0.4-0.6 cm yr^{-1}, in comparison to the western region which was estimated to be 0.7-1.0 cm yr^{-1} and the southern region at 2.0-3.0 cm yr^{-1}. The core collected in the southeastern region of the lagoon was only dated to an age of 7.4 (± 0.6) years of age. Discrete sediment laminations within the core (Fig. 39, Core 2B) were highly organic or fine clay material, and may be between 3.3 (± 0.5) years and 6.9 (± 0.6) years of age. The western core had clear signs of bioturbation (Fig. 39, Core 3B), suggesting that the sediment was reworked by marine organisms and therefore not suitable for sediment dating below 11 cm depth (10.5 ± 1.0 years).

All of the cores collected at Wooloweyah Lagoon were less than 60 years of age and reached a shell layer at the bottom (Fig. 39). The shells were identified as the bivalves *Anadara trapezia* and *Spisula trigonella*. Based on the extrapolated age of the northern and southeastern cores, there is potentially a difference of 37.5 to 54.2 years at the base of the cores (i.e. the shell layer). The sediment at the shell layer is approximately 50.0-62.5 years in the northern core, 8.3-12.5 years in the southeastern core, and 20.0-28.6 years in the western core.

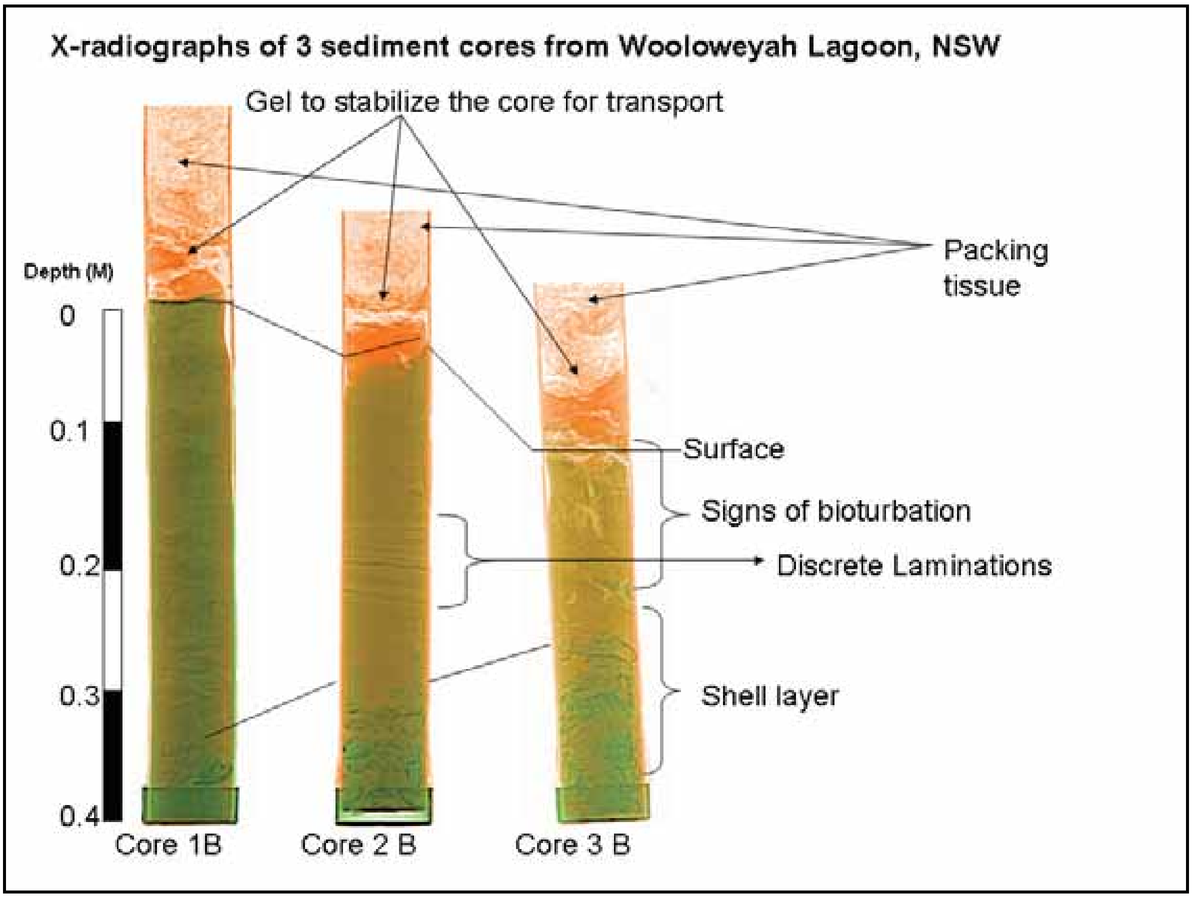

Figure 39: X-rays of sediment cores collected from Wooloweyah Lagoon (ANSTO 2009).

3.5. Catchment and habitat assessment

Drainage density prior to construction of drains was approximately 0.023 km ha^{-1}, in comparison to the current drainage density of approximately 0.036 km ha^{-1}. The large network of drains and natural creeks which drain the Wooloweyah Lagoon catchment is shown in Fig. 2. Micalo Island, Palmers Island, south of Palmers Channel, and the western/southern flats of the lagoon catchment are the most heavily drained areas within the catchment.

The primary land use within the catchment is grazing (55% of catchment) and sugar cane (24% of catchment) (Foley & White 2007). The area of sugar cane has reduced slightly over time, particularly on Palmers Island, due to waterlogging. The majority of agriculture is located on the western flats of the catchment, and on Palmers Island. Land use on Micalo Island is primarily grazing, and there is also a non-operational prawn farm which now acts essentially as a constructed wetland. The remainder of land use within the Wooloweyah Lagoon catchment is national parks and reserves (19%) and urban development (3%) (Foley & White 2007).

The bank condition of applicable monitoring sites is given in Table 5. The majority of areas were classified as stable, and 7 of the 17 sites assessed were classified as good with minor spot erosion. Only one site was classified as having moderate erosion (R6 at Shallow Channel). The majority of sites had either grasses or mangroves as the dominant form of riparian vegetation, and only two sites had evidence of cattle (E3 and E4 in the Taloumbi Ring Drain) (Table 5).

Much of the Wooloweyah Lagoon catchment has been mapped as high probability of acid sulfate soils (ASS) within 1-3 m of the ground surface (Fig. 40). Adjacent to the lagoon along the western and southern shore there is a high probability of ASS at or near the ground surface. To the northeast of the lagoon, there is a low probability of ASS at or near the surface, and between 1-3 m below the ground surface (Fig. 40). A number of test pits have been undertaken throughout the catchment and identified varying degrees of actual and potential ASS (see Tulau 1999; Warren 1991, Bowman 1991 and Planners North 1991 cited in Woodhouse 2001: 54-55). Large scalds from ASS oxidation have also been reported on Micalo Island (Planners North 1991 cited in Woodhouse 2001: 55).

Seagrass, saltmarsh and mangroves have been mapped by NSW DPI (2006) within the Wooloweyah Lagoon catchment (Fig. 41). The total area of mangrove was 214.20 ha, saltmarsh 161.51 ha, and seagrass 14.97 ha. Observations of seagrass areas within the lagoon during monitoring rounds indicated that seagrass cover is not very dense. There was often drift algae within the seagrass beds.

Table 5: Bank condition of monitoring sites, August 2008. See Table 2 for erosion classifications.

Site	Veg. Type	Erosion	Pugging	Structures	Substrate Type	Land Use
R1	natives, mangroves	good	N	floodgate	mud/silt	sugar cane
R2	grasses	good	N	levee	mud	rural-residential
R3	natives/mangroves	good	N	jetty, road	mud/silt	grazing
R4	natives/mangroves	stable	N	levee, road	mud	grazing
R5	sandfire, grasses	good	N	levee, floodgate	mud	grazing
R6	mangroves	moderate	N	road/causeway	mud/silt	road
R7	mangroves	good	N	power line to road	mud/sand	reserve
R8	natives, paperbark swamp	good	N	boat ramp	mud/sand	reserve/boat launch
E1	grass/reeds	stable	N	floodgates	mud	grazing
R16/E2	grass	stable	N	floodgates	mud	grazing
E3	grass	stable	Y	floodgates	silt/mud	grazing
E4	grass/reeds	stable	Y	floodgates	silt/mud	grazing
E5	grass	stable	N	N	silt/mud	National Park
E6	native bush/casuarinas	stable	N	N	silt/mud	National Park
E7	native bush	stable	N	N	mud/sand	nature reserve
E8	grass/reeds	stable	N	floodgates	mud	sugar cane/grazing
E9	grass/reeds	good	N	floodgates	mud	sugar cane

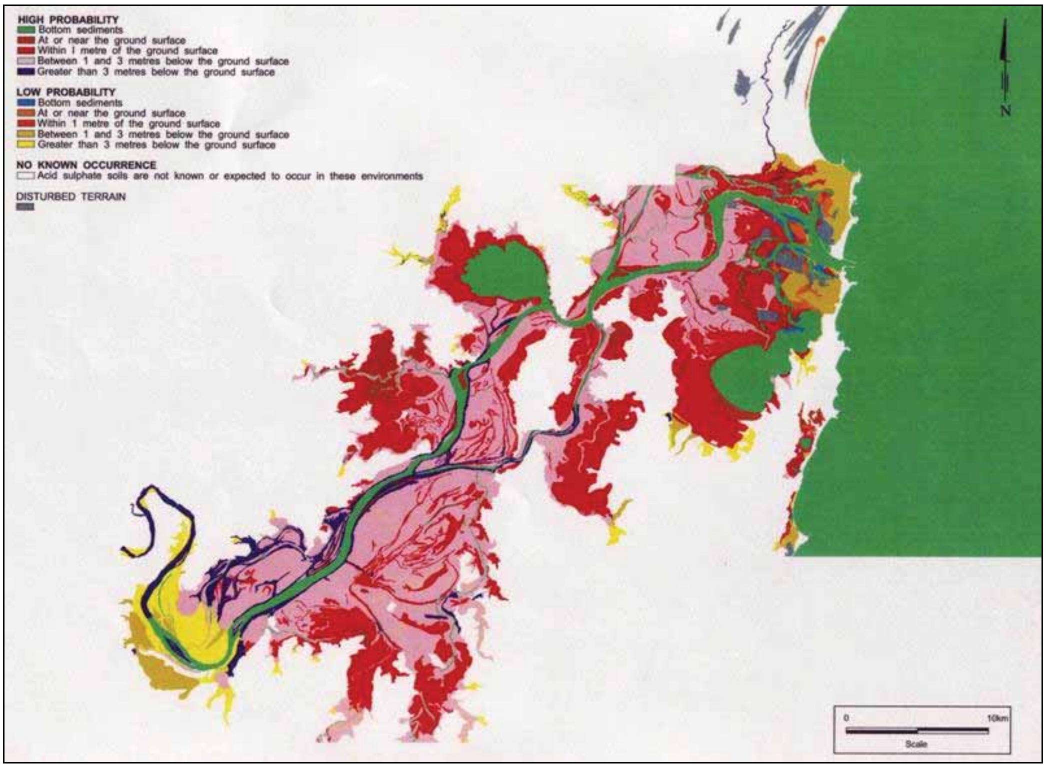

Figure 40: Acid sulfate soils risk map of the Wooloweyah area (MHL 2000).

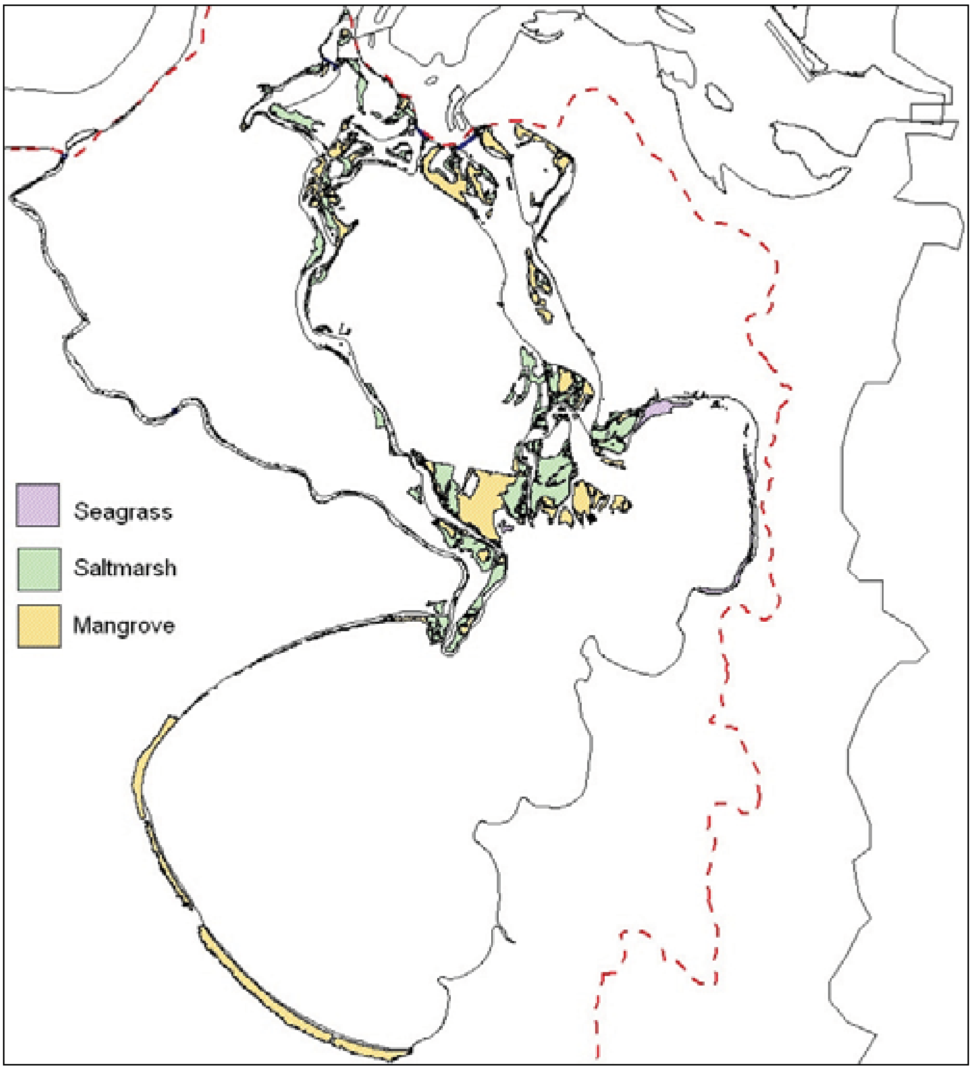

Figure 41: Location of seagrass, saltmarsh and mangrove within the Wooloweyah Lagoon catchment (mapped by NSW DPI 2006). Mangroves are also present along sections of Palmers, Micalo and Oyster Channels.

4. Discussion

4.1. Turbidity

The dominant process of sediment resuspension, and thus turbidity, within shallow lakes is usually wind-induced waves (Cózar *et al.* 2005), which is a function of wind speed, direction and duration. It has been noted in the past by Williams (1987) that clarity was generally poor within Wooloweyah Lagoon due to resuspension of bottom sediments during windy periods. Evidence from the condition assessment indicated that this was particularly the case with south-southeasterly winds. Turbidity within the lagoon was also influenced by the clarity of runoff entering the system during high rainfall events. An increase in turbidity between October and November 2008 corresponded with increased trawler activity on the lagoon, however, this also coincided with increased rainfall and increased turbidity of runoff water entering the lagoon. Furthermore, winds were predominantly northerly during this period, and average turbidity values corresponded with values associated with northerly winds. Therefore, while trawling may have had some impact on the turbidity within the lagoon, the results of the condition assessment indicate that this was not significant in comparison to the effect of wind-induced waves, and any change in lagoon turbidity due to trawling alone was unable to be identified due to the combination of climatic conditions occurring at the time.

Sediment resuspension due to wind-induced waves is dependent on the duration of wind from a certain direction, and consequently the turbidity may differ between times when wind speed and direction are the same (Cózar *et al.* 2005). This accounted for the weak correlation between lagoon turbidity and wind speed, and high turbidity recorded with winds from all directions. However, general conclusions could be drawn from the results of the assessment in terms of turbidity and the effect of wind. Average turbidity was highest when the wind was from the south and southeast, which was also when average wind speed was highest. Therefore, wind speed played an important role in the turbidity of Wooloweyah Lagoon. The effect of winds from the south and southeast would also be enhanced due to the shape of the lagoon, with more open water in the southeastern region. Although the location of the logger may have created some bias with correspondence between turbidity and wind direction (i.e. the higher turbidity when winds were from an easterly direction may have been due to the longer fetch, and thus more well-developed wind-waves than those associated with winds from the west), the fact that the strongest winds were associated with southerlies and southeasterlies (the third and fourth most predominant wind directions) indicates that the highest rates of resuspension within the lagoon were a function of these strong south-southeasterlies and there was limited bias by the location of the logger.

Sediment resuspension can have a number of negative ecological impacts, primarily relating to nutrients and light attenuation (Cózar *et al.* 2005). Both wave energy and sediment resuspension can have considerable impacts on the vegetation within shallow lakes (Cózar *et al.* 2005), and a change in light attenuation due to suspended sediment may also affect the presence and abundance of macrophytes such as seagrass (Bailey & Hamilton 1997). The presence of seagrass within the northeastern region of the lagoon suggests that this is a calmer environment with less sediment resuspension, and poor light due to sediment resuspension may account for the lack of seagrass along the southern and western shallows of the lagoon where turbidity is high. Due to sedimentation processes within the lagoon, the sediments become a store of nutrients which may then be released into the water column during resuspension (Cózar *et al.* 2005).

The HRC (1999) advocated that the turbidity trigger value range of 5-25 NTU be adopted for the Clarence catchment, although the report also noted that values within Wooloweyah Lagoon were higher at the time. It was suggested that Wooloweyah Lagoon may naturally be a highly turbid system, and that an assessment of the natural background turbidity be conducted to determine the appropriate actions (HRC 1999). The results of the condition assessment indicate that turbidity within the lagoon is highly variable, and highlighted the importance of continuous data recording throughout a range of climatic conditions. This was particularly exemplified through the difference between the 12-month average from regular monthly sampling (8 NTU in Lagoon South) and the logger (45 NTU). The regular monthly sampling was generally conducted during calm conditions for safety reasons, and therefore may bias the average conditions within the lagoon. Furthermore, average turbidity values during the condition assessment were lower than those reported by Williams (1987), Lancaster (1990) and Woodhouse (2001). Based on the results from the turbidity logger, the correlation of high turbidity with winds primarily from the south and southeast, and higher turbidity values reported in earlier studies, it is recommended that the maximum turbidity recommendation for Wooloweyah Lagoon be raised to 35 NTU to account for this natural variation. While increased turbidity due to resuspension can cause reduced light attenuation and increase nutrient concentrations in the water column, the natural processes which are causing this at Wooloweyah Lagoon suggests that the aquatic flora and fauna within the lagoon has adapted to these poorer conditions.

The recommended maximum turbidity should remain at 25 NTU elsewhere within the catchment, as the maximum values recorded were predominantly less than this value. Increased turbidity within Palmers Channel was most likely a result of sediment inputs from the drains during high rainfall and erosion of the banks due to boats. Sampling of event-based sites (i.e. drains and creeks) indicated that in times of increased rainfall, areas under sugarcane had the highest turbidity of runoff water. The National Park also had turbidity values higher than runoff from land used for grazing (i.e. Taloumbi), and was similar to values within the cane drains (Middle Road and Carrs Drains) during low rainfall events. Although soil loss from the catchment is highly dependent on land use, soil type (e.g. texture, structure and organic content) also plays an important role in the erosion potential of the landscape. Sampling of the event-based sites in August 2008 provided some baseline, non-rainfall values with which to compare the event sampling rounds during the assessment period. The turbidity of water in the National Park creeks (11 NTU) was slightly higher than that measured in Middle Road Drain and Carrs Drain (both 8 NTU). The higher turbidity values from the National Park suggest that at least some areas within the Wooloweyah Lagoon catchment may have a high erosion potential.

While the recommendation of a maximum value for the turbidity of runoff water is not warranted (since creeks and drains were only monitored following rainfall events when it is expected that turbidity would be higher than normal conditions), it is important that soil erosion is still kept to a minimum through management to ensure that excessive loads of sediment are not entering the waterway. The smaller tidal prism of Palmers Channel, in comparison to Oyster Channel, means it is not as well flushed and therefore there is a potential for sediments and associated nutrients (discussed below) to be concentrated within the channel.

4.2. Nutrients

Within the lagoon and channels, Palmers Channel generally had the highest average concentrations of nutrients (with the exception on ammonia) over the assessment period. Concentrations of TP were above the HRC (1999) trigger value of 0.05 mg L^{-1} during a number of sample periods, although this coincided with increased rainfall and higher TP concentrations in the discharge waters of Middle Road Drain and Carrs Drain. While TN, nitrate and ammonia were elevated in Palmers Channel, there was no consistent pattern between sites over the assessment period. Fluctuations in nitrogen concentrations were related to rainfall, with high concentrations recorded after high rainfall. Furthermore, the elevated concentrations of nitrogen within Palmer Channel could be attributed to the high nitrogen concentrations within Carrs Drain and Middle Road Drain. While the nutrient trigger value was often exceeded in Palmers Channel, this generally coincided with rainfall events and therefore the application of a trigger value is not appropriate.

Discharge water was predominantly poorest from Carrs Drain and Middle Road Drain, especially during the November 2008 and 1st April 2009 event. However, Carrs Drain did not appear to have a high discharge rate, and therefore contribution to the high nutrient concentrations in Palmers Channel may be very little. Stagnation of drain water can result in increased nutrient concentrations in the water column, and thus the higher nutrient load in Carrs Drain may be due to this factor rather than runoff from the surrounding agricultural landscape. This theory is supported by the fact that nutrient concentrations were highest in Carrs Drain (with the exception of ammonia) during the baseline (non-event) August 2008 sampling. In contrast, Middle Road Drain had relatively low nutrient concentrations during August 2008 and generally had the highest nutrient concentrations of all discharge sites following subsequent rainfall events. Water was observed flowing out of Middle Road Drain after the higher rainfall events in April, May and June 2009, and therefore may have had more of an effect on Palmers Channel water quality than Carrs Drain. Decreased concentrations of nutrients after the 1st April rainfall event suggests that much of the nutrients from the surrounding land was removed with the first significant rainfall, i.e. a 'first flush' effect.

Another factor which may have been contributing to increased water column nutrient loads at Carrs Drain and Middle Road Drain was elevated sediment nutrient concentrations. The elevated turbidity within these drains, in comparison to other drains and creeks, may be due to sediment resuspension rather than sediments being washed off the surrounding land, and thus the mobilisation of sediment nutrients into the water column. Increased turbidity even in smaller rainfall events suggests that this is a possible nutrient source which needs further detailed investigation.

Concentrations of nutrients within Wooloweyah Lagoon were variable, with TP, orthophosphate and nitrate predominantly below the HRC (1999) trigger value. In comparison, concentrations of TN, ammonia and nitrite were often above the trigger value recommended by the HRC (1999). The concentration of TN in runoff water was higher than TP, and may have contributed to the higher concentrations of TN in the lagoon and channels, particularly during June and July 2009. Nutrient concentrations (i.e. total and soluble) within the lagoon and channels generally increased in response to higher rainfall (and thus higher flows), which was in contrast to the findings of Williams (1987) who found that TP and TN concentrations increased in the lagoon during low flow conditions.

Total phosphorus concentrations in the Taloumbi Drain were predominantly above the HRC (1999) trigger value, and along with orthophosphate and TN, was generally higher than in the lagoon. However, Carrs Drain and Middle Road Drain had much higher nutrient concentrations than the Taloumbi Drain (although only during rainfall events). Further detailed studies are needed to determine if the considerable increase in nutrient loads within the drains, in comparison to the creeks, following rainfall was due to drain sediment resuspension or runoff from the surrounding agricultural land. Monitoring of Carrs Drain and Middle Road Drain during non-rainfall periods also needs to be conducted to further identify potential sources/reasons for the high nutrient loads. Specific sources of nutrients from agriculture may include cattle manure (Lancaster 1990), top-dressing of pasture, (Williams 1987) and fertilisers from sugarcane crops (Woodhouse 2001).

Nutrient concentrations from the northern creek, which is believed to be a surface water overflow path from the wetland which Yamba STP pumps treated sewage into, were often higher than those recorded in the National Park creeks. It has been suggested by MHL (1999) that this northern 'STP' creek is not a significant source of nutrients to the lagoon as flows only occur during wet weather when there would be considerable dilution. Given this fact, and a lack of detailed nutrient measurements at the time, Woodhouse (2001) assumed that nutrient contributions from the STP were negligible. While this study indicates that the nutrient loads within the runoff water are high, nutrient contributions could still be assumed as negligible due to the better flushing of the northern region of the lagoon (in contrast to other areas), and the small amount of discharge water relative to the lagoon waterbody. Further detailed studies are required to quantify the actual loads, however, given the augmentation of the STP and change to ebb-flow release into the Clarence River, further studies may not be warranted.

In contrast to TP, TN concentrations remained high after the flood in May 2009. This may have been due to preferential binding of TP with the sediments, and would account for the very high concentrations of TP in sediments in contrast to the relatively low concentrations of TN. Following the flood, concentrations of phosphate and nitrate within the sediments was considerably higher, indicating that sediments from the catchment contributed a large amount of soluble nutrients to the lagoon system. This can increase the potential for nutrient input from the sediments to the water column during resuspension, and thus affect habitat such as seagrass through the promotion of increased algal growth and potential smothering of the vegetation. Bailey and Hamilton (1997) note that in shallow lakes, sediments often act as a source of phosphorous, particularly during resuspension. However, it is unclear from the results of the condition assessment how much sediment resuspension contributed to water column nutrients, as rainfall patterns appeared to be the primary cause of nutrient fluxes within the water column.

Chl-*a* concentrations were above the HRC (1999) trigger value of 0.004 mg L^{-1} for the majority of sites and sample periods. Similar to results reported by Williams (1987), chl-*a* concentrations within Lagoon South had an average of 0.011 mg L^{-1}. However, algal blooms were not observed at the time of sampling, in contrast to that reported by the Williams (1987) study. At the event-based sampling locations, chl-*a* concentrations were variable spatially and temporally, and were on average lower from April 2009 onwards. No direct correlation was determined between chl-*a* and nutrient concentrations, due to the fact that longer-term preceding conditions influence the concentration of algae within a system. Therefore, while nutrient concentrations were elevated at some locations, overall conditions were not suitable for algal blooms to occur during the condition assessment.

4.3. Other water quality parameters

Since ASS have been identified within the Wooloweyah Lagoon catchment, the decrease in pH can be directly attributed to the presence of these soils. However, the majority of ASS within the catchment are potential ASS, 1-2 m below the surface (Tulau 1999). Thus, there would most likely have been limited recent oxidation of ASS, partially accounting for the pH remaining above 6 in the lagoon and channels, and above 5 in the drains and creeks. Furthermore, there may have been some buffering provided by the relatively saline water in the drains and lagoon. A study by Davison and Wilson (2003) found that during the 2002 drought there was no significant acid discharge during rainfall events, and a 4-month study by White (2009b) also found that pH within the Taloumbi drainage network remained above 6 following increased rainfall, and that there was no indication of recent oxidation of ASS. Therefore, although ASS are present within the Wooloweyah Lagoon catchment, the area has been mapped as a high risk ASS area (Tulau 1999), and water quality indicator values at times were less than the trigger value of 7 pH (although only during rainfall periods), the soils do not appear to pose a significant threat to water quality within the catchment.

The lower salinity of Palmers Channel, in contrast to the other channels, was most likely due to a combination of two factors. Firstly, Palmers Channel has higher freshwater inputs than the other channels due to the large number of drains which discharge into it and increased distance from the Clarence River mouth. The second factor is that only approximately 15% of the tidal prism which enters Wooloweyah Lagoon is via Palmers Channel, in comparison to 85% of the tidal prism through Oyster Channel (Soros-Longworth & McKenzie Pty Ltd 1978). Therefore, the majority of water which flows through Palmers Channel is a mixture of the saline inflow water (from the lagoon) and the freshwater inputs from the river and drains.

Although average salinity within the lagoon was similar between the northern and southern regions, it was more variable in the Lagoon South zone. This was due to differences in freshwater inputs and flushing mechanisms of each region. The Lagoon North zone is relatively well flushed due to the tidal hydraulics of the lagoon and channels. In contrast, the Lagoon South zone is primarily only flushed when there are large freshwater inputs from the Taloumbi drainage network, and also overland flow. Therefore, salinity of the southern region was generally more variable as a result of (relatively) sudden changes in freshwater inputs.

Aside from the fact that the creeks are subject to daily tidal influence due to the open connection with the lagoon, observations at the time of sampling indicated that wind-waves in the lagoon forced saline water into the creeks. The dominant wind direction during these more saline sampling rounds confirmed that wind-generated waves were coming from a westerly direction, thereby forcing saline water into the National Park creeks. Variable salinity within the drains was most likely due to leaking floodgates, opening of gates on drains with management plans (Carrs Drain and Middle Road Drain), and also salts flushed from sediments on the floodplain during increased rainfall. The relatively high salinity within the Taloumbi Drain over the assessment period was most likely a function of leaking floodgates, cracked culverts, and leakage through the Ring Drain Levee along the western side of Wooloweyah Lagoon (Foley & White 2007). Leaking floodgates are a particular problem along the Taloumbi Ring Drain due to the age of the structures, and furthermore, wind wave action in the lagoon causes the gates to 'flap' and allows saline lagoon water into the drainage network.

Dissolved oxygen concentrations were predominantly acceptable (i.e. above the trigger value of 6 mg L^{-1}; HRC 1999) throughout the condition assessment, and were generally higher than those reported in previous studies (e.g. Lancaster 1990; Woodhouse 2001). Dissolved oxygen concentrations greater than 10 mg L^{-1} were recorded on several occasions, and may have been due to wind disturbance, water temperature, high algae photosynthesis rates, or a combination of these factors. Low DO recorded in Palmers Channel during April 2009 was most likely due to the poor quality of discharge water from Middle Road and Carrs Drains at this time. This provides further evidence of the influence that runoff water from the catchment has on Palmers Channel, in contrast to the other channels which are under greater tidal influence from the main river channel, and thus more well flushed.

4.4. Sedimentation

The sediment core from the northeastern area of the Lagoon indicated that a significant event occurred approximately 7-10 years ago, as there was an indication of disturbance possibly due to rapid sedimentation. This significant event may represent the 2001 flood, which would account for the rapid sediment accumulation. After this time there was a decrease in sandiness and mass accumulation rate of sediments, suggesting that not only was there less marine sediment entering this region but also an overall decrease in the amount of sediment being deposited. The northeastern region is characterised as being prone to sediment movement (ANSTO 2009) due to the strong tidal influence, and may account for the lower sedimentation rate within this region. The anecdotal evidence of sediment accumulation in the form of a delta at the entrance to Oyster Channel in the lagoon may then be a result of sediment movement from elsewhere within the lagoon, rather than new sediment being transported from the main Clarence River channel. However, a number of additional sediment cores would need to be collected and analysed to confirm this theory. The sedimentation rate in the northeastern region of the lagoon was determined to be an average of 0.4-0.6 cm yr^{-1} (within the top 9 cm), considerably lower than the southeastern region (2-3 cm yr^{-1}).

Discrete sediment laminations were found within the southeastern core, and were highly organic or fine clay material dated to between 3.3 (± 0.5) and 6.9 (± 0.6) years of age. The presence of laminations indicates that this region is a relatively calm environment, protected from wave generated mixing and not subject to strong tidal influence (ANSTO 2009). The layers of fine organic material may represent periods of high rainfall when finer sediments were washed from the catchment and settled in the calm waters, while during drier periods larger sediments can accumulate. Rapid accumulation of sediment due to the calmer environment accounts for the relatively young age of sediment (7.4 ± 0.6 years) at the base of the core.

A conceptual model of sediment transport in coastal lagoons has been developed by OzCoasts (2009), and is shown in Fig. 42. Wooloweyah Lagoon is subject to most of the processes shown in the model, which include: limited sediment input; accretion of mudflats; deposition and erosion from intertidal flats; fine sediment deposition; resuspension of fine sediments by wind-waves; infilling by coarse marine sediments; and washover deposits during storm events (although this is not common at Wooloweyah Lagoon). Sediment inputs from the catchment are primarily during high rainfall, while infilling by coarse marine sediments occurs at the entrance to the lagoon and forms a tidal delta (OzCoasts 2009). Inputs of fine sediments from the catchment contribute to the formation of mudflats and intertidal flats, which is aided by the presence of saltmarsh. Fine sediments which are not trapped along the shoreline are deposited into the central basin or other areas protected by wind-waves, with seagrass areas promoting the sedimentation and stabilisation of the substrate (OzCoasts 2009). Where there is a lack of seagrass and other vegetation within the water body, such as at Wooloweyah Lagoon, resuspension of the fine sediment is common and contributes to the high turbidity (OzCoasts 2009).

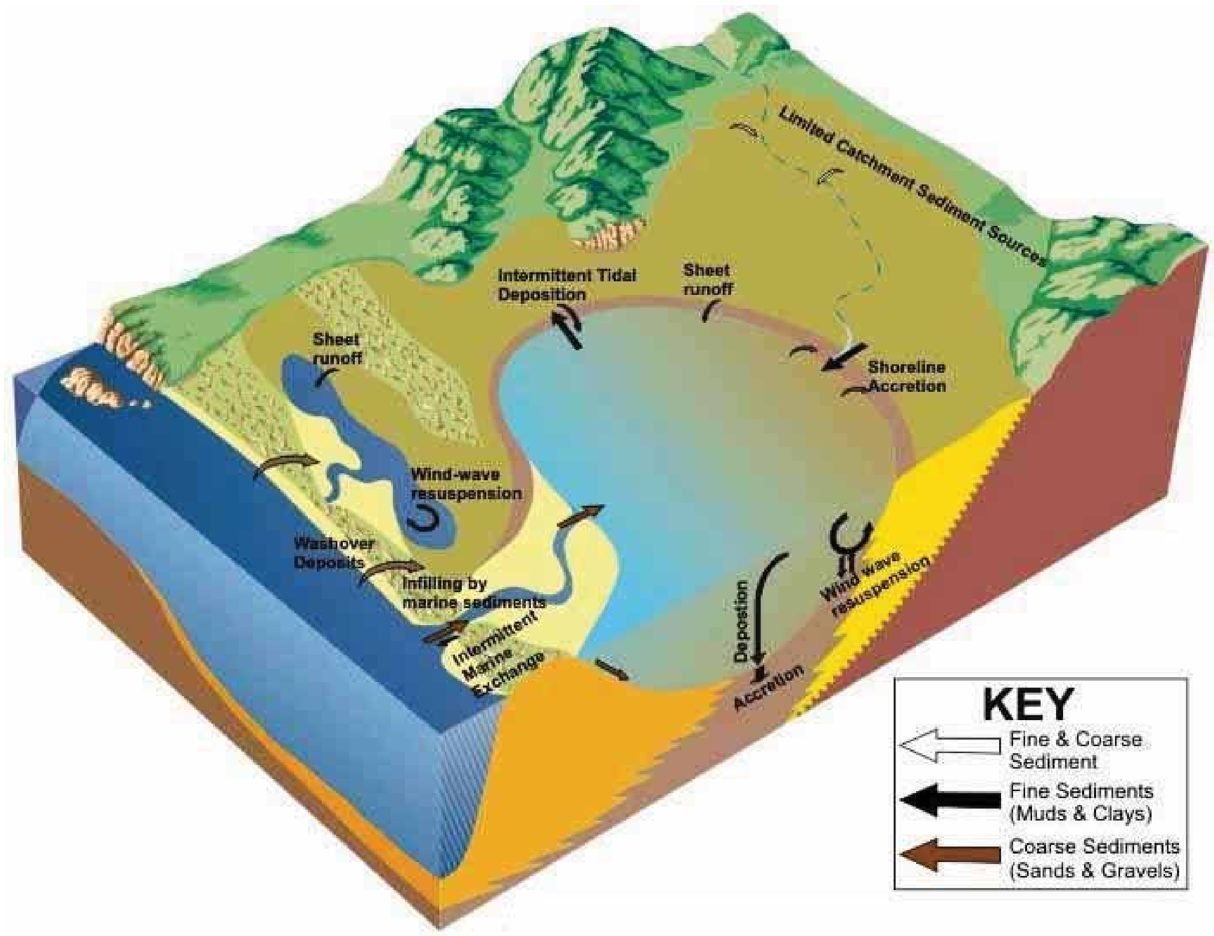

Figure 42: Sediment transport in a coastal lagoon (sourced from OzCoasts 2009).

All of the cores collected at Wooloweyah Lagoon intercepted a shell layer at variable depths. The bivalves were identified as *A. trapezia* and *Spisula trigonella*, which live in calm intertidal environments with fine muddy/sandy substrate, such as mangroves and seagrass beds. The distribution of *Anadara trapezia* is influenced by a number of factors including energy levels, wave action, salinity, water temperature, food availability and substrate character (Dixon 1975 cited in Murray-Wallace *et al*. 2000). The preferred habitat of *A. trapezia* has been identified as shallow, low-energy environments with soft, fine sediments and significant seagrass (Kendrick *et al*. 1991 cited in cited in Murray-Wallace *et al*. 2000). The presence of an old shell bed at Wooloweyah Lagoon may indicate that there was a sudden decline in food source or a change in a number of the environmental conditions. These shells are also found in the Taloumbi Ring Levee, as this was built up from the spoil from construction of the Taloumbi Ring Drain. The presence of the shell in sediments behind the levee suggests that the lagoon previously extended much further inland, and is supported by the occurrence of relict shorelines on the western flats of the lagoon catchment (Fig. 3).

The western core site, while subject to reduced tidal influence similar to the southern site, is more exposed to the wind and therefore is subject to higher rates of sediment resuspension. Furthermore, this site had clear signs of bioturbation, suggesting that the sediment may be reworked by marine organisms. ANSTO (2009) noted that shells were found in parts of the sediment core, and the area where the core was collected from is known by commercial fishermen as 'The Shells' (G. Dawson pers. comm. 29 July 2008). The signs of bioturbation and presence of shells within the sediment core above the shell layer indicates the presence of live benthic animals within this region of the lagoon.

4.5. Catchment assessment

The drainage density of the Wooloweyah Lagoon catchment has been increased through the construction of drains, primarily during the 1960s. Many of the natural freshwater creeks, especially to the south of Palmers Channel, were connected to the lagoon via the drains. A number of levees were also constructed, the main one being the Taloumbi Ring Levee along the western and southern shore of the lagoon. As a result of the flood mitigation structures (drains, levees and floodgates), saline water has been excluded from the lowland flats and water is now quickly removed from the slightly higher areas. Associated with this change in hydrology has been a change in habitat from wetlands and saltmarsh to a pasture and sugarcane dominated landscape. The loss of wetlands and saltmarsh along the shores of the lagoon and channels has reduced the natural filtering of runoff water, and may contribute to higher levels of nutrients and turbidity of runoff water entering the lagoon and channels.

Different types of land use have different sources of pollutants to waterways, and this is especially so in the Wooloweyah Lagoon catchment which is a mixture of sugarcane, grazing, urbanisation, rural-residential, and small aquaculture ventures. The primary pollutant from these types of land use is often nutrients, with increased sediment runoff a secondary pollutant. However, results from this study indicated that turbidity was relatively high in discharge water from Yuraygir National Park. Therefore, soils within the catchment may have an increased erosion potential and thus agriculture may not be resulting in increased sediment loss from the catchment.

While the bank condition assessment of applicable sites indicated that only minor erosion was occurring, observations in the field suggest that other locations are affected by more serious bank erosion. This is primarily near the entrance to Wooloweyah Lagoon in Palmers Channel, and also in Oyster Channel. Boat wash is often blamed for causing the erosion in Palmers Channel, however, there is evidence to suggest that the channel is migrating rather than widening. Measurements of channel width from historical and current aerial photographs indicated that the northern shore of Palmers Channel is eroding while the southern shore is accreting, and thus the channel is remaining the same width (P. Rose pers. comm. 23 September 2009). In contrast Oyster Channel is widening, and due to the lack of boat activity along this channel this may be a natural process. Mangroves and grasses were the dominant forms of riparian vegetation within the catchment and there was no consistent pattern of more erosion occurring along grassed riparian zones than those with larger plants such as trees. The only site which had a moderate erosion classification was R6 at the Shallow Channel Bridge, and this classification was attributed to the high velocity flow which now occurs through the culverts (installed in mid-2008 prior to the start of the condition assessment period).

Acid sulfate soils occur within the Wooloweyah Lagoon catchment, and a slight decrease in pH after high rainfall reflects this fact that there was discharge of some acidic water. However, pH of surface water throughout the study remained above 5, indicating that ASS were not having a significant effect on water quality within the lagoon, main channels and lower regions of the drains (i.e. near the mouth of the drain). Similarly, a study by Davison and Wilson (2003) reported no significant acidic discharge from the Taloumbi drainage network during high rainfall following the 2002 drought. A more recent study by White (2009b) also recorded no acidic surface water within the Taloumbi drainage network, although a slight decrease in pH and increase in metal concentrations (aluminium and iron) was recorded after rainfall. Both Davison and Wilson (2003) and White (2009b) noted that the groundwater within the Taloumbi drainage area was acidic, however, there did not appear to be any effect on the drain water quality. White (2009b) suggested that the groundwater gradient may be away from the drains, thus accounting for the better drain water quality in comparison to groundwater. Increased active management (i.e. opening floodgates during non-flood periods, the installation of tidal gates, etc.) over recent years is most likely contributing to reduced ASS oxidation and the improvement in water quality in contrast to that reported in studies from the early 1990's (see Warren 1991, Bowman 1991, and Planners North 1991 cited in Woodhouse 2001: 54-55). Further studies are required to determine the locations of small-scale ASS priority areas within the Wooloweyah Lagoon catchment, and to examine the groundwater-surface water interaction within these areas.

Macrophyte mapping undertaken by NSW DPI (2006) indicated that no mangroves or saltmarsh were present on the eastern side of the lagoon, while the majority of seagrass was located within the northeastern corner of the lagoon. The density of seagrass within the mapped areas was quite sparse, based on observations in the field during each monitoring round, and drift algae was often present within much of the seagrass area. The value of this habitat is questionable due to the poor state it appeared to be in throughout the condition assessment, although prawns were occasionally sighted within the seagrass and swans were seen grazing on the seagrass bed areas at times. The mangrove habitat around Wooloweyah Lagoon is also quite variable, with some areas such as the southern shoreline of the lagoon having dense cover in contrast to the northwestern shoreline (below Palmers Channel) where mangrove density is sparse. The main cause of this difference in density around the shores of the lagoon appears to be due to bank erosion from wind-waves. The western side is more prone to wave action from the strong southeasterly winds, and (possibly) in combination with pugging by cattle has resulted in the loss of a number of mangroves. At the start of the condition assessment period in August 2008, Clarence Valley Council placed rock fillets out from the eroding bank to provide a calm settling environment for sediments and mangroves to establish. By the end of the condition assessment period in July 2009, a large amount of sediment had settled behind the rock fillets, and mangrove shoots were beginning to appear.

The area of saltmarsh habitat was considerably smaller than mangrove habitat mapped within the catchment, and the majority is located near the entrances of Palmers, Micalo and Oyster Channels to the lagoon, especially on Micalo Island. A number of rehabilitation projects have been completed on Micalo Island, primarily by private landholders and through the Banrock Station Oyster Channel Project. A number of comments on the Draft Coastal Zone Management Plan for Wooloweyah Lagoon (White 2009a), received by Clarence Valley Council during the public exhibition phase, called for decommissioning the Taloumbi Ring levee to reinstate saltmarsh habitat. However, the wetlands along the western shoreline of the lagoon were naturally fresh-brackish systems due to a natural levee along the lagoon shore (Foley & White 2007). This levee was only overtopped during spring high tides. Photographs taken during the construction of the Taloumbi Ring Drain show that the wetland area was dominated by freshwater species (M. Foley 2009, pers. comm. 1 October). In contrast, the southern shoreline of the lagoon supported areas of saltmarsh due to the lack of a natural levee. Much of this saltmarsh habitat is now gone due to the construction/raising of the levee. However, it should be noted that while the map presented in Fig. 41 only indicates mangroves along the southern shore of Wooloweyah Lagoon, saltmarsh may also be present but as a less dominant community. Observations in the field further north along the western shoreline indicate that saltmarsh is present on the lagoon-side of the levee, and also overlapping with mangrove habitat on the landward-side of the Taloumbi Ring Drain. Thus, the total area of saltmarsh within the Wooloweyah Lagoon catchment may be more widespread than indicated by the macrophyte habitat mapping presented here.

5. Conclusions

The condition assessment confirmed that nutrients and turbidity were the main issues relating to the health of Wooloweyah Lagoon system, and that the high turbidity was due to natural processes (wind-wave sediment resuspension). It is recommended that the maximum turbidity recommendation for Wooloweyah Lagoon be raised to 35 NTU. The recommended maximum turbidity should remain at 25 NTU elsewhere within the catchment, as the maximum values recorded were predominantly less than this value. High turbidity may be contributing the poor condition of seagrass within the lagoon, however, a detailed study is required to confirm or determine other factors which may also be having an impact.

Elevated nutrient and chlorophyll-*a* concentrations were recorded at a number of sites, primarily in Palmers Channel, Middle Road Drain and Carrs Drain, although no algal blooms were observed during the assessment. The scope of this study did not allow a detailed investigation of discharge rates and the impact of drainage water quality on the lagoon or main channels. Further work is required to quantify the nutrient loads discharged from Carrs Drain, as this drain may not contribute as much to the higher nutrient concentrations within Palmers Channel as observations in the field suggested low discharge rates. Similarly, high nutrient loads recorded in creek water from near the Yamba STP may have little effect on the water quality of the lagoon due to a combination of the northern area being well flushed and the relative amount of discharge water in comparison to the lagoon waterbody. The relationship between high drain sediment nutrient load, turbidity, and drain water nutrient concentrations needs to be investigated further to determine if this is a primary source of nutrients within drainage water, rather than runoff from the surrounding agricultural land use.

No significant acidic discharge from drains or creeks was recorded during the condition assessment, suggesting that although the much of the catchment has been classified as high-risk ASS, there is little impact on the waterways. Further studies are required to determine the locations of small-scale ASS priority areas within the Wooloweyah Lagoon catchment, and to examine the groundwater-surface water interaction within these areas.

The condition assessment should be repeated every 2-3 years, as recommended in Strategy WQ2 of the *Coastal Zone Management Plan for Wooloweyah Lagoon* (White 2009a). However, the frequency and scale of monitoring will ultimately be dependent on available funding. By conducting the condition assessment at regular intervals, the effects of implemented actions (pertaining to water quality) may be detected, and this would also partially fulfil the monitoring criteria for the Australian Governments Natural Resource Management Monitoring, Evaluation, Reporting and Improvement (MERI) Framework.

6. References

ANZECC and ARMCANZ (2000), *Australian Guidelines for Water Quality Monitoring and Reporting: Summary*. Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand, Australia.

Australian Heritage Commission (1999), *Register of the National Estate Database: Lower Clarence River Area*. Retrieved from http://www/erin.gov.au

ANSTO (2009), *Report on ^{210}Pb and ^{137}Cs Dating of Lake Wooloweyah Sediment Cores*. Prepared by Atun Zawadzki, Australian Nuclear Science and Technology Organisation, for Clarence Valley Council. Lucas Heights, NSW.

Bailey MC and Hamilton DP (1997), Wind induced sediment resuspension: A lake-wide model, *Ecological Modelling*, vol. 99, pp. 217-228.

Burns C, Gosling A, Golus C, and Westlake M (2007), *Wetland Assessments Techniques Manual for Australian Wetlands, version 3.5*. WetlandCare Australia, Ballina, NSW.

Butcher R (2003), *Options for the Assessment and Monitoring of Wetland Condition in Victoria*. State of Victoria, State Water Quality Monitoring and Assessment Committee.

Cózar A, Gálvez JA, Hull V, García CM and Loiselle SA (2005), Sediment resuspension by wind in a shallow lake of *Esteros del Iberá* (Argentina): A model based on turbidimetry, *Ecological Modelling*, vol. 186, pp. 63-76.

Davison L and Wilson P (2003), *Palmers Channel Comparative Acid Neutralisation Demonstration*. Clarence River County Council, Grafton, NSW.

DECC (2009), *Using the ANZECC Guidelines and Water Quality Objectives in NSW*. Retrieved 2 November 2009 from http://www.environment.nsw.gov.au/water/usinganzeccandwqos.htm

Dent D (1986), *Acid Sulphate Soils: A Baseline for Research and Development*. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

DSE (2006), *Index of Wetland Condition: Review of Wetland Assessment Methods*. Victorian Government Department of Sustainability and Environment, Melbourne, Vic.

Environment Australia (2001), *A Directory of Important Wetlands in Australia*, Third Edition. Environment Australia, Canberra.

Foley M and White N (2007), *Management Options for the Wooloweyah Ring Drain and Palmers Channel Drainage Systems*. Clarence Valley Council, Grafton, NSW.

Hashimoto TR and Hudson J (1999), *Clarence Estuary Processes Study: A Review of Catchment – Estuarine Geology and Geomorphology*. Coastal and Marine Geosciences Report No. CLEPS99_1 prepared for NSW Department of Public Works and Services, Manly Hydraulics Laboratory, NSW.

HRC (1999), *Independent Inquiry into the Clarence River System*. Healthy Rivers Commission of New South Wales, Sydney, NSW.

Lancaster G (1990), *Physicochemical Conditions and Seasonal Changes in Wooloweyah Lagoon, Yamba, NSW*. Thesis for Degree of Bachelor of Applied Science with honours, University of New England, Northern Rivers, Lismore, NSW.

Lennon J, Pearson M, Marshall D, Sullivan S, McConvell P, Nicholls W and Johnston D (2001), Natural and cultural heritage, *Australia State of Environment Report 2001 Theme Report*. CSIRO Publishing on behalf of the Department of the Environment and Heritage, Canberra.

MHL (1999), *Yamba Sewerage Augmentation Groundwater Study*. Manly Hydraulics Laboratory, NSW Department of Public Works and Services, Report No. MHL911.

MHL (2000), *Clarence River Estuary Processes Study – Volume 1*. Manly Hydraulics Laboratory, NSW Department of Public Works and Services, Report No. MHL971.

Murray-Wallace CV, Beu AG, Kendrick GW, Brown LJ, Belperio AP and Sherwood JE (2000), Palaeoclimatic implications of the occurrence of the arcoi bivalve *Anadara trapezia* (Deshayes) in the Quaternary of Australisia, *Quaternary Science Reviews*, vol. 19, pp. 559-590.

NSW DPI (2006), *Estuarine Macrophytes of the Northern and Southern Comprehensive Coastal Assessment Regions*. Mapping compiled by the NSW Department of Primary Industries, Port Stephens Research Centre, NSW.

NSW DPWS (1998), *Yamba Sewerage Augmentation Interim Works: Review of Environmental Factors*. Report No. 97146, prepared for Maclean Shire Council. NSW Department of Public Works and Services.

NSW Government (1992), *Estuary Management Manual*. NSW Government, NSW.

NSW PWD (1991), *Angourie Sewerage Investigation Report*. Report No. LI 156, prepared for Maclean Shire Council. NSW Public Works Department.

OzCoasts (2009), *Sediment Transport in Coastal Lagoons and Strandplains*. Retrieved 18 August 2009 from http://www.ozcoasts.org.au/conceptual_mods/geomorphic/coast_lagoon/cl_sed_trans.jsp#sedtran6

Rohweder D (2006), *Shorebird Values and Threats in the Clarence Estuary. A Guide for Clarence Valley Council Staff*. Sandpiper Environmental. Unpublished Report.

Sammut J, White I and Melville MD (1996), Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulfate soils, *Marine and Freshwater Research*, vol. 47, pp. 669-684.

Sinclair Knight Merz (2005), *Yamba Sewerage Augmentation Environmental Impact Statement*. Department of Commerce Report No. 04082. Sinclair Knight Merz, St Leonards, NSW.

Soros-Longworth and McKenzie Pty Ltd (1978), *Clarence River Waterway Planning Study.* NSW Department of Public Works Report No. 78006.

Tulau MJ (1999), *Acid Sulphate Soil Priority Management Areas on the Lower Clarence Floodplain*. NSW Department of Land and Water Conservation, Sydney, NSW.

White N (2009a), *Draft Wooloweyah Lagoon Management Plan*. Clarence Valley Council, Grafton, NSW.

White NS (2009b), *Hydrology, Water Quality and Management Strategies of a Coastal Floodplain Wetland, New South Wales, Australia*. Thesis for Doctor of Philosophy, University of New England, Armidale.

Williams R (1987), *Water Quality in the Clarence River*. State Pollution Control Commission Northern Rivers Study No. 3, Sydney, NSW.

Winders, Barlow and Morrison Pty Ltd (1987), *Prawn Pond Discharge Investigation*. Report No. 3391 for Aquadia Pty Ltd.

Woodhouse S (2001), *Wooloweyah Lagoon Yamba, NSW: Management Strategy*. Clarence Valley Council, Grafton, NSW.

Appendix A1 – Description of Sites and Access

Site No.	Site Name	Access Type	Water Body	Comments
R1	Palmers Channel-Marshs Drain	South Bank Road	Palmers Channel	Major agricultural drain flowing into Palmers Channel
R2	Palmers Channel-McKenzie/Castle Drain	North Bank Road	Palmers Channel	Major agricultural drain flowing into Palmers Channel
R3	Romiaka Channel Bridge	Side road off Yamba Road	Romiaka Channel	Sample lagoon-side of bridge
R4	Micalo Channel-Notts Drain	Private access from Middle Road	Micalo Channel	Access track opposite Lollbacks Lane
R5	Micalo Channel	Private access from North Bank Road	Micalo Channel	Dry access only
R6	Shallow Channel Bridge	Micalo Road off Yamba Road	Shallow Channel	Sample lagoon-side of culvert
R7	Oyster Channel Bridge	Parking area off Oyster Channel Road	Oyster Channel	Sample lagoon-side of bridge
R8	Oyster Channel Boat Ramp	Carrs Drive	Oyster Channel	
R9	Wooloweyah Lagoon-Yamba STP	Boat	Lagoon	Seagrass and STP inputs
R10	Wooloweyah Lagoon-Wooloweyah Township	Boat	Lagoon	Urban landscape
R11	Wooloweyah Lagoon Central North	Boat	Lagoon	Deepest area of Lagoon
R12	Palmers Channel Delta	Boat	Lagoon	At red marker post
R13	Wooloweyah Lagoon Central South	Boat	Lagoon	
R14	Wooloweyah Lagoon South	Boat	Lagoon	
R15	Wooloweyah Lagoon West	Boat	Lagoon	At turbidity logger
R16 /E2	Taloumbi Radial Drain No. 2	Taloumbi Ring Levee	Drain	Major agricultural drain flowing into Lagoon
E1	Taloumbi Radial Drain No. 1	Taloumbi Ring Levee	Drain	Major agricultural drain flowing into Lagoon
E3	Taloumbi Radial Drain No. 3	Boat from lagoon	Drain	Major agricultural drain flowing into Lagoon
E4	Taloumbi Radial Drain No. 4	Boat from lagoon	Drain	Major agricultural drain flowing into Lagoon
E5	Yuraygir National Park South	Boat from lagoon	Creek	Drainage from undisturbed landscape
E6	Yuraygir National Park North	Boat from lagoon	Creek	Drainage from boundary of disturbed/undisturbed landscape
E7	Yamba STP Overflow	Boat from lagoon	Creek	Major surface water flow path for STP discharge from woodland/wetland
E8	Palmers Island-Middle Road Drain	North Bank Road	Drain	Major agricultural drain flowing into Palmers Channel
E9	Palmers Channel-Carrs Drain	South Bank Road	Drain	Major agricultural drain flowing into Palmers Channel

Appendix A2 – Sample Site Coordinates (WGS84)

Site ID.	Latitude	Longitude
R1	29° 27' 10" S	153° 15' 56" E
R2	29° 28' 03" S	153° 17' 58" E
R3	29° 25' 25" S	153° 17' 54" E
R4	29° 26' 40" S	153° 17' 40" E
R5	29° 27' 46" S	153° 18' 18" E
R6	29° 25' 48" S	153° 18' 32" E
R7	29° 25' 51" S	153° 18' 56" E
R8	29° 27' 11" S	153° 19' 46" E
R9	29° 27' 41" S	153° 20' 29" E
R10	29° 28' 32" S	153° 20' 40" E
R11	29° 28' 53" S	153° 19' 31" E
R12	29° 29' 17" S	153° 18' 40" E
R13	29° 30' 02" S	153° 18' 35" E
R14	29° 30' 44" S	153° 17' 42" E
R15 (turbidity logger)	29° 29' 41" S	153° 17' 34" E
R16/E2	29° 29' 29" S	153° 16' 46" E
E1	29° 28' 59" S	153° 17' 42" E
E3	29° 30' 09" S	153° 16' 30" E
E4	29° 30' 45" S	153° 16' 51" E
E5	29° 30' 49" S	153° 19' 06" E
E6	29° 30' 05" S	153° 19' 32" E
E7	29° 27' 26" S	153° 20' 34" E
E8	29° 27' 29" S	153° 16' 44" E
E9	29° 26' 16" S	153° 15' 31" E

Appendix A3 – Water Quality Data

REGULAR WATER QUALITY

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
R1	Palmers Channel-Marshs Drain	27-Aug-08	12:50	7.60	17800	19.8	8.53	10	0.034	0.000	0.453	0.000	0.002	0.018	0.021	2.1
R1	Palmers Channel-Marshs Drain	25-Sep-08	12:36	7.90	22600	20.2	7.08	1.4	0.079	<0.005	0.667	0.038	<0.005	0.047	0.013	0.9
R1	Palmers Channel-Marshs Drain	27-Oct-08	13:52	7.71	25200	23.9	7.20	1.4	0.016	0.01	0.274	<0.005	<0.005	0.017	0.007	0.7
R1	Palmers Channel-Marshs Drain	18-Nov-08	12:05	7.69	24200	21.9	7.15	18	0.057	0.019	0.415	0.052	0.006	0.123	<0.001	<0.1
R1	Palmers Channel-Marshs Drain	17-Dec-08	11:35	7.79	29900	26.5	6.56	26	0.062	0.044	0.343	<0.005	<0.005	0.045	<0.001	<0.1
R1	Palmers Channel-Marshs Drain	20-Jan-09	11:28	7.62	17300	25.5	7.09	6	0.018	<0.005	0.261	<0.005	<0.005	0.011	0.005	0.5
R1	Palmers Channel-Marshs Drain	17-Feb-09	11:40	7.16	15610	26.2	6.99	2.4	0.04	0.016	0.356	0.066	0.005	0.061	0.004	0.4
R1	Palmers Channel-Marshs Drain	17-Mar-09	12:00	7.44	16120	25.3	6.16	7.4	0.054	0.007	0.747	<0.005	<0.005	0.011	0.013	1.3
R1	Palmers Channel-Marshs Drain	15-Apr-09	14:20	6.75	538	25.1	2.84	24	0.194	0.069	1.283	0.08	0.012	0.139	0.007	0.7
R1	Palmers Channel-Marshs Drain	13-May-09	12:50	7.27	6680	21.3	7.04	0.8	0.061	0.031	0.729	0.144	0.011	0.089	0.01	1.0
R1	Palmers Channel-Marshs Drain	16-Jun-09	12:57	6.98	2490	19.3	7.13	14	0.051	0.012	0.679	0.225	<0.005	0.115	0.003	0.3
R1	Palmers Channel-Marshs Drain	21-Jul-09	15:50	7.35	9000	18.4	9.32	9.54	0.033	<0.005	0.491	0.013	<0.005	0.038	0.006	0.6
R2	Palmers Channel-McKenzie/Castle Drain	27-Aug-08	10:15	7.80	26400	17.6	8.59	10	0.022	0.000	0.308	0.009	0.002	0.025	0.016	1.6
R2	Palmers Channel-McKenzie/Castle Drain	25-Sep-08	11:58	8.12	27800	18.9	8.45	1.4	0.078	<0.005	1.035	0.008	<0.005	0.026	0.023	1.6
R2	Palmers Channel-McKenzie/Castle Drain	27-Oct-08	12:23	7.66	31900	22.4	6.86	1.6	0.018	<0.005	0.278	<0.005	<0.005	0.138	0	0
R2	Palmers Channel-McKenzie/Castle Drain	18-Nov-08	11:04	7.87	32000	19.5	7.97	30	0.065	<0.005	0.476	0.001	0.002	0.058	<0.001	<0.1
R2	Palmers Channel-McKenzie/Castle Drain	17-Dec-08	10:53	8.04	31100	25.5	7.06	15	0.04	0.02	0.317	<0.005	<0.005	0.054	0.011	1.1
R2	Palmers Channel-McKenzie/Castle Drain	20-Jan-09	10:40	7.38	18600	25.4	6.92	4	0.021	<0.005	0.336	<0.005	<0.005	0.006	0.009	0.9
R2	Palmers Channel-McKenzie/Castle Drain	17-Feb-09	11:13	7.23	15810	25.9	6.78	2	0.03	0.013	0.37	0.084	0.006	0.09	0.005	0.5
R2	Palmers Channel-McKenzie/Castle Drain	17-Mar-09	11:20	7.92	26900	23.8	7.15	15.6	0.059	<0.005	0.742	<0.005	<0.005	0.013	0.02	2
R2	Palmers Channel-McKenzie/Castle Drain	15-Apr-09	15:30	6.53	2070	24.7	4.41	24	0.157	0.056	1.134	0.106	0.01	0.174	0.007	0.7
R2	Palmers Channel-McKenzie/Castle Drain	13-May-09	10:50	7.58	13100	17.8	-	1.2	0.042	0.005	0.658	0.007	<0.005	0.033	0.007	0.7
R2	Palmers Channel-McKenzie/Castle Drain	16-Jun-09	12:00	6.82	6850	15.0	9.84	9	0.018	<0.005	0.506	<0.005	<0.005	0.009	0.004	0.4
R2	Palmers Channel-McKenzie/Castle Drain	21-Jul-09	12:45	6.93	9050	16.2	9.70	11.5	0.029	<0.005	0.503	0.019	<0.005	0.038	0.006	0.6
R3	Romiaka Channel Bridge	27-Aug-08	9:15	7.48	30700	17.3	7.93	8	0.017	0.000	0.264	0.013	0.002	0.039	0.010	1.0
R3	Romiaka Channel Bridge	25-Sep-08	11:24	7.68	27800	19.4	8.00	0.6	0.019	<0.005	0.496	0.055	<0.005	0.033	0.003	0.2
R3	Romiaka Channel Bridge	27-Oct-08	11:32	7.64	33000	23.4	7.70	1	0.011	<0.005	0.198	<0.005	<0.005	0.071	0.002	0.2
R3	Romiaka Channel Bridge	18-Nov-08	10:18	7.67	31000	20.1	7.04	7	0.024	<0.005	0.28	0.039	0.007	0.152	<0.001	<0.1
R3	Romiaka Channel Bridge	17-Dec-08	10:20	7.80	31200	26.2	6.68	6	0.017	0.013	0.167	0.008	<0.005	0.041	<0.001	<0.1

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
R3	Romiaka Channel Bridge	20-Jan-09	9:58	7.72	33500	24.4	7.18	5	0.009	<0.005	0.181	<0.005	<0.005	<0.005	0.002	0.2
R3	Romiaka Channel Bridge	17-Feb-09	10:42	7.69	33700	26.3	8.75	2	0.021	<0.005	0.204	0.014	0.001	0.198	0.003	0.3
R3	Romiaka Channel Bridge	17-Mar-09	10:45	7.41	26500	24.3	6.52	4.6	0.031	<0.005	0.743	<0.005	<0.005	0.039	0.005	0.5
R3	Romiaka Channel Bridge	15-Apr-09	14:25	6.71	10530	25.1	7.59	17	0.046	0.016	0.701	0.03	0.007	0.092	0.005	0.5
R3	Romiaka Channel Bridge	13-May-09	11:24	6.70	20000	19.8	8.07	2.6	0.023	0.007	0.428	0.019	<0.005	0.037	0.044	4.4
R3	Romiaka Channel Bridge	16-Jun-09	11:45	6.73	15710	16.8	8.53	7	0.018	0.006	0.4	0.027	<0.005	0.035	0.003	0.3
R3	Romiaka Channel Bridge	21-Jul-09	14:25	7.33	16400	18.7	8.52	7.88	0.022	<0.005	0.477	0.025	<0.005	0.028	0.005	0.5
R4	Micalo Channel-Notts Drain	27-Aug-08	9:30	7.31	30600	17.1	7.53	10	0.023	0.000	0.369	0.003	0.001	0.059	0.016	1.6
R4	Micalo Channel-Notts Drain	25-Sep-08	11:40	8.13	27800	22.8	9.35	1.0	0.077	<0.005	0.672	0.016	<0.005	0.037	0.000	0.0
R4	Micalo Channel-Notts Drain	27-Oct-08	11:55	7.32	34000	25.3	7.65	2.4	0.016	<0.005	0.256	<0.005	<0.005	0.301	0.005	0.5
R4	Micalo Channel-Notts Drain	18-Nov-08	10:39	7.82	31800	20.2	9.38	12	0.043	<0.005	0.339	0.011	0.002	0.079	0.005	0.5
R4	Micalo Channel-Notts Drain	17-Dec-08	10:37	7.80	30800	29.2	8.40	14	0.017	0.012	0.246	<0.005	<0.005	0.119	<0.001	<0.1
R4	Micalo Channel-Notts Drain	20-Jan-09	10:17	7.75	33700	25.3	7.06	13	0.012	<0.005	0.196	<0.005	<0.005	<0.005	0.002	0.2
R4	Micalo Channel-Notts Drain	17-Feb-09	10:55	7.64	33400	26.3	7.17	2.8	0.031	<0.005	0.255	0.006	0.001	0.139	0.006	0.6
R4	Micalo Channel-Notts Drain	17-Mar-09	11:05	8.07	26900	28.2	12.12	5	0.021	<0.005	0.383	<0.005	<0.005	0.061	0.006	0.6
R4	Micalo Channel-Notts Drain	15-Apr-09	15:00	7.11	7770	24.9	8.49	22	0.078	0.008	0.958	<0.005	0.006	0.016	0.028	2.8
R4	Micalo Channel-Notts Drain	13-May-09	11:47	7.26	19400	21.7	9.51	3	0.027	<0.005	0.484	<0.005	<0.005	0.026	0.004	0.4
R4	Micalo Channel-Notts Drain	16-Jun-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R4	Micalo Channel-Notts Drain	21-Jul-09	14:50	7.25	15600	20.8	9.78	6.09	0.027	<0.005	0.491	0.026	<0.005	0.018	0.008	0.8
R5	Micalo Channel	27-Aug-08	10:00	7.60	30600	18.7	8.23	15	0.023	0.000	0.327	0.007	0.001	0.073	<0.001	<0.1
R5	Micalo Channel	25-Sep-08	12:12	8.16	28300	21.1	9.05	1.4	0.015	<0.005	1.006	0.010	<0.005	0.038	0.015	1.0
R5	Micalo Channel	27-Oct-08	12:43	7.58	34600	24.6	7.98	1.4	0.014	<0.005	0.26	<0.005	<0.005	0.078	0.007	0.7
R5	Micalo Channel	18-Nov-08	11:22	7.72	31500	20.2	7.96	22	0.045	<0.005	0.423	0.016	0.004	0.152	0.009	0.9
R5	Micalo Channel	17-Dec-08	11:08	7.85	30900	31.0	8.86	22	0.033	0.011	0.426	<0.005	<0.005	0.033	<0.001	<0.1
R5	Micalo Channel	20-Jan-09	11:01	7.61	34000	25.8	7.30	16	0.013	<0.005	0.216	<0.005	<0.005	<0.005	0.003	0.3
R5	Micalo Channel	17-Feb-09	11:25	7.79	32600	26.0	7.49	4	0.044	<0.005	0.362	0.02	0	0.066	0.01	1
R5	Micalo Channel	17-Mar-09	11:35	7.52	26500	25.7	7.17	11	0.053	0.005	0.645	0.01	<0.005	0.075	0.014	1.4
R5	Micalo Channel	15-Apr-09	-	-	-	-	-	-	-	-	-	-	-	-	-	
R5	Micalo Channel	13-May-09	12:23	7.25	18600	21.9	8.06	2.8	0.031	<0.005	0.54	<0.005	<0.005	0.015	0.008	0.8
R5	Micalo Channel	16-Jun-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R5	Micalo Channel	21-Jul-09	15:20	7.15	15030	20.7	8.50	19	0.037	<0.005	0.578	0.035	<0.005	0.041	0.01	1

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
R6	Shallow Channel Bridge	27-Aug-08	8:50	7.12	29600	17.0	8.74	9	0.018	0.000	0.226	0.003	0.000	0.033	0.010	1.0
R6	Shallow Channel Bridge	25-Sep-08	11:13	8.06	28400	19.6	9.58	2.0	0.018	<0.005	0.647	<0.005	<0.005	0.013	0.008	0.5
R6	Shallow Channel Bridge	27-Oct-08	11:20	7.63	33000	23.8	8.08	2	0.014	<0.005	0.247	<0.005	<0.005	0.019	0.003	0.3
R6	Shallow Channel Bridge	18-Nov-08	10:06	7.71	32100	20.2	7.58	16	0.037	<0.005	0.311	0.031	0.006	0.132	0.001	0.1
R6	Shallow Channel Bridge	17-Dec-08	10:10	7.93	31200	25.2	7.24	11	0.012	0.009	0.179	0.008	<0.005	0.02	<0.001	<0.1
R6	Shallow Channel Bridge	20-Jan-09	9:45	7.94	32900	24.4	7.86	4	0.016	<0.005	0.196	<0.005	<0.005	<0.005	0.003	0.3
R6	Shallow Channel Bridge	17-Feb-09	10:30	7.87	32500	25.0	8.24	3.8	0.037	<0.005	0.307	<0.005	0	0.014	0.007	0.7
R6	Shallow Channel Bridge	17-Mar-09	10:35	7.69	25300	25.0	8.35	9.6	0.034	0.009	0.492	0.039	<0.005	0.074	0.009	0.9
R6	Shallow Channel Bridge	15-Apr-09	14:00	7.18	12000	26.0	7.60	11	0.045	0.021	0.595	0.033	0.007	0.07	0.011	1.1
R6	Shallow Channel Bridge	13-May-09	11:15	6.73	20800	19.4	8.61	1.6	0.025	0.006	0.47	0.017	<0.005	0.038	0.005	0.5
R6	Shallow Channel Bridge	16-Jun-09	11:30	7.02	15680	16.9	8.81	9	0.02	0.006	0.454	0.037	<0.005	0.032	0.004	0.4
R6	Shallow Channel Bridge	21-Jul-09	14:15	7.18	18700	21.3	8.80	35	0.041	<0.005	0.538	0.023	<0.005	0.018	0.006	0.6
R7	Oyster Channel Bridge	27-Aug-08	8:30	7.60	30700	16.5	9.10	4	0.015	0.000	0.221	0.001	0.000	0.032	0.009	0.9
R7	Oyster Channel Bridge	25-Sep-08	11:00	8.09	28500	18.2	8.96	1.2	0.028	<0.005	0.415	0.027	<0.005	0.005	0.003	0.2
R7	Oyster Channel Bridge	27-Oct-08	10:50	7.85	31900	22.2	8.10	1.4	0.011	<0.005	0.178	<0.005	<0.005	0.005	0.003	0.3
R7	Oyster Channel Bridge	18-Nov-08	9:50	7.73	31800	20.1	7.62	10	0.034	0.006	0.303	0.03	0.006	0.176	<0.001	<0.1
R7	Oyster Channel Bridge	17-Dec-08	9:55	7.88	31100	26.0	7.31	10	0.023	0.01	0.161	0.009	<0.005	0.036	<0.001	<0.1
R7	Oyster Channel Bridge	20-Jan-09	9:25	7.85	32300	23.3	7.56	8	0.013	<0.005	0.196	<0.005	<0.005	<0.005	0.002	0.2
R7	Oyster Channel Bridge	17-Feb-09	10:15	7.97	31400	25.3	8.32	2.4	0.032	0.005	0.245	0.008	0.002	0.036	0.004	0.4
R7	Oyster Channel Bridge	17-Mar-09	10:22	7.46	24100	24.6	8.05	6.6	0.033	<0.005	0.442	0.013	<0.005	0.057	0.007	0.7
R7	Oyster Channel Bridge	15-Apr-09	13:45	7.00	11940	25.0	6.74	18	0.045	0.021	0.586	0.064	0.009	0.147	0.01	1
R7	Oyster Channel Bridge	13-May-09	11:04	6.54	19500	19.3	8.39	1.4	0.022	0.007	0.425	0.017	<0.005	0.038	0.003	0.3
R7	Oyster Channel Bridge	16-Jun-09	11:20	6.79	13720	18.5	10.09	8	0.013	0.006	0.441	0.023	<0.005	0.015	0.006	0.6
R7	Oyster Channel Bridge	21-Jul-09	13:55	7.35	17100	19.2	8.94	14	0.031	0.005	0.399	0.028	<0.005	0.026	0.005	0.5
R8	Oyster Channel Boat Ramp-Carrs Drive	27-Aug-08	8:20	7.98	30700	15.5	8.10	3	0.012	0.000	0.193	0.001	0.000	0.026	0.010	1.0
R8	Oyster Channel Boat Ramp-Carrs Drive	25-Sep-08	10:30	8.12	27200	18.1	9.01	0.4	0.054	<0.005	0.562	0.032	<0.005	0.007	0.004	0.3
R8	Oyster Channel Boat Ramp-Carrs Drive	28-Oct-08	10:25	7.91	31900	21.7	8.17	1	0.01	<0.005	0.206	<0.005	<0.005	0.019	0.003	0.3
R8	Oyster Channel Boat Ramp-Carrs Drive	18-Nov-08	9:38	7.55	32500	20.3	-	7	0.03	<0.005	0.302	0.032	0.006	0.195	0.004	0.4
R8	Oyster Channel Boat Ramp-Carrs Drive	17-Dec-08	10:45	7.93	31700	24.6	-	5	0.01	0.008	0.133	<0.005	<0.005	0.009	<0.001	<0.1
R8	Oyster Channel Boat Ramp-Carrs Drive	21-Jan-09	10:05	8.10	32300	24.7	7.83	3	0.008	<0.005	0.169	<0.005	<0.005	<0.005	0.002	0.2
R8	Oyster Channel Boat Ramp-Carrs Drive	17-Feb-09	10:11	7.83	30600	23.7	-	2	0.024	<0.005	0.24	0.019	0.001	0.028	0.005	0.5

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
R8	Oyster Channel Boat Ramp-Carrs Drive	17-Mar-09	10:12	7.62	16100	23.2	-	3	0.02	<0.005	0.356	<0.005	<0.005	0.063	0.004	0.4
R8	Oyster Channel Boat Ramp-Carrs Drive	15-Apr-09	9:05	6.80	10920	21.8	6.19	12	0.044	0.017	0.675	0.028	0.007	0.149	0.007	0.7
R8	Oyster Channel Boat Ramp-Carrs Drive	13-May-09	12:25	7.89	19400	18.6	-	1.2	0.017	0.005	0.422	0.001	0.008	0.036	0.003	0.3
R8	Oyster Channel Boat Ramp-Carrs Drive	16-Jun-09	13:15	7.80	9390	17.2	10.13	11	0.02	<0.005	0.464	<0.005	<0.005	0.012	0.008	0.8
R8	Oyster Channel Boat Ramp-Carrs Drive	21-Jul-09	13:40	7.38	15320	19.3	8.64	125	0.191	0.005	1.335	0.023	<0.005	0.015	0.018	1.8
R9	Wooloweyah Lagoon-Yamba STP	27-Aug-08	8:45	8.04	30200	15.6	8.00	5	0.014	0.000	0.234	0.000	0.000	0.011	0.009	0.9
R9	Wooloweyah Lagoon-Yamba STP	25-Sep-08	10:42	8.34	28100	17.1	-	0.4	0.02	<0.005	0.513	0.022	<0.005	0.020	0.005	0.3
R9	Wooloweyah Lagoon-Yamba STP	28-Oct-08	10:42	7.93	32900	22.0	8.19	1	0.014	<0.005	0.259	<0.005	<0.005	0.03	0.004	0.4
R9	Wooloweyah Lagoon-Yamba STP	18-Nov-08	9:50	7.63	33000	19.8	-	8	0.017	<0.005	0.205	0	0.002	0.059	0.002	0.2
R9	Wooloweyah Lagoon-Yamba STP	17-Dec-08	10:29	7.94	31100	25.4	-	12	0.026	0.01	0.203	<0.005	<0.005	0.012	<0.001	<0.1
R9	Wooloweyah Lagoon-Yamba STP	21-Jan-09	10:17	7.96	32800	26.0	7.88	5	0.01	<0.005	0.168	<0.005	<0.005	<0.005	0.002	0.2
R9	Wooloweyah Lagoon-Yamba STP	17-Feb-09	10:26	7.82	33400	23.8	-	2.4	0.023	<0.005	0.227	<0.005	0.001	0.022	0.003	0.3
R9	Wooloweyah Lagoon-Yamba STP	17-Mar-09	10:27	7.39	27000	23.4	-	7.8	0.035	<0.005	0.484	<0.005	<0.005	0.015	0.008	0.8
R9	Wooloweyah Lagoon-Yamba STP	15-Apr-09	9:15	7.03	11180	22.4	6.58	17	0.035	0.008	0.647	0.017	0.006	0.1	0.024	2.4
R9	Wooloweyah Lagoon-Yamba STP	13-May-09	12:15	7.95	19700	19.5	-	2	0.022	0.005	0.462	0.009	<0.005	0.033	0.003	0.3
R9	Wooloweyah Lagoon-Yamba STP	29-May-09	10:15	6.26	3450	17.8	6.61	31	0.034	0.007	0.471	0.036	<0.005	0.08	0.003	0.3
R9	Wooloweyah Lagoon-Yamba STP	16-Jun-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R9	Wooloweyah Lagoon-Yamba STP	21-Jul-09	11:44	7.55	15600	16.3	9.22	7.3	0.009	<0.005	0.377	0.036	<0.005	0.027	0.005	0.5
R10	Wooloweyah Lagoon-Wooloweyah Township	27-Aug-08	9:11	8.07	30100	15.9	8.30	3	0.013	0.000	0.252	0.005	0.000	0.020	0.009	0.9
R10	Wooloweyah Lagoon-Wooloweyah Township	25-Sep-08	10:20	8.06	25700	17.7	-	0.8	0.007	<0.005	0.493	0.025	<0.005	0.023	0.005	0.3
R10	Wooloweyah Lagoon-Wooloweyah Township	28-Oct-08	11:10	7.88	31200	22.5	8.16	1.4	0.017	<0.005	0.316	<0.005	<0.005	0.051	0.005	0.5
R10	Wooloweyah Lagoon-Wooloweyah Township	18-Nov-08	10:10	7.88	32800	20.6	-	36	0.055	<0.005	0.447	0.031	0.006	0.227	0.008	0.8
R10	Wooloweyah Lagoon-Wooloweyah Township	17-Dec-08	9:34	8.02	30900	25.0	-	48	0.05	0.012	0.409	<0.005	<0.005	0.013	0.005	0.5
R10	Wooloweyah Lagoon-Wooloweyah Township	21-Jan-09	10:44	7.88	33100	26.2	7.36	5	0.012	<0.005	0.21	<0.005	<0.005	<0.005	0.003	0.3
R10	Wooloweyah Lagoon-Wooloweyah Township	17-Feb-09	10:30	7.84	33700	23.9	-	3.6	0.033	<0.005	0.263	<0.005	0	0.016	0.009	0.9
R10	Wooloweyah Lagoon-Wooloweyah Township	17-Mar-09	10:32	7.51	27400	22.9	-	6	0.037	<0.005	0.565	0.017	<0.005	0.133	0.009	0.9
R10	Wooloweyah Lagoon-Wooloweyah Township	15-Apr-09	9:50	7.14	10890	23.0	7.16	15	0.049	0.009	0.619	0.011	0.006	0.077	0.017	1.7
R10	Wooloweyah Lagoon-Wooloweyah Township	13-May-09	12:10	7.79	18500	18.7	-	1.4	0.024	<0.005	0.493	0.007	<0.005	0.027	0.006	0.6
R10	Wooloweyah Lagoon-Wooloweyah Township	16-Jun-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R10	Wooloweyah Lagoon-Wooloweyah Township	21-Jul-09	11:36	7.24	13100	16.0	9.90	7.5	0.019	<0.005	0.458	0.02	<0.005	<0.005	0.007	0.7
R11	Wooloweyah Lagoon Central North	27-Aug-08	9:23	8.08	29600	16.4	8.30	8	0.014	0.000	0.240	0.006	0.000	0.015	0.009	0.9

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
R11	Wooloweyah Lagoon Central North	25-Sep-08	10:57	8.25	28300	17.6	-	1.2	<0.005	<0.005	0.553	0.024	<0.005	0.018	0.009	0.6
R11	Wooloweyah Lagoon Central North	28-Oct-08	11:20	7.93	32800	22.1	8.38	1.6	0.014	<0.005	0.245	<0.005	<0.005	0.046	0.003	0.3
R11	Wooloweyah Lagoon Central North	18-Nov-08	10:18	7.87	33000	20.4	-	170	0.195	<0.005	0.823	0.021	0.005	0.109	0.012	1.2
R11	Wooloweyah Lagoon Central North	17-Dec-08	9:40	8.05	31700	24.9	-	36	0.052	0.011	0.361	<0.005	<0.005	0.037	0.015	1.5
R11	Wooloweyah Lagoon Central North	21-Jan-09	10:52	7.88	33700	25.5	6.93	5	0.018	<0.005	0.266	<0.005	<0.005	<0.005	0.004	0.4
R11	Wooloweyah Lagoon Central North	17-Feb-09	10:38	7.89	32900	23.8	-	3.8	0.048	<0.005	0.462	<0.005	0	0.018	0.013	1.3
R11	Wooloweyah Lagoon Central North	17-Mar-09	10:39	7.87	27400	22.6	-	6	0.048	<0.005	0.614	<0.005	<0.005	0.006	0.015	1.5
R11	Wooloweyah Lagoon Central North	15-Apr-09	10:07	7.13	10800	23.4	7.51	11	0.037	0.005	0.646	<0.005	0.003	0.037	0.016	1.6
R11	Wooloweyah Lagoon Central North	13-May-09	12:05	7.44	16600	18.8	-	1.2	0.022	<0.005	0.507	<0.005	<0.005	0.031	0.007	0.7
R11	Wooloweyah Lagoon Central North	29-May-09	9:40	6.30	3930	17.7	6.52	33	0.033	0.008	0.47	0.031	<0.005	0.092	0.003	0.3
R11	Wooloweyah Lagoon Central North	16-Jun-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R11	Wooloweyah Lagoon Central North	21-Jul-09	11:30	7.44	12620	16.7	9.48	7.77	0.02	<0.005	0.425	0.018	<0.005	<0.005	0.006	0.6
R12	Palmers Channel Delta	27-Aug-08	12:51	8.07	26900	18.3	8.60	5	0.018	0.000	0.308	0.000	0.000	0.007	0.011	1.1
R12	Palmers Channel Delta	25-Sep-08	12:20	8.13	28500	18.0	-	1.8	0.057	<0.005	1.049	0.012	<0.005	0.013	0.018	1.2
R12	Palmers Channel Delta	28-Oct-08	14:10	7.80	31800	23.8	8.98	2.2	0.025	<0.005	0.415	<0.005	<0.005	0.005	0.011	1.1
R12	Palmers Channel Delta	18-Nov-08	12:40	7.52	33100	20.4	-	19	0.051	<0.005	0.443	0.007	0.001	0.197	0.008	0.8
R12	Palmers Channel Delta	17-Dec-08	9:48	8.16	32300	24.6	-	13	0.029	0.011	0.332	<0.005	<0.005	0.019	0.013	1.3
R12	Palmers Channel Delta	21-Jan-09	13:13	8.00	33900	26.8	8.64	13	0.051	<0.005	0.513	<0.005	<0.005	<0.005	0.009	0.9
R12	Palmers Channel Delta	17-Feb-09	11:50	7.52	33400	24.2	-	3	0.036	<0.005	0.327	<0.005	0	0.023	0.013	1.3
R12	Palmers Channel Delta	17-Mar-09	11:48	7.84	26200	24.3	-	11.8	0.058	0.008	0.778	0.11	<0.005	0.035	0.016	1.6
R12	Palmers Channel Delta	15-Apr-09	13:00	6.86	9820	23.9	7.02	12	0.117	0.023	0.998	<0.005	0.008	0.061	0.022	2.2
R12	Palmers Channel Delta	13-May-09	11:05	7.86	14470	18.1	-	1.4	0.021	<0.005	0.54	<0.005	<0.005	0.012	0.007	0.7
R12	Palmers Channel Delta	29-May-09	9:30	6.07	3550	18.2	6.85	29	0.035	0.005	0.519	0.019	<0.005	0.075	0.003	0.3
R12	Palmers Channel Delta	16-Jun-09	10:30	7.75	7490	14.2	-	4	0.011	<0.005	0.484	<0.005	<0.005	0.01	0.004	0.4
R12	Palmers Channel Delta	21-Jul-09	9:05	7.55	9730	14.3	9.63	9.3	0.023	<0.005	0.477	0.017	<0.005	0.017	0.006	0.6
R13	Wooloweyah Lagoon Central South	27-Aug-08	10:03	8.09	27000	16.6	8.50	4	0.014	0.000	0.274	0.008	0.000	0.017	0.016	1.6
R13	Wooloweyah Lagoon Central South	25-Sep-08	11:12	8.20	28300	17.8	-	1.0	0.033	<0.005	1.029	<0.005	<0.005	0.017	0.023	1.6
R13	Wooloweyah Lagoon Central South	28-Oct-08	12:45	7.66	28700	23.6	8.30	2.6	0.022	<0.005	0.404	<0.005	<0.005	0.067	0.006	0.6
R13	Wooloweyah Lagoon Central South	18-Nov-08	10:40	8.01	33000	20.5	-	8	0.03	<0.005	0.296	0	0	0.039	<0.001	<0.1
R13	Wooloweyah Lagoon Central South	17-Dec-08	10:12	8.23	31500	24.8	-	10	0.024	0.011	0.266	<0.005	<0.005	0.031	0.009	0.9
R13	Wooloweyah Lagoon Central South	21-Jan-09	11:18	7.99	33500	26.4	8.10	7	0.046	<0.005	0.471	<0.005	<0.005	<0.005	0.009	0.9

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L-1)	Turbidity (NTU)	TP (mg L-1)	Orthophosphate (mg L-1)	TN (mg L-1)	Nitrate (mg L-1)	Nitrite (mg L-1)	Ammonia (mg L-1)	Chl-*a* (mg L-1)	Algal biomass (mg L-1)
R13	Wooloweyah Lagoon Central South	17-Feb-09	10:44	7.91	33500	23.7	-	6	0.064	<0.005	0.621	<0.005	0	0.015	0.021	2.1
R13	Wooloweyah Lagoon Central South	17-Mar-09	10:48	7.50	27700	22.9	-	5.8	0.055	<0.005	0.746	<0.005	<0.005	0.008	0.013	1.3
R13	Wooloweyah Lagoon Central South	15-Apr-09	10:35	7.04	10930	23.1	7.77	9	0.041	0.003	0.69	<0.005	0.003	0.024	0.013	1.3
R13	Wooloweyah Lagoon Central South	13-May-09	11:55	7.89	14860	18.5	-	1	0.018	<0.005	0.542	<0.005	<0.005	0.009	0.007	0.7
R13	Wooloweyah Lagoon Central South	16-Jun-09	11:30	8.25	7890	15.0	-	5	0.013	<0.005	0.469	<0.005	<0.005	0.008	0.004	0.4
R13	Wooloweyah Lagoon Central South	21-Jul-09	9:25	7.50	10810	14.9	9.83	7.47	0.021	<0.005	0.469	0.013	0.006	0.017	0.006	0.6
R14	Wooloweyah Lagoon South	27-Aug-08	10:40	8.09	26800	17.0	8.40	5	0.016	0.000	0.307	0.000	0.000	0.004	0.016	1.6
R14	Wooloweyah Lagoon South	25-Sep-08	11:20	8.22	28100	18.0	-	1.4	0.068	<0.005	0.824	<0.005	<0.005	0.007	0.025	1.7
R14	Wooloweyah Lagoon South	28-Oct-08	12:55	7.81	32300	22.8	8.61	2.6	0.019	<0.005	0.329	<0.005	<0.005	0.117	0.007	0.7
R14	Wooloweyah Lagoon South	18-Nov-08	11:21	8.00	33100	20.5	-	15	0.045	<0.005	0.458	0.014	0	0.094	0.014	1.4
R14	Wooloweyah Lagoon South	17-Dec-08	10:05	8.45	32000	24.9	-	7	0.028	0.012	0.358	<0.005	<0.005	0.098	0.007	0.7
R14	Wooloweyah Lagoon South	21-Jan-09	12:00	8.12	33100	26.7	8.54	7	0.04	<0.005	0.499	<0.005	<0.005	<0.005	0.01	1
R14	Wooloweyah Lagoon South	17-Feb-09	10:58	7.90	32700	24.1	-	6.6	0.051	<0.005	0.59	<0.005	0	0.079	0.015	1.5
R14	Wooloweyah Lagoon South	17-Mar-09	10:57	7.69	28200	23.1	-	5.4	0.05	<0.005	0.688	<0.005	<0.005	0.025	0.012	1.2
R14	Wooloweyah Lagoon South	15-Apr-09	11:05	6.77	10870	24.1	7.53	9	0.039	0.005	0.66	<0.005	0.003	0.024	0.011	1.1
R14	Wooloweyah Lagoon South	13-May-09	11:42	7.88	13190	18.6	-	1	0.021	<0.005	0.565	<0.005	<0.005	0.01	0.009	0.9
R14	Wooloweyah Lagoon South	29-May-09	11:05	6.13	5090	18.7	7.08	31	0.023	0.006	0.433	0.024	<0.005	0.077	0.002	0.2
R14	Wooloweyah Lagoon South	16-Jun-09	11:20	8.37	7010	14.6	-	5	0.013	<0.005	0.446	<0.005	<0.005	0.009	0.004	0.4
R14	Wooloweyah Lagoon South	21-Jul-09	9:45	7.67	9500	15.0	10.07	10.1	0.023	<0.005	0.469	0.017	<0.005	0.007	0.005	0.5
R15	Wooloweyah Lagoon West	27-Aug-08	11:44	8.08	26400	17.8	8.30	5	0.021	0.000	0.352	0.000	0.000	0.016	0.013	1.3
R15	Wooloweyah Lagoon West	25-Sep-08	11:54	8.15	28100	18.0	-	1.6	0.146	<0.005	1.449	<0.005	<0.005	0.006	0.046	3.1
R15	Wooloweyah Lagoon West	28-Oct-08	13:55	7.86	31500	23.4	9.40	2.6	0.03	<0.005	0.398	<0.005	<0.005	0.208	0.01	1
R15	Wooloweyah Lagoon West	18-Nov-08	12:28	7.86	33100	20.1	-	12	0.045	<0.005	0.415	0.019	0.001	0.133	0.009	0.9
R15	Wooloweyah Lagoon West	17-Dec-08	9:55	8.20	32100	24.6	-	12	0.048	0.013	0.422	<0.005	<0.005	0.046	0.008	0.8
R15	Wooloweyah Lagoon West	21-Jan-09	12:57	8.03	33800	26.6	7.93	19	0.049	<0.005	0.502	<0.005	<0.005	<0.005	0.011	1.1
R15	Wooloweyah Lagoon West	17-Feb-09	11:06	7.84	33700	23.9	-	2.8	0.044	<0.005	0.462	<0.005	0	0.014	0.021	2.1
R15	Wooloweyah Lagoon West	17-Mar-09	11:25	7.00	27100	24.3	-	7.4	0.054	<0.005	0.814	<0.005	<0.005	0.007	0.02	2
R15	Wooloweyah Lagoon West	15-Apr-09	12:42	7.01	11040	24.4	7.89	11	0.048	0.004	0.757	<0.005	0.002	0.018	0.015	1.5
R15	Wooloweyah Lagoon West	13-May-09	11:35	7.64	13040	19.2	-	1.2	0.028	<0.005	0.626	<0.005	<0.005	0.013	0.009	0.9
R15	Wooloweyah Lagoon West	29-May-09	12:37	6.19	3900	19.7	6.10	13	0.017	<0.005	0.434	0.019	<0.005	0.06	0.006	0.6
R15	Wooloweyah Lagoon West	16-Jun-09	10:40	7.87	8270	14.1	-	4	0.014	0.006	0.478	0.012	<0.005	0.019	0.004	0.4

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
R15	Wooloweyah Lagoon West	21-Jul-09	10:35	7.78	9720	15.6	9.65	8.6	0.023	<0.005	0.481	0.02	<0.005	0.008	0.005	0.5
R16	Taloumbi Radial Drain No. 2	27-Aug-08	11:45	7.36	19100	19.4	8.16	4	0.021	0.000	0.479	0.004	0.001	0.013	0.018	1.8
R16	Taloumbi Radial Drain No. 3	25-Sep-08	13:00	8.14	14410	19.6	10.07	1.0	0.042	<0.005	1.031	0.011	<0.005	0.006	0.009	0.6
R16	Taloumbi Radial Drain No. 4	27-Oct-08	14:30	8.54	21700	26.4	13.69	2.8	0.055	0.008	0.75	0.005	<0.005	0.007	0.018	1.8
R16	Taloumbi Radial Drain No. 5	18-Nov-08	12:32	7.02	29300	22.1	3.96	8	0.116	0.033	0.722	0.002	0.001	0.048	0.022	2.2
R16	Taloumbi Radial Drain No. 6	17-Dec-08	11:57	7.76	20500	28.9	10.35	7	0.055	0.025	0.782	<0.005	<0.005	0.012	0.001	0.1
R16	Taloumbi Radial Drain No. 7	20-Jan-09	12:10	7.8	34300	27.3	11.78	5	0.062	0.013	0.599	<0.005	<0.005	<0.005	0.012	1.2
R16	Taloumbi Radial Drain No. 8	17-Feb-09	11:42	7.57	31500	-	-	3.4	0.083	0.005	0.72	<0.005	0	0.009	0.03	3
R16	Taloumbi Radial Drain No. 9	17-Mar-09	12:25	7.06	19100	26.2	6.38	2.8	0.067	0.017	0.937	0.016	<0.005	0.083	0.018	1.8
R16	Taloumbi Radial Drain No. 10	15-Apr-09	12:33	6.12	493	23.6	0.62	9	0.356	0.113	2.473	<0.005	0.03	0.037	0.006	0.6
R16	Taloumbi Radial Drain No. 11	13-May-09	13:28	6.80	836	20.3	6.02	3.6	0.116	0.043	1.955	<0.005	0.037	0.171	0.013	1.3
R16	Taloumbi Radial Drain No. 12	16-Jun-09	10:43	6.23	2880	14.7	5.26	8	0.051	0.008	0.956	0.015	<0.005	0.194	0.004	0.4
R16	Taloumbi Radial Drain No. 13	21-Jul-09	10:30	6.50	2410	17.4	4.47	10.1	0.049	<0.005	1.145	0.021	0.005	0.169	0.013	1.3

EVENT WATER QUALITY

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
E1	Radial 1	27-Aug-08	12:20	8.10	17800	20.4	13.80	1	0.015	0.000	0.467	0.000	0.000	0.011	0.016	1.6
E1	Radial 1	5-Sep-08	11:38	7.72	19500	18.2	9.26	3	0.024	0.002	0.535	0.000	0.000	0.009	0.002	0.2
E1	Radial 1	1-Nov-08	12:21	7.51	24700	21.1	5.48	12	0.159	0.074	0.932	0.015	0.003	0.168	0.014	1.4
E1	Radial 1	1-Feb-09	13:05	7.99	34500	24.9	9.44	3	0.071	0.032	0.337	0	0	0.01	0.014	1.4
E1	Radial 1	1-Apr-09	12:35	6.00	1318	27.8	3.89	6.4	0.24	0.137	1.485	0.102	0.009	0.091	0.007	0.7
E1	Radial 1	15-Apr-09	12:53	6.41	579	26.2	3.59	16	0.483	0.198	2.376	<0.005	0.02	0.133	0.018	1.8
E1	Radial 1	29-May-09	12:55	6.11	1123	21.9	4.06	60	0.087	0.011	0.758	0.006	0.005	0.081	0.005	0.5
E1	Radial 1	23-Jun-09	11:55	5.75	100.2	18.7	4.40	16	0.079	0.026	0.839	<0.005	0.007	0.024	0.004	0.4
E2	Radial 2	27-Aug-08	11:45	7.36	19100	19.4	8.16	4	0.021	0.000	0.479	0.004	0.001	0.013	0.018	1.8
E2	Radial 2	5-Sep-08	11:18	6.75	19900	19.4	5.93	4	0.022	0.001	0.530	0.020	0.001	0.025	0.004	0.4
E2	Radial 2	1-Nov-08	12:32	7.02	29300	22.1	3.96	8	0.116	0.033	0.722	0.002	0.001	0.048	0.022	2.2
E2	Radial 2	1-Feb-09	12:52	8.09	32400	26.1	11.95	6	0.071	0.012	0.662	0	0	0.008	0.029	2.9
E2	Radial 2	1-Apr-09	12:25	6.01	895	25.4	3.20	7.4	0.18	0.12	1.592	0.184	0.011	0.095	0.008	0.8
E2	Radial 2	15-Apr-09	12:33	6.12	493	23.6	0.62	9	0.356	0.113	2.473	<0.005	0.03	0.037	0.006	0.6
E2	Radial 2	29-May-09	12:20	6.21	487	20.0	3.13	69	0.142	0.021	0.779	0.006	0.006	0.034	0.002	0.2
E2	Radial 2	23-Jun-09	11:45	5.55	82.1	19.3	3.96	24	0.054	0.013	0.721	<0.005	0.009	0.012	0.007	0.7
E3	Radial 3	27-Aug-08	11:25	7.18	15240	18.3	7.20	3	0.021	0.000	0.586	0.000	0.001	0.009	0.016	1.6
E3	Radial 3	5-Sep-08	12:32	7.02	14740	18.5	-	10	0.046	0.000	0.768	0.018	0.002	0.017	0.013	1.3
E3	Radial 3	1-Nov-08	11:59	6.82	25200	20.0	-	8	0.085	<0.005	0.950	0.014	0.002	0.107	0.020	2.0
E3	Radial 3	1-Feb-09	12:40	7.59	30000	25.5	6.87	8	0.058	0.004	0.766	0.033	0.003	0.082	0.021	2.1
E3	Radial 3	1-Apr-09	12:05	5.78	1970	26.6	2.71	6.4	0.062	0.009	1.176	0.018	0.005	0.112	0.007	0.7
E3	Radial 3	15-Apr-09	12:21	5.91	358	24.4	0.89	12	0.205	0.053	1.867	<0.005	0.021	0.037	0.009	0.9
E3	Radial 3	29-May-09	12:00	6.14	462	19.8	4.06	17	0.068	0.016	0.625	0.006	0.008	0.018	0.001	0.1
E3	Radial 3	23-Jun-09	11:25	5.43	106.5	18.9	3.78	12	0.065	0.013	0.749	<0.005	0.006	0.013	0.005	0.5
E4	Radial 4	27-Aug-08	11:00	7.44	8700	19.1	7.60	4	0.037	0.000	0.730	0.002	0.003	0.009	0.035	3.5
E4	Radial 4	5-Sep-08	12:11	7.35	22900	18.2	5.90	26	0.040	0.000	0.562	0.023	0.001	0.059	0.008	0.8
E4	Radial 4	1-Nov-08	11:42	7.43	26500	19.8	-	8	0.062	<0.005	0.798	0.022	0.003	0.125	0.015	1.5
E4	Radial 4	1-Feb-09	12:20	7.79	30600	25.8	7.18	66	0.05	0.001	0.851	0	0.001	0.188	0.025	2.5

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
E4	Radial 4	1-Apr-09	11:55	5.49	1420	25.0	4.31	7	0.032	<0.005	0.988	0.02	0.005	0.152	0.007	0.7
E4	Radial 4	15-Apr-09	12:00	5.93	869	26.4	1.82	12	0.202	0.037	1.887	<0.005	0.021	0.195	0.006	0.6
E4	Radial 4	29-May-09	11:35	6.11	2240	19.5	4.56	15	0.038	0.005	0.643	0.005	0.005	0.057	0.003	0.3
E4	Radial 4	23-Jun-09	11:05	-	371	18.1	5.92	17	0.033	0.007	0.619	<0.005	0.005	0.026	0.016	1.6
E5	NP South	27-Aug-08	10:25	7.57	26100	18.8	5.80	11	0.025	0.000	0.416	0.006	0.001	0.079	0.015	1.5
E5	NP South	5-Sep-08	11:52	7.70	23800	18.7	8.20	20	0.031	0.000	0.439	0.007	0.001	0.022	0.009	0.9
E5	NP South	1-Nov-08	11:14	7.76	31700	20.7	-	30	0.050	<0.005	0.504	0.000	0.001	0.064	0.014	1.4
E5	NP South	1-Feb-09	11:50	8.07	33100	24.4	7.63	22	0.043	0.001	0.544	0	0	0.011	0.03	3
E5	NP South	1-Apr-09	11:30	5.73	3530	23.3	5.16	9.4	0.017	<0.005	1.202	0.003	0.011	0.034	0.003	0.3
E5	NP South	15-Apr-09	10:55	5.84	5350	23.0	4.99	34	0.038	0.003	1.152	<0.005	0.011	0.05	0.006	0.6
E5	NP South	29-May-09	10:55	5.45	3180	18.1	4.58	24	0.019	<0.005	0.641	0.015	0.005	0.056	0.004	0.4
E5	NP South	23-Jun-09	10:45	-	79.8	16.4	7.19	13	0.018	<0.005	0.749	0.005	0.021	0.03	0.002	0.2
E6	NP North	27-Aug-08	9:42	7.27	27200	18.2	3.40	10	0.024	0.000	0.517	0.021	0.001	0.206	0.015	1.5
E6	NP North	5-Sep-08	11:29	7.43	25300	17.7	6.90	50	0.317	0.000	0.979	0.020	0.001	0.162	0.011	1.1
E6	NP North	1-Nov-08	10:33	7.20	31300	20.5	-	52	0.069	<0.005	0.737	0.018	0.003	0.307	0.016	1.6
E6	NP North	1-Feb-09	10:50	7.64	31800	23.1	4.30	12	0.037	0.002	0.57	0.008	0.001	0.059	0.019	1.9
E6	NP North	1-Apr-09	11:14	5.87	3100	23.1	5.84	17.8	0.026	0.005	1.26	0.014	0.008	0.038	0.002	0.2
E6	NP North	15-Apr-09	10:25	6.50	9870	24.1	6.56	26	0.036	0.004	0.901	<0.005	0.005	0.058	0.01	1
E6	NP North	29-May-09	10:40	5.75	4230	17.9	2.87	20	0.03	<0.005	0.942	0.018	<0.005	0.166	0.002	0.2
E6	NP North	23-Jun-09	10:30	-	259	16.7	7.52	39	0.028	<0.005	0.913	0.009	0.012	0.022	0.009	0.9
E7	STP	27-Aug-08	8:55	7.90	30900	15.2	6.40	2	0.014	0.000	0.281	0.000	0.000	0.049	0.011	1.1
E7	STP	5-Sep-08	11:00	7.07	23300	16.7	5.30	8	0.124	0.003	0.701	0.003	0.003	0.055	0.019	1.9
E7	STP	1-Nov-08	10:02	6.62	18400	18.8	-	72	0.508	0.323	2.866	0.001	0.004	0.573	<0.001	<0.1
E7	STP	1-Feb-09	10:14	7.34	27800	22.2	3.82	3	0.026	0.002	0.513	0.041	0.001	0.01	0.004	0.4
E7	STP	1-Apr-09	10:47	6.37	438	22.4	2.80	2	0.102	0.063	1.54	0.013	0.012	0.08	0.004	0.4
E7	STP	15-Apr-09	9:40	6.65	495	22.0	3.02	4	0.257	0.212	1.722	<0.005	0.014	0.058	0.001	0.1
E7	STP	29-May-09	10:05	6.08	3090	16.8	2.13	3.5	0.074	0.03	1.089	0.011	<0.005	0.104	0.001	0.1
E7	STP	23-Jun-09	10:10	-	493	16.7	4.25	7	0.09	0.09	0.823	0.006	0.008	0.019	0.001	0.1
E8	Middle Rd Drain	27-Aug-08	10:30	7.75	24500	18.1	9.52	8	0.033	0.003	0.419	0.001	0.000	0.014	0.020	2.0

Site	Name	Date	Time	pH	Salinity (ppm)	Temp (°C)	DO (mg L^{-1})	Turbidity (NTU)	TP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	Nitrate (mg L^{-1})	Nitrite (mg L^{-1})	Ammonia (mg L^{-1})	Chl-*a* (mg L^{-1})	Algal biomass (mg L^{-1})
E8	Middle Rd Drain	5-Sep-08	10:45	6.82	24700	18.7	7.73	8	0.038	0.002	0.439	0.041	0.005	0.053	0.003	0.3
E8	Middle Rd Drain	1-Nov-08	10:53	7.74	31600	20.4	7.19	32	0.072	0.009	0.505	0.105	0.010	0.180	0.005	0.5
E8	Middle Rd Drain	1-Feb-09	14:00	7.71	30500	27.7	8.23	14	0.054	0	0.576	0.009	0.001	0.008	0.024	2.4
E8	Middle Rd Drain	1-Apr-09	14:11	6.16	285	27.2	3.51	18	0.231	0.155	3.459	2.124	0.034	0.195	0.007	0.7
E8	Middle Rd Drain	15-Apr-09	15:15	6.89	508	24.5	4.73	100	0.354	0.07	1.544	0.002	0.009	0.131	0.012	1.2
E8	Middle Rd Drain	29-May-09	13:35	6.39	66.4	21.5	2.95	55	0.128	0.043	0.58	0.008	0.005	0.053	0.003	0.3
E8	Middle Rd Drain	23-Jun-09	13:50	5.99	90.9	19.2	6.34	55	0.114	0.037	0.762	0.011	<0.005	0.021	0.012	1.2
E9	Carrs Drain	27-Aug-08	13:00	7.95	8180	20.3	10.62	8	0.111	0.068	0.807	0.001	0.002	0.008	0.036	3.6
E9	Carrs Drain	5-Sep-08	10:53	6.94	7200	17.5	6.80	40	0.375	0.119	1.020	0.000	0.001	0.007	0.009	0.9
E9	Carrs Drain	1-Nov-08	13:10	7.22	5850	20.2	3.71	44	1.064	0.684	3.883	2.233	0.198	0.771	0.024	2.4
E9	Carrs Drain	1-Feb-09	14:10	7.62	24400	26.7	6.94	5	0.153	0.073	0.521	0.016	0.001	0.009	0.009	0.9
E9	Carrs Drain	1-Apr-09	14:30	6.19	862	27.3	1.83	12.4	0.496	0.367	5.288	3.386	0.105	0.55	0.01	1
E9	Carrs Drain	15-Apr-09	14:30	6.23	553	23.1	0.86	64	0.66	0.13	2.411	<0.005	0.018	0.071	0.005	0.5
E9	Carrs Drain	29-May-09	13:45	6.24	69.7	19.2	2.12	58	0.098	0.026	0.6	0.013	0.007	0.062	0.002	0.2
E9	Carrs Drain	23-Jun-09	14:05	5.97	92.5	17.7	3.92	65	0.191	0.056	1.085	0.083	0.008	0.057	0.008	0.8

SEDIMENT NUTRIENT CONCENTRATIONS

Site	Name	Date	TP (ppm)	TN (%N)	Nitrate (ppm)	Phosphate (ppm)	Ammonia (ppm)
E1	Taloumbi 1	27-Oct-08	328	0.29	0.13	0.05	38.0
E1	Taloumbi 1	20-Jan-09	260	0.2001	0.21	0.06	26.2
E1	Taloumbi 1	15-Apr-09	289	0.192	0.2	<0.1	16.1
E1	Taloumbi 1	21-Jul-09	444.4	0.4	1.8	0.3	16.2
E3	Taloumbi 3	27-Oct-08	546	0.43	0.27	0.08	59.2
E3	Taloumbi 3	21-Jan-09	296	0.2864	0.2	<0.1	39.95
E3	Taloumbi 3	15-Apr-09	363	0.425	<0.1	0.12	17.7
E3	Taloumbi 3	21-Jul-09	329.6	0.2	1.5	0.6	6.6
E4	Taloumbi 4	27-Oct-08	369	0.22	0.13	0.01	37.2
E4	Taloumbi 4	21-Jan-09	346	0.3519	0.14	0.12	24
E4	Taloumbi 4	15-Apr-09	324	0.263	0.12	0.25	11.9
E4	Taloumbi 4	29-May-09	762.79	0.5011	0.54	0.1	39.86
E4	Taloumbi 4	21-Jul-09	488.1	0.4	<0.01	0.4	27.6
E5	NP South	28-Oct-08	325	0.29	0.13	0.02	34.3
E5	NP South	21-Jan-09	224	0.2071	0.13	0.06	18.8
E5	NP South	15-Apr-09	179	0.198	0.1	0.19	8.6
E5	NP South	29-May-09	126.41	0.1513	0.019	0.13	9.2
E5	NP South	21-Jul-09	190.4	0.2	2.0	0.4	8.4
E6	NP North	28-Oct-08	283	0.22	0.16	0.02	19.6
E6	NP North	21-Jan-09	211	0.2289	0.21	0.04	35.8
E6	NP North	15-Apr-09	186	0.086	<0.1	<0.1	6.7
E6	NP North	29-May-09	188.48	0.08609	0.19	0.06	6.42
E6	NP North	21-Jul-09	113.0	0.1	2.2	0.5	3.0
E7	STP Creek	28-Oct-08	152	0.18	0.12	0.53	20.5
E7	STP Creek	21-Jan-09	157	0.1429	0.09	0.51	41.3
E7	STP Creek	15-Apr-09	105	0.087	0.06	0.25	8
E7	STP Creek	29-May-09	154.25	0.1432	0.25	0.11	6.22
E7	STP Creek	21-Jul-09	124.5	0.1	1.1	0.5	4.9
E8	Middle Rd Drain	27-Oct-08	972	0.15	0.27	0.54	13.4
E8	Middle Rd Drain	20-Jan-09	396	0.2088	0.25	0.1	30.5
E8	Middle Rd Drain	15-Apr-09	303	0.176	0.11	0.14	15.2
E8	Middle Rd Drain	29-May-09	381.4	0.1802	0.39	0.06	13.54
E8	Middle Rd Drain	21-Jul-09	350.2	0.2	3.1	0.7	5.3
E9	Carrs Drain	27-Oct-08	539	0.32	0.55	0.21	37.9
E9	Carrs Drain	20-Jan-09	418	0.29	0.3	0.3	31.2
E9	Carrs Drain	15-Apr-09	406	0.343	0.2	0.11	22.5
E9	Carrs Drain	29-May-09	445.97	0.2661	0.38	0.13	17.14
E9	Carrs Drain	21-Jul-09	629.8	0.4	1.6	0.5	12.9
R1	Palmers Channel-Marshs Drain	27-Oct-08	511	0.26	<0.05	0.18	21.2
R1	Palmers Channel-Marshs Drain	20-Jan-09	321	0.1648	<0.1	0.16	22.2
R1	Palmers Channel-Marshs Drain	15-Apr-09	386	0.184	0.06	<0.1	15.7
R1	Palmers Channel-Marshs Drain	21-Jul-09	423.0	0.1	3.7	1.0	12.3
R10	Wooloweyah Lagoon-Wooloweyah Township	28-Oct-08	227	0.09	0.19	0.31	8.4
R10	Wooloweyah Lagoon-Wooloweyah Township	21-Jan-09	204	0.03574	0.19	0.29	8.7
R10	Wooloweyah Lagoon-Wooloweyah Township	15-Apr-09	206	0.073	0.13	0.16	6.4
R10	Wooloweyah Lagoon-Wooloweyah Township	21-Jul-09	341.9	0.2	0.8	0.4	6.8
R11	Wooloweyah Lagoon Central North	28-Oct-08	222	0.08	0.11	0.25	7.1
R11	Wooloweyah Lagoon Central North	21-Jan-09	183	0.01943	0.07	0.22	6.2
R11	Wooloweyah Lagoon Central North	15-Apr-09	265	0.078	<0.1	0.07	6.8

Site	Name	Date	TP (ppm)	TN (%N)	Nitrate (ppm)	Phosphate (ppm)	Ammonia (ppm)
R11	Wooloweyah Lagoon Central North	29-May-09	335.61	0.1	<0.01	0.09	6.52
R11	Wooloweyah Lagoon Central North	21-Jul-09	238.2	0.1	0.6	0.4	4.8
R12	Palmers Channel Delta	28-Oct-08	304	0.14	0.18	0.14	15.1
R12	Palmers Channel Delta	21-Jan-09	231	0.08799	0.05	0.1	15.3
R12	Palmers Channel Delta	15-Apr-09	251	0.092	0.09	0.05	6.8
R12	Palmers Channel Delta	29-May-09	267.76	0.06789	0.17	0.14	5.89
R12	Palmers Channel Delta	21-Jul-09	346.8	0.1	0.8	0.4	4.4
R13	Wooloweyah Lagoon Central South	28-Oct-08	296	0.13	0.12	0.10	19.5
R13	Wooloweyah Lagoon Central South	21-Jan-09	283	0.07878	0.09	0.1	16.4
R13	Wooloweyah Lagoon Central South	15-Apr-09	291	0.118	<0.1	<0.1	14.6
R13	Wooloweyah Lagoon Central South	21-Jul-09	340.7	0.2	0.6	0.2	7.2
R14	Wooloweyah Lagoon South	28-Oct-08	286	0.17	0.13	0.05	25.4
R14	Wooloweyah Lagoon South	21-Jan-09	271	0.1018	0.05	0	17.5
R14	Wooloweyah Lagoon South	15-Apr-09	247	0.127	<0.1	<0.1	12.5
R14	Wooloweyah Lagoon South	29-May-09	351.87	0.1649	0.22	0.06	10.95
R14	Wooloweyah Lagoon South	21-Jul-09	308.8	0.0	1.0	0.2	5.7
R15	Wooloweyah Lagoon West	28-Oct-08	335	0.18	0.16	0.07	21.6
R15	Wooloweyah Lagoon West	21-Jan-09	280	0.1021	0.1	0.07	14.9
R15	Wooloweyah Lagoon West	15-Apr-09	270	0.132	<0.1	<0.1	12.9
R15	Wooloweyah Lagoon West	29-May-09	344.56	0.1469	0.23	0.09	8.89
R15	Wooloweyah Lagoon West	21-Jul-09	343.0	0.2	0.7	0.3	5.7
R16/E2	Taloumbi Radial Drain No. 2	27-Oct-08	392	0.44	0.20	0.02	49.4
R16/E2	Taloumbi Radial Drain No. 3	20-Jan-09	294	0.3218	0.2	0.05	38
R16/E2	Taloumbi Radial Drain No. 4	15-Apr-09	283	0.277	<0.1	0.15	22.4
R16/E2	Taloumbi Radial Drain No. 5	29-May-09	406.63	0.3294	3.24	0.07	24.82
R16/E2	Taloumbi Radial Drain No. 6	21-Jul-09	428.8	0.5	2.0	0.6	11.8
R2	Palmers Channel-McKenzie/Castle Drain	27-Oct-08	296	0.15	0.19	0.23	17.1
R2	Palmers Channel-McKenzie/Castle Drain	20-Jan-09	360	0.1941	0.14	0.1	35.5
R2	Palmers Channel-McKenzie/Castle Drain	15-Apr-09	336	0.198	0.17	0.1	16.2
R2	Palmers Channel-McKenzie/Castle Drain	21-Jul-09	51.3	0.0	1.7	0.6	3.6
R3	Romiaka Channel Bridge	27-Oct-08	141	0.07	0.22	0.11	6.8
R3	Romiaka Channel Bridge	20-Jan-09	49	<0.01	0.08	0.2	4.6
R3	Romiaka Channel Bridge	15-Apr-09	76	0.023	<0.1	0.36	3.6
R3	Romiaka Channel Bridge	21-Jul-09	73.6	0.0	1.8	0.9	3.0
R4	Micalo Channel-Notts Drain	27-Oct-08	154	0.15	0.19	0.17	14.3
R4	Micalo Channel-Notts Drain	20-Jan-09	174	0.1527	0.07	0.3	18.1
R4	Micalo Channel-Notts Drain	15-Apr-09	79	0.03	<0.1	0.14	3.2
R4	Micalo Channel-Notts Drain	21-Jul-09	346.1	0.2	1.1	0.3	4.6
R5	Micalo Channel	27-Oct-08	230	0.15	0.27	0.08	13.8
R5	Micalo Channel	20-Jan-09	328	0.1718	0.16	0.1	22.9
R5	Micalo Channel	15-Apr-09	-	-	-	-	-
R5	Micalo Channel	21-Jul-09	401.8	0.3	1.2	0.2	12.4
R6	Shallow Channel Bridge	27-Oct-08	340	0.25	0.21	0.11	28.3
R6	Shallow Channel Bridge	20-Jan-09	183	0.05474	0.11	0.14	10.2
R6	Shallow Channel Bridge	15-Apr-09	167	0.051	<0.1	0.06	4.5
R6	Shallow Channel Bridge	21-Jul-09	212.8	0.1	1.0	0.4	6.8
R7	Oyster Channel Bridge	27-Oct-08	212	0.07	0.32	0.11	8.0
R7	Oyster Channel Bridge	20-Jan-09	264	0.03208	0.14	0.86	13.2
R7	Oyster Channel Bridge	15-Apr-09	70	0.015	<0.1	0.5	2
R7	Oyster Channel Bridge	21-Jul-09	243.1	0.1	1.4	1.2	4.0

Site	Name	Date	TP (ppm)	TN (%N)	Nitrate (ppm)	Phosphate (ppm)	Ammonia (ppm)
R8	Oyster Channel Boat Ramp-Carrs Drive	28-Oct-08	95	0.06	0.13	0.25	9.0
R8	Oyster Channel Boat Ramp-Carrs Drive	21-Jan-09	103	<0.01	0.11	0.48	3.7
R8	Oyster Channel Boat Ramp-Carrs Drive	15-Apr-09	40	0.008	0.07	0.48	1.8
R8	Oyster Channel Boat Ramp-Carrs Drive	21-Jul-09	125.3	0.1	1.3	0.8	3.6
R9	Wooloweyah Lagoon-Yamba STP	28-Oct-08	111	0.05	0.18	0.14	5.9
R9	Wooloweyah Lagoon-Yamba STP	21-Jan-09	98	<0.01	0.11	0.35	4.4
R9	Wooloweyah Lagoon-Yamba STP	15-Apr-09	134	0.036	0.06	0.11	3.6
R9	Wooloweyah Lagoon-Yamba STP	29-May-09	122.53	0.03219	0.19	0.13	3.67
R9	Wooloweyah Lagoon-Yamba STP	21-Jul-09	134.4	0.1	0.8	0.4	3.1

Appendix A4 – ANSTO Report on Sediment Cores at Wooloweyah Lagoon

Australian Government

ansto
Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

Project number:	2008rc0067 – Core 1 2008rc0068 – Core 2 2008rc0069 – Core 3
Client Organisation:	Clarence Valley Council (NSW, Australia)
Contacts:	Ms Nicole White
Project name:	Sedimentation rate study at Lake Wooloweyah, Yamba, NSW
Number of samples analysed:	33 samples for ^{210}Pb dating by alpha spectrometry 11 samples for ^{137}Cs dating by gamma spectrometry 33 sample for grain size analysis

Aim

The aim of the project is to study recent accumulation rates of sediment at Lake Wooloweyah, Yamba, NSW. Records in natural archives such as lake sediments can be used in the assessment of changing erosion rates in a catchment arising from changing land use (Appleby, 2001), which will lead to a changes in sediment supply to the lake. In July 2008, Clarence Valley Council requested ANSTO to collect and undertake the analysis of sediment cores from 3 sites at Lake Wooloweyah (see Figure 1 for core collection sites). The sediment cores were analysed at ANSTO Low Level Radiochemistry Laboratory. The sedimentation rate at each site was determined by the lead-210 dating method.

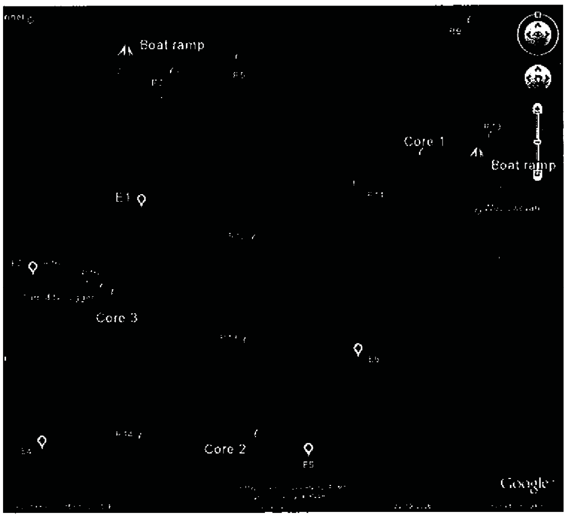

Figure 1. Sampling locations (Core 1, 2, 3) at Lake Wooloweyah, Yamba, NSW.

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

Core collection and sampling

3 sediment cores were collected and sampled on 21 October 2008. Each sediment core was collected in a 5.3 cm diameter polycarbonate tube attached to a messenger driven gravity corer (Kajak et al., 1965). The core was sampled immediately after collection, using a vertical-type extruder and sliced at 0.5 cm interval in the top 5 cm and 1 cm interval below 5 cm depth. A duplicate core was collected at each site, but was kept in the polycarbonate tube without being sampled. Table 1 shows sediment core location sites, lengths and water depths.

Table1 – Lake Wooloweyah sediment core location sites, lengths and water depths.

	Core 1	Core 2	Core 3
GPS location	153°20'06"E 29°28'42"S	153°18'42"E 29°30'45"S	153°17'29"E 29°29'43"S
Core length (cm)	25	25	23
Water depth (cm)	85	83	96

Sediment core samples were taken to ANSTO Low Level Radiochemistry Laboratory for lead-210 (^{210}Pb) and caesium-137 (^{137}Cs) dating. The duplicate sediment cores were scanned in an x-ray machine.

Lead-210 and Caesium-137 dating background

The naturally occurring radioactive uranium-238 (^{238}U) decays through a series of intermediates to radium-226 (^{226}Ra) then radon-222 (^{222}Rn) and ultimately to ^{210}Pb. ^{210}Pb in turn decays to bismuth-210 (^{210}Bi) then polonium-210 (^{210}Po) before finally decaying to stable ^{206}Pb. The ^{210}Pb in sediments comprise both supported and unsupported components. The supported ^{210}Pb is in equilibrium with all of the members of the decay chain that precede it. Unsupported ^{210}Pb is derived from the portion of ^{222}Rn (a noble gas) which diffuses through the soil interstitial pore space and is "lost" from its parent. The escaped ^{222}Rn can diffuse into the atmosphere where it rapidly decays, with a half life of 3.8 days, to ^{210}Pb which attaches to aerosol particles and settles out of the atmosphere as dry fallout or during rainfall events. This unsupported ^{210}Pb derived from atmospheric fallout will enter the system as either direct input, falling directly into the lake or stream, or be delayed and enter the sediment as indirect input, falling elsewhere in the catchment and washed into the lake or river. In either event, once deposited and incorporated in the sediment, the activity of unsupported ^{210}Pb will be solely a function of the amount present initially and its half life ($t_{½}$ = 22.26 years) (Goldberg, 1963 and Oldfield and Appleby, 1984).

The *in-situ* production of supported ^{210}Pb can be measured indirectly by measuring the activity of ^{226}Ra using either alpha or gamma spectrometry. Unsupported ^{210}Pb cannot be measured directly and so is inferred from the activity of total ^{210}Pb minus the activity of supported ^{210}Pb. The activity of total ^{210}Pb

Australian Government

ansto
Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

can be determined by either measuring ^{210}Pb directly using gamma spectrometry or measuring its progeny, ^{210}Po (using alpha spectrometry), with which it is assumed to be in secular equilibrium.

Two ^{210}Pb dating models are commonly used for calculating sediment rates: the CRS (constant rate of ^{210}Pb supply) and the CIC (constant initial ^{210}Pb concentration) models. The basic assumption of the CRS model is that the rate of supply of fallout ^{210}Pb to the core site is constant, reflecting the constant flux of ^{210}Pb from the atmosphere. The CIC (constant initial ^{210}Pb concentration) model assumes that sediments in the core all had the same initial unsupported ^{210}Pb concentration at the time they were laid down on the bed of the lake, regardless of differences in the sedimentation rate (Walling, et al., 2002).

The anthropogenic radioisotope ^{137}Cs, a result of atmospheric nuclear bomb testing can be used to validate ages calculated using the ^{210}Pb dating method (Appleby, 2001, and Walling et al., 2002). ^{137}Cs is usually present in environmental samples and can be used as an independent verifier of sediment age. Sediments deposited prior to atomic testing in 1954 should not have a ^{137}Cs signature. A subsurface peak in ^{137}Cs activity identifies the year 1963 at which time atmospheric testing was at its maximum.

Changes in grain size can affect the adsorption of unsupported ^{210}Pb to sediments. Studies have shown that there can be an increase in unsupported ^{210}Pb activity with an increase in the specific surface area of sediments (He and Walling, 1996). Therefore, the grain size distribution of sediments used for ^{210}Pb dating need to be investigated to ascertain if there are other factors influencing the unsupported ^{210}Pb activity other than radioactive decay.

Radioanalytical methodology

Samples for ^{210}Pb dating were chemically processed using the following ANSTO methods: ENV-I-044-031 Sedimentation rate determination; ENV-I-044-006 Bulk iron removal by ether extraction; ENV-I-044-023 Polonium analysis; and ENV-I-044-027 ^{226}Ra analysis.
Each dried sediment sample was spiked with ^{209}Po and barium-133 (^{133}Ba) yield tracers. Each sediment sample was subsequently leached with hot concentrated acids to release polonium and radium. Polonium was autoplated onto silver disks after adding the reducing agent hydroxylammonium chloride. Radium was co-precipitated with $BaSO_4$ on a membrane filter source. The activities of the sample sources were determined by spectrometry methods.

Samples for ^{137}Cs analysis were dried and packed into petri dishes and sealed with silicone sealant. Some samples were packed with Na_2CO_3, an inert material, to fill up the petri dish. The ratio of sample mass to Na_2CO_3 mass in each petri dish was determined.

Samples for grain size analysis were processed using the following ANSTO method: ENV-I-007-001 Particle Size Analysis using Laser Diffraction. Each wet sample was dispersed in water and pumped through a measurement chamber in a Malvern Mastersizer S laser particle analyser. The Malvern

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of
Lake Wooloweyah sediment cores

Mastersizer S uses laser diffraction to determine the particle size distribution of solids with a diameter in the range 0.05 µm to 880 µm. Solid particles outside this range are undetected.

Dry bulk densities were estimated from the moisture content for each sample:

Dry bulk density = Dry sample weight / (volume of water + volume of sediment) Where: dry sample weight = weight of sample after drying (g), volume of water = weight of water loss after drying (g)/ density of water (1g/cm^3) and volume of sediment = weight of wet sediment (g)/density of wet sediment (2.5 g/cm^3).

Spectrometry

Sample sources prepared for alpha spectrometry were counted according to the following ANSTO method: ENV-I-044-001 Alpha spectrometry. Each silver disk (^{210}Po/^{209}Po source) and membrane filter (^{226}Ra/^{133}Ba source) was counted by alpha spectrometry. The membrane filter was also counted by gamma spectrometry to measure ^{133}Ba tracer activity. Chemical yield recoveries of ^{210}Po and ^{226}Ra were calculated using the recoveries of ^{209}Po and ^{133}Ba tracers.

Sample sources for gamma spectrometry analysis were counted according to the following ANSTO method: ENV-I-044-040 Operation of the Compton Suppression Gamma Spectrometers in B34 using Genie 2000 software.

The activities of ^{137}Cs in the samples were determined by gamma spectrometry.

The ^{137}Cs activity of each sample was determined using the 662 keV peak after subtraction of the ^{214}Bi peak interference. Activities quoted are decay corrected to the date of sample receipt. Quoted uncertainties are 1σ counting errors and less than (<) values are quoted at the 95% confidence interval. The detector system energy calibration was carried out using a National Institute of Standards and Technology (NIST) traceable ^{154}Eu/^{155}Eu/^{125}Sb multi-nuclide standard source and the detector system efficiency calibration was determined using IAEA reference materials including RGU-1, RGTh-1, RGK-1 and Soil-6.

Results

Table 2 shows Lake Wooloweyah Core 1: ANSTO sample ID, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb. Grain size distributions, CIC and CRS models calculated ages, CRS model mass accumulation rates and ^{137}Cs activities are shown on Table 3. Total, supported and unsupported ^{210}Pb activities for OB1 sediment samples are plotted against depth and shown on Figures 2, 3, and 4 respectively.

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 4 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

Australian Government

ansto

Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

Table 4 shows Lake Wooloweyah Core 2: ANSTO sample ID, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb. Grain size distributions, CIC and CRS models calculated ages, CRS model mass accumulation rates and ^{137}Cs activities are shown on Table 5. Total, supported and unsupported ^{210}Pb activities for OB1 sediment samples are plotted against depth and shown on Figures 5, 6, and 7 respectively.

Table 6 shows Lake Wooloweyah Core 3: ANSTO sample ID, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb. Grain size distributions, CIC and CRS models calculated ages, CRS model mass accumulation rates and ^{137}Cs activities are shown on Table 7. Total, supported and unsupported ^{210}Pb activities for OB1 sediment samples are plotted against depth and shown on Figures 8, 9, and 10 respectively.

Figure 11 shows the x-ray images of the 3 duplicate cores.

Interpretation

Core 1:
The unsupported ^{210}Pb activities for this core exhibit an overall decreasing trend with increasing depth (see Figure 4). Between 0 and 4 cm unsupported ^{210}Pb activities show a decay trend, with increasing depth.
Between 4 and 6 cm unsupported ^{210}Pb activities fluctuate, indicating disturbance (or mixing) of the sediment layers, may be due to a rapid sedimentation rate. Between 6 and 20 cm unsupported ^{210}Pb activities decrease with increasing depth.

Estimation of the sediment ages was calculated using the CIC and CRS ^{210}Pb dating models (see Table 3). For the CIC dating model, it was assumed the sediment layers between 4 and 6 are of the same age (fast sedimentation rate). The CIC model mass accumulation rates are shown below. The CRS model mass accumulation rates are shown on Table 3.

CIC model mass accumulation rates:

0-4 cm	:	0.18 ± 0.02 g/cm^2/year	$R^2 = 0.9851$
4-6 cm	:	N/A	
6-16 cm	:	0.68 ± 0.14 g/cm^2/year	$R^2 = 0.8853$

Using the CIC and CRS models age calculations (shown on Table 3), the sedimentation rate in the top 9 cm of this core is about 0.4-0.6 cm/year.

Unsupported ^{210}Pb activities for this core are relatively lower than the other two cores (see Table2). This is most likely due to lower percentage of <63 μm grain size (therefore, more sandy) in comparison to the other two cores (see Table 3). ^{210}Pb (and other metals) adsorb poorly to sandy material. The grain size data also shows a change in sediment material at about 6 cm. The top 6 cm of the core is less sandy than the bottom part of the core.

2008rc0067, 68, 69
Lake Wooloweyah sediment cores — Report prepared by: Atun Zawadzki

Page 5 of 15 — Report checked by: Henk Heijnis

Date: 11 May 2009

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION

New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

A significant event may have caused the change in mass accumulation rate as well as the change in sediment type at around 6 cm depth. According to the CRS model this event occurred about 7-10 years from the sampling date.

The presence of ^{137}Cs activity in the whole sediment core down to 25 cm indicates the sediment layers are less than 60 years old (see Table 3). Deeper and older sediment more than 60 years age, should not contain ^{137}Cs activity.

Core 2:
Unsupported ^{210}Pb activities for this core exhibit a slight decay trend, with increasing depth, between 0 and 14 cm (see Figure 7). Below 14 cm unsupported ^{210}Pb activities fluctuate, deviating from the decay trend. The x-ray of this core shows discreet sediment laminations between 10 and 20 cm (see Figure 11). Fluctuations of unsupported ^{210}Pb activities in this part of the core may be caused by the presence or absence of dark layers (shown on the x-ray) being included or excluded during sampling. The dark layers represent highly organic or fine clay material which should yield higher unsupported ^{210}Pb activity.

The grain size data shows the core sediment material is close to being uniform except for the top layer and the layer at 15 cm (see Table 5). The 15 cm layer is the same layer where ^{210}Pb activity had increased and deviated from the decay trend.

Estimation of the sediment ages was calculated using the CIC and CRS ^{210}Pb dating models (see Table 5). For the CIC model, only unsupported ^{210}Pb data between 0 and 14 cm were used in the calculations and extrapolated down to 21 cm. The CIC model mass accumulation rate is shown below. The CRS model mass accumulation rates are shown on Table 5.

CIC model mass accumulation rate:
0-14 cm : 1.0 ± 0.2 g/cm^2/year $R^2 = 0.9231$

Using the CIC and CRS models age calculations (shown on Table 5), the sedimentation rate in the top 16 cm of this core is about 2-3 cm/year.

The calculated sediment ages show relatively recent sediment over the length of the core collected. The activity of unsupported ^{210}Pb at the bottom of the core (22-23 cm) is still relatively high (>10 Bq/kg). Sediment layers below 23 cm should still be dateable by the ^{210}Pb dating method, down to the layers where unsupported ^{210}Pb activity reaches background level i.e. <10 Bq/kg. However, we were unable to collect the deeper part of the core due to the presence of shells at 23 cm depth (see x-ray, Figure 11).

The presence of ^{137}Cs activity in almost the whole sediment core down to 25 cm indicates the sediment layers are less than 60 years old (see Table 5). Although ^{137}Cs activity was not detected at the sediment layer 15-20 cm, it can be assumed this layer is less than 60 years old, since ^{137}Cs was

Australian Government

ansto

Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of
Lake Wooloweyah sediment cores

detected immediately beneath this layer at 20-25 cm. Deeper sediment older than 60 years age should not contain ^{137}Cs activity.

Core 3:
Shells were found in parts of the sediment core (see x-ray, Figure 11). Unsupported ^{210}Pb activities for this core exhibit a decay trend with increasing depth between 0-11cm (see Figure 10). Between 11 and 14 cm unsupported ^{210}Pb activities increase, deviating from the decay trend. This is most likely due to burrowing of organisms, bringing higher activity sediment (and sandy material) from the top part of the core (with higher unsupported ^{210}Pb activity) to the lower part of the core. The x-ray image of this core shows light shade spots, representing sandy materials and possible burrowing tracks in the top 10 cm. (Note: the cores which were x-rayed were not those which were analysed for ^{210}Pb activities).

The grain size data shows the sediment material is close to being uniform except for the layer at 11 cm where the <2 and <63 μm fractions were much lower than the rest of the sediment core, indicating higher percentage of sandy material (see Table 7). This is the same depth where ^{210}Pb activity increased and deviated from the decay trend. Estimation of the sediment ages was calculated using the CIC and CRS ^{210}Pb dating models. Only the top 11 cm unsupported ^{210}Pb activities were used to calculate both the CIC and CRS model ages. Below 11 cm the unsupported ^{210}Pb activities show mixing of sediment, therefore were not used in the age calculations. The CIC model mass accumulation rates are shown below. The CRS model mass accumulation rates are shown on Table 7.

CIC model mass accumulation rates:

0-6 cm	:	0.9 ± 0.6 g/cm^2/year	R^2 = 0.7132
6-11 cm	:	0.24 ± 0.05 g/cm^2/year	R^2 = 0.9539

Using the CIC and CRS models age calculations (shown on Table 7), the sedimentation rate in the top 11 cm of this core is about 0.7-1 cm/year.

The presence of ^{137}Cs activity in the sediment core down to 20 cm indicates the sediment layers are less than 60 years old (see Table 7).

Conclusion

There is a distinct difference in sediment type and sedimentation rates between the Northern part (Core 1) of the lake and the Southern part (Cores 2 & 3). All the sediment cores collected were less than 60 years old and all had reached a layer of shells at the bottom of the core (see x-ray images, Figure 11).

Sediments collected from the Southern part are finer in nature and were deposited in a quieter environment (less prone to disturbance by excessive boating and tidal movements). This is clearly shown in core 2, where clear laminations are visible in the sediment (see Figure 11), indicating the

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of
Lake Wooloweyah sediment cores

absence of physical (wave generated·mixing) as well as the absence of bioturbation. The x-ray image and ^{210}Pb profile of Core 3 shows clear signs of bioturbation (caused by marine organisms), therefore this core was not suitable for ^{210}Pb dating.

Relying on the ^{210}Pb sediment chronologies from Cores 1 and 2 (0.4-0.6 and 2-3 cm/year, respectively), the sedimentation rate is much higher in the Southern part than the Northern part of the lake. It seems that the Southern part acts as a sediment sink and the Northern Part is more prone to sediment movement (rather than deposition) caused by tidal flows.

References

1. Appleby, P.G., 2001. Chronostratigraphic techniques in recent sediments. In: W.M. Last and J.P. Smol (Eds.), Tracking environmental change using lake sediments, vol 1: Basin analysis, coring and chronological techniques (pp 171 – 203). Dordrecht: Kluwer Academic Publishers
2. Goldberg, E.D., 1963. Geochronology with lead-210. In: *Radioactive Dating.* I.A.E.A., Vienna: 121-131.
3. He, Q. and Walling, D.E., 1996. Interpreting particle size effects in the adsorption of ^{137}Cs and unsupported ^{210}Pb by mineral soils and sediments. *J.Environ.Radioactivity.* 30 (2), 117-137.
4. Kajak,Z., et.al. In: W.M. Last and J.P. Smol (Eds.), Tracking environmental change using lake sediments, vol 1: Basin analysis, coring and chronological techniques (pp 82-84). Dordrecht: Kluwer Academic Publishers.
5. Oldfield, F. and Appleby, P.G., 1984. Empirical testing of ^{210}Pb-dating models for lake sediments. In: Hayworth EY and Lund JWG (Eds). *Lake Sediments and Environmental History.* Leicester University Press, 93-124.
6. Walling, D.E., He, Q. and Appleby, P.G., 2002. Conversion models for use in soil-erosion, soil-redistribution and sedimentation investigations. In: Zapata, F. *Handbook for the assessment of soil erosion and sediment using environmental radionuclides.* Kluwer Academic Publishers, 111-164.

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 8 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

Australian Government

ansto

Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

Table 2 – Lake Wooloweyah Core 1: ANSTO sample ID, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb.

ANSTO ID	Depth (cm)	Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)	Count Date	Total Pb-210 (mBq/g) or (Bq/kg)	Supported Pb-210 (mBq/g) or (Bq/kg)	Unsupported ^{210}Pb Decay corrected to 21-Oct-08 (mBq/g) or (Bq/kg)
L000	0.0 - 0.5	0.40	0.1 ± 0.1	07-Nov-08	32.1 ± 0.6	5.9 ± 0.4	26.2 ± 0.7
L058	1.5 - 2.0	0.82	1.0 ± 0.1	16-Dec-08	28.8 ± 1.0	5.3 ± 0.4	23.6 ± 1.1
L226	3.0 - 3.5	1.13	2.5 ± 0.2	17-Feb-09	21.6 ± 1.2	4.6 ± 0.4	17.2 ± 1.3
L059	3.5 - 4.0	1.11	3.0 ± 0.2	16-Dec-08	19.8 ± 0.5	3.7 ± 0.3	16.2 ± 0.6
L227	4.0 - 4.5	1.25	3.6 ± 0.2	17-Feb-09	26.5 ± 0.8	2.7 ± 0.2	24.0 ± 0.8
L228	4.5 - 5.0	1.44	4.3 ± 0.2	17-Feb-09	28.0 ± 1.0	4.4 ± 0.3	23.8 ± 1.1
L001	5.0 - 6.0	0.97	5.2 ± 0.5	07-Nov-08	33.6 ± 0.5	6.3 ± 0.4	27.3 ± 0.7
L229	6.0 - 7.0	1.41	6.4 ± 0.5	17-Feb-09	27.0 ± 0.8	4.4 ± 0.3	22.8 ± 0.9
L060	8.0 - 9.0	1.12	8.9 ± 0.5	16-Dec-08	29.2 ± 1.0	3.7 ± 0.3	25.7 ± 1.0
L061	12 - 13	1.27	13.7 ± 0.5	16-Dec-08	22.5 ± 0.8	3.9 ± 0.3	18.7 ± 0.9
L002	15 - 16	1.32	17.6 ± 0.6	07-Nov-08	16.9 ± 0.3	2.2 ± 0.2	14.7 ± 0.4
L062	19 - 20	1.52	23.3 ± 0.6	16-Dec-08	7.7 ± 0.3	2.3 ± 0.2	5.4 ± 0.3
L063	23 - 24	1.48	29.3 ± 0.6	16-Dec-08	9.1 ± 0.3	3.2 ± 0.5	5.9 ± 0.5

Table 3 – Lake Wooloweyah Core 1: ANSTO sample ID, depths, grain size distributions, CIC and CRS models calculated ages, CRS model mass accumulation rates and ^{137}Cs activities.

ANSTO ID	Depth (cm)	Grain size < 2 µm Content (%)	Grain size < 63 µm Content (%)	Calculated CIC Ages (years)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates g/cm^2/y	ANSTO ID	Depth (cm)	^{137}Cs Decay corrected to 21-Oct-08 (mBq/g) or (Bq/kg)
L000	0.0 - 0.5	13.59	72.82	0.6 ± 0.6	0.2 ± 0.1	0.6 ± 0.6	L226	5 - 10	1.5 ± 0.5
L058	1.5 - 2.0	8.55	72.51	5.7 ± 1.0	1.5 ± 0.4	0.7 ± 0.2	L227	10 - 15	1.8 ± 0.2
L226	3.0 - 3.5	8.78	75.60	14 ± 2	3.4 ± 0.5	0.7 ± 0.1	L228	15 - 20	0.9 ± 0.2
L059	3.5 - 4.0	11.07	79.33	17 ± 2	4.0 ± 0.5	0.8 ± 0.1	L229	20 - 25	1.0 ± 0.2
L227	4.0 - 4.5	11.91	81.09	17 ± 2	4.8 ± 0.6	0.8 ± 0.1			
L228	4.5 - 5.0	11.48	72.68	17 ± 2	5.9 ± 0.6	0.7 ± 0.1			
L001	5 - 6	12.01	92.43	17 ± 2	7.6 ± 0.6	0.7 ± 0.1			
L229	6 - 7	8.00	43.49	19 ± 2	9.9 ± 0.7	0.65 ± 0.04			
L060	8 - 9	6.89	44.52	23 ± 2	15.1 ± 0.8	0.59 ± 0.03			
L061	12 - 13	10.26	71.96	30 ± 3	26.8 ± 0.9	0.51 ± 0.02			
L002	15 - 16	2.80	26.06	35 ± 4	37.0 ± 1.0	0.48 ± 0.01			
L062	19 - 20	3.84	28.70		48.6 ± 1.1	0.48 ± 0.01			
L063	23 - 24	4.86	37.92						

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 9 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION

New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

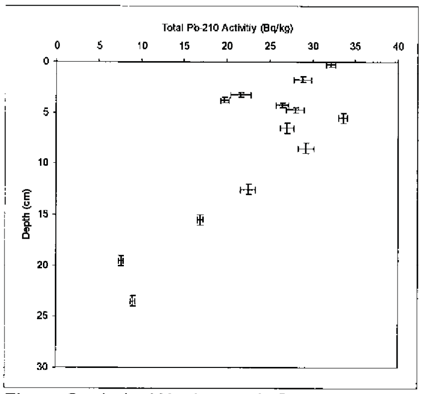

Figure 2 – Lake Wooloweyah Core 1: Total ^{210}Pb (^{210}Po) activity versus depth.

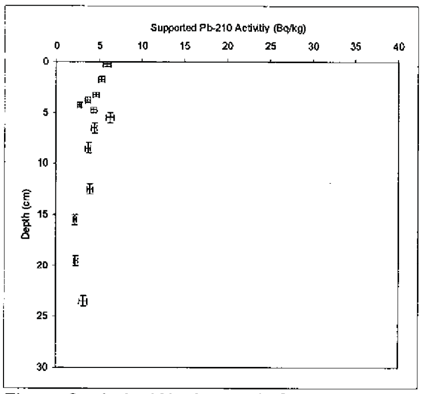

Figure 3 – Lake Wooloweyah Core 1: Supported ^{210}Pb (^{226}Ra) activity versus depth.

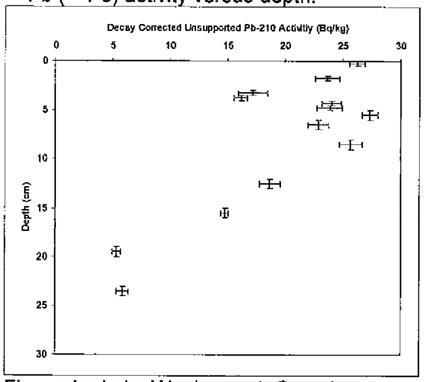

Figure 4 – Lake Wooloweyah Core 1: Unsupported ^{210}Pb activity versus depth.

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 10 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

Australian Government

ansto

Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of
Lake Wooloweyah sediment cores

Table 4 – Lake Wooloweyah Core 2: ANSTO sample ID, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb.

ANSTO ID	Depth (cm)	Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)	Count Date	Total Pb-210 (mBq/g) or (Bq/kg)	Supported Pb-210 (mBq/g) or (Bq/kg)	Unsupported 210Pb Corrected to reference date 21-Oct-08 (mBq/g) or (Bq/kg)
L003	0.0 - 0.5	0.25	0.1 ± 0.1	07-Nov-08	57.8 ± 1.6	11.6 ± 1.0	46.3 ± 1.9
L064	2.5 - 3.0	0.42	0.9 ± 0.1	16-Dec-08	51.4 ± 1.3	8.5 ± 0.6	43.1 ± 1.5
L004	5 - 6	0.54	2.2 ± 0.2	07-Nov-08	47.9 ± 2.3	6.3 ± 0.5	41.7 ± 2.3
L065	10 - 11	0.60	5.1 ± 0.2	16-Dec-08	48.9 ± 1.3	11.4 ± 0.9	37.7 ± 1.6
L219	13 - 14	0.57	6.8 ± 0.3	17-Feb-09	43.7 ± 1.3	6.5 ± 0.5	37.6 ± 1.4
L005	15 - 16	0.63	8.0 ± 0.3	07-Nov-08	47.1 ± 1.9	5.0 ± 0.4	42.2 ± 2.0
L220	17 - 18	0.75	9.4 ± 0.3	17-Feb-09	32.7 ± 1.2	6.8 ± 0.5	26.2 ± 1.3
L221	19 - 20	0.67	10.8 ± 0.3	17-Feb-09	44.3 ± 1.3	6.0 ± 0.4	38.8 ± 1.4
L066	20 - 21	0.66	11.5 ± 0.3	16-Dec-08	41.9 ± 1.1	10.1 ± 0.8	31.9 ± 1.4
L222	22 - 23	0.69	12.84 ± 0.29	17-Feb-09	39.6 ± 1.1	7.1 ± 0.5	32.8 ± 1.3

Table 5 – Lake Wooloweyah Core 2: ANSTO sample ID, depths, grain size distributions, CIC and CRS models calculated ages, CRS model mass accumulation rates and ^{137}Cs activities.

ANSTO ID	Depth (cm)	Grain size < 2 µm Content (%)	Grain size < 63 µm Content (%)	Calculated CIC Ages (years)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates g/cm2/y	ANSTO ID	Depth (cm)	^{137}Cs Decay corrected to 21-Oct-08 (mBq/g) or (Bq/kg)
L003	0.0 - 0.5	5.4	67.7	0.1 ± 0.1	0.0 ± 0.1	1.5 ± 2.9	L230	5 - 10	2.7 ± 0.6
L064	2.5 - 3.0	12.6	96.7	0.9 ± 0.2	0.6 ± 0.3	1.5 ± 0.7	L231	10 - 15	3.3 ± 0.6
L004	5.0 - 6.0	10.8	93.8	2.2 ± 0.4	1.5 ± 0.4	1.5 ± 0.4	L232	15 - 20	< 0.3
L065	10 - 11	14.2	95.7	4.9 ± 0.9	3.3 ± 0.5	1.5 ± 0.3	L233	20 - 25	4.3 ± 0.5
L219	13 - 14	11.7	97.0	6.6 ± 1.1	4.4 ± 0.6	1.5 ± 0.2			
L005	15 - 16	13.2	86.7	7.8 ± 1.3	5.3 ± 0.6	1.5 ± 0.2			
L220	17 - 18	13.4	91.1	9.1 ± 1.5	6.1 ± 0.6	1.5 ± 0.2			
L221	19 - 20	12.3	93.2	10.5 ± 1.8	6.9 ± 0.6	1.6 ± 0.1			
L066	20 - 21	13.5	95.6	11.1 ± 1.9	7.4 ± 0.6	1.6 ± 0.1			
L222	22 - 23	15.2	93.6						

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 11 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

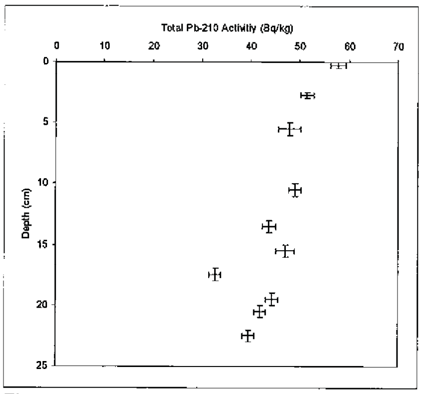

Figure 5 – Lake Wooloweyah Core 2: Total ^{210}Pb (^{210}Po) activity versus depth.

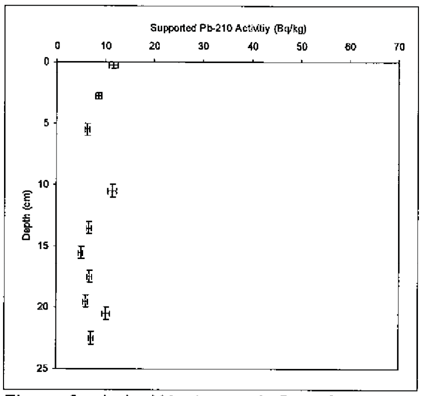

Figure 6 – Lake Wooloweyah Core 2: Supported ^{210}Pb (^{226}Ra) activity versus depth.

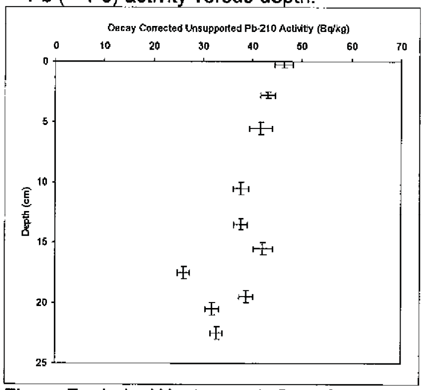

Figure 7 – Lake Wooloweyah Core 2: Unsupported ^{210}Pb activity versus depth.

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 12 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

Table 6 – Lake Wooloweyah Core 3: ANSTO sample ID, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb.

ANSTO ID	Depth (cm)	Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)	Count Date	Total Pb-210 (mBq/g) or (Bq/kg)	Supported Pb-210 (mBq/g) or (Bq/kg)	Unsupported 210Pb Decay corrected to 21-Oct-08 (mBq/g) or (Bq/kg)
L006	0.0 - 0.5	0.33	0.1 ± 0.1	07-Nov-08	53.3 ± 1.5	6.5 ± 0.5	46.8 ± 1.6
L067	2.5 - 3.0	0.36	0.9 ± 0.1	16-Dec-08	54.8 ± 1.5	11.5 ± 0.8	43.5 ± 1.7
L007	5 - 6	0.56	2.2 ± 0.2	07-Nov-08	48.6 ± 1.7	5.4 ± 0.4	43.2 ± 1.7
L068	9 - 10	0.63	4.6 ± 0.2	16-Dec-08	41.0 ± 1.1	7.4 ± 0.6	33.8 ± 1.2
L223	10 - 11	0.69	5.2 ± 0.2	17-Feb-09	33.8 ± 1.3	5.7 ± 0.4	28.4 ± 1.4
L224	11 - 12	0.56	5.8 ± 0.3	17-Feb-09	51.2 ± 1.2	5.2 ± 0.4	46.4 ± 1.3
L069	12 - 13	0.55	6.4 ± 0.3	16-Dec-08	51.0 ± 1.0	9.7 ± 0.7	41.5 ± 1.3
L225	13 - 14	0.64	7.0 ± 0.3	17-Feb-09	83.9 ± 2.1	9.4 ± 0.6	75.3 ± 2.2
L008	15 - 16	0.76	8.4 ± 0.3	07-Nov-08	23.1 ± 0.8	9.9 ± 0.8	13.2 ± 1.1
L070	18 - 19	0.83	10.8 ± 0.3	16-Dec-08	15.9 ± 0.4	10.2 ± 0.7	5.7 ± 0.8

Table 7 – Lake Wooloweyah Core 3: ANSTO sample ID, depths, grain size distributions, CIC and CRS models calculated ages, CRS model mass accumulation rates and ^{137}Cs activities.

ANSTO ID	Depth (cm)	Grain size < 2 µm Content (%)	Grain size < 63 µm Content (%)	Calculated CIC Ages (years)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates g/cm2/y	ANSTO ID	Depth (cm)	^{137}Cs Decay corrected to 21-Oct-08 (mBq/g) or (Bq/kg)
L006	0.0 - 0.5	8.2	84.7	0.1 ± 0.1	0.2 ± 0.2	0.49 ± 0.54	L234	5 - 10	2.2 ± 1.0
L067	2.5 - 3.0	14.2	95.9	1.1 ± 0.7	1.9 ± 0.6	0.50 ± 0.15	L235	10 - 15	4.3 ± 1.8
L007	5 - 6	13.0	91.2	2.5 ± 1.6	4.5 ± 0.8	0.49 ± 0.08	L236	15 - 20	1.9 ± 0.8
L068	9 - 10	14.7	92.3	12.3 ± 2.7	9.3 ± 0.9	0.49 ± 0.05			
L223	10 - 11	12.8	95.2	15.1 ± 3.2	10.5 ± 1.0	0.50 ± 0.05			
L224	11 - 12	7.0	57.2						
L069	12 - 13	12.5	94.7						
L225	13 - 14	15.7	92.4						
L008	15 - 16	14.4	95.6						
L070	18 - 19	12.6	96.5						

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 13 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

Australian Government

ansto
Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

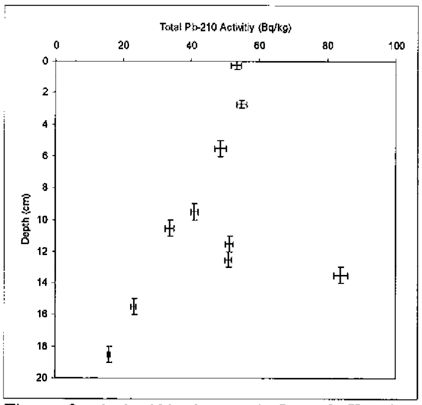

Figure 8 – Lake Wooloweyah Core 3: Total ^{210}Pb (^{210}Po) activity versus depth.

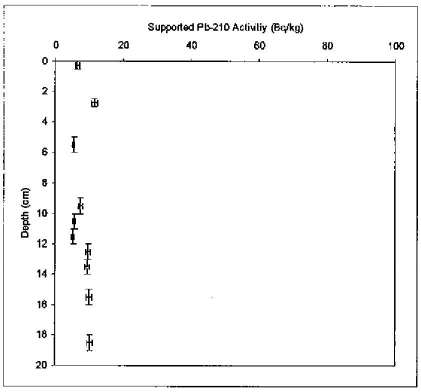

Figure 9 – Lake Wooloweyah Core 3: Supported ^{210}Pb (^{226}Ra) activity versus depth.

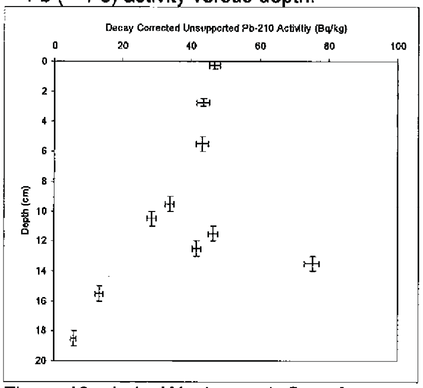

Figure 10 – Lake Wooloweyah Core 3: Unsupported ^{210}Pb activity versus depth.

2008rc0067, 68, 69
Lake Wooloweyah sediment cores

Report prepared by: Atun Zawadzki

Page 14 of 15

Report checked by: Henk Heijnis

Date: 11 May 2009

Australian Government

ansto
Nuclear-based science benefiting all Australians

11 May 2009
Report on ^{210}Pb and ^{137}Cs dating of Lake Wooloweyah sediment cores

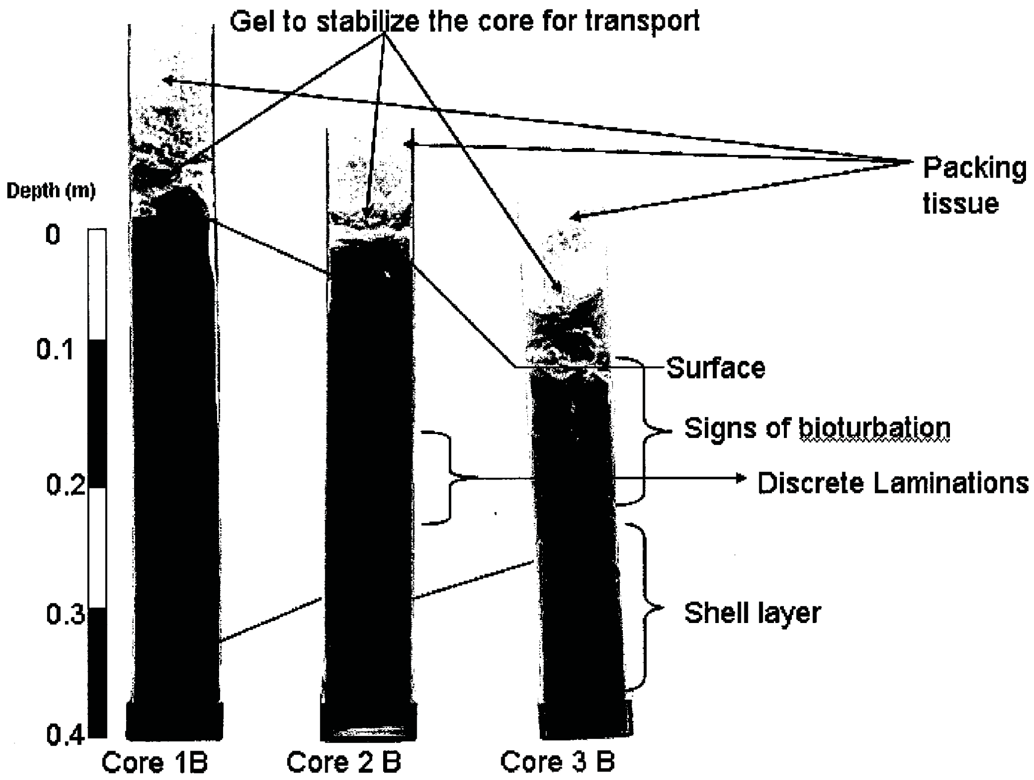

Figure 11 – Lake Wooloweyah duplicate sediment cores x-ray images.

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (PMB 1, Menai NSW 2234) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

APPENDIX B – SUMMARY OF MANAGEMENT OPTIONS FROM FOLEY AND WHITE (2007)

Taloumbi/Wooloweyah Management Area

Description

This area encompasses the foreshore of Lake Wooloweyah and the drainage system around the lake including, the ring drain and levee, and the Taloumbi Radial drains. It is mainly wet low lying country that was fresh and brackish wetlands prior to flood mitigation works. The main land use in this area is grazing.

Issues and Management Options

Issue 1 - Changes to wetlands due to the ring drain levee

Management Objectives	Options	Benefits	Potential problems, or obstacles
To restore natural tidal inundation to inter tidal marshlands adjacent to Lake Wooloweyah.	Move the ring levee and floodgates be moved inland by up to 1km. Lands affected by the proposal (about 800ha) were to be purchased, or landowners compensated through incentives (Smith 2002).	▪ Improvement of large area of fish and waterbird habitat. ▪ Possible commercial gain for professional fishing industries and improved recreational fishing.	▪ Cost of purchasing land and moving/reconstructing the levee system. ▪ Project could not proceed if one or more landowners do not want to sell their land. ▪ Loss of agricultural production from grazing. ▪ Possible effects on drainage in other parts of the system. ▪ Potential for more extensive regular tidal inundation than prior to levee construction in 1966. Some areas that were previously freshwater wetlands would become brackish. ▪ Potential for death of casuarinas and paperbarks that have established behind the levee. ▪ Potential for “blackwater” events.
To retain increased levels of water on some of the previously fresh water wetlands that have been over drained	A combination of low levees and possibly water retention structures	▪ Beneficial for freshwater species especially water birds. ▪ May reduce the encroachment of casuarinas and melaleucas. ▪ Increased grazing productivity - favourable habitat for freshwater couch and soft rush.	Difficult access and swampy conditions may be an impediment to construction.

Issue 2 - Fish passage, fish habitat and water quality in the ring and radial drains no.2 to 4

Management Objectives	Options	Benefits	Potential problems, or obstacles
▪ Improve fish passage between Lake Wooloweyah and the ring and radial drains. ▪ Reduce the risk of fish kills in the ring drain by allowing fish to escape to the lake during low oxygen events. ▪ Increase the amount of water exchange between the ring drain system and Lake Wooloweyah to improve water quality and neutralise any acid products produced in the drainage system with sea water.	**Option 1** - Install a tidally operated floodgate on the Palmers Channel end of the ring drain, and "lightweight fish gates" on the floodgates at radial drains No.2 and No.4.	▪ A large area of potential habitat would be more accessible to aquatic fauna and potential for fish kills would be reduced. Also possible commercial gain for professional fishing industries and recreational fishing. ▪ Improved water quality and neutralisation of any acid produced in the drainage system. ▪ Easier to control flows into the system and less potential for overtopping of drains than with tidal gates. ▪ Would be open more often than tidal gates when the water levels in the Lake are higher due to tidal accumulation or runoff from the catchment. ▪ Larger number of openings to the lake than option 2. ▪ This option may initiate some flow of water along the ring drain, and increase "flushing" affects.	▪ There is little "freeboard" in the ring and radial drains and many low points on the drain banks. Structures would have to be carefully managed to prevent drain overtopping which would affect grazing lands (applies to both options 1 and 2). ▪ Size of fish gate openings slightly smaller than tidal gates. ▪ Fish gates would not open during rising tides.
	Option 2 - Install two tidal floodgates – one on the Palmers Channel end of the ring drain, and the other on the floodgates at radial drain No.3.	▪ Environmental benefits would be similar to option 1. ▪ Tidal gates would have lightly larger openings and be open during rising tides at times when the level of the lake is not elevated.	▪ More difficult to control water going into the ring drain and a higher risk of overtopping. ▪ Floats on the tidal gates would tend to hold them shut during periods when the water levels in the Lake are elevated. ▪ May not operate effectively due to the limited daily tidal range in Lake Wooloweyah.

Issue 3 - Erosion on North West foreshore of Lake Wooloweyah

Management Objectives	Options	Benefits	Potential problems, or obstacles
To stabilise existing bank erosion along the north west margin of Lake Wooloweyah.	**Option 1:** Rock "fillets" placed 3-5m in front of the eroding bank.	▪ Stabilises the eroding bank. ▪ Provides a suitable habitat for mangrove regeneration at the toe of the bank. ▪ Provides an area of aquatic habitat behind the rock fillets.	▪ High cost. The project would require enough rock to construct up to 3km of rock fillets. ▪ Difficult access to areas with thick mangroves along the bank. ▪ Rock fillets would be more expensive than rock revetment in this situation due to the soft bottom, the depth of water and the greater amount of rock required.
	Option 2: Continue with rock revetment of unstable bank.	▪ Stabilises the eroding bank. ▪ Lower cost than option 1.	▪ High cost. ▪ Difficult access to areas with thick mangroves along the bank. ▪ Few added environmental benefits.

Little Reedy Creek management area

Description

Little Reedy Creek is approximately 3.0km long. The creek originally drained into the low lying marsh country behind Lake Wooloweyah, and would have been a series of fresh water holes prior to flood mitigation works. The creek now drains out through Radial drain No.2. The upper creek connects to the drainage systems in the northern part of the Palmers Channel area. When water levels are high in the Wooloweyah ring drain, water can move through Little Reedy Creek and affect the Palmers Island/Marshes and Palmers Island/Carrs drainage systems.

For most of the year the creek is shallow and saline due to saline water movement from the radial drain. There are extensive areas of low lying wetlands that drain into Little Reedy Creek, including a large area of low elevation paperbark dominated back swamp. This area has a high potential for acid discharges, as it is mapped on acid sulfate soil risk maps as having a high probability of acid sulfate material being at or near the surface. Paperbark swamps in the Clarence also typically have high soil conductivity due to soil macropores (cracks and old root canals).

Issues and Management Options

Originally this was a fresh water creek with a higher water level than currently. The creek was over drained when Radial drain no.2 was constructed. In some low lying areas saline water regularly overtops the creek banks and has caused scalds. Groundwater levels in high risk acid sulfate soil areas have been affected by drainage of Little Reedy Creek. This has increased the potential for acid discharges. The creek frequently stagnates and algae blooms in the warm dry periods of the year, as creek levels drop and the water becomes warmer. Saline water from the ring drain sometimes feeds through Little Reedy Creek and into the Palmers Island/Marshes and Palmers Island/Carrs drainage systems. This can adversely affect cane growing in low areas around Palmers Channel.

Management Objectives	Options	Benefits	Potential problems, or obstacles
▪ Restore the creek to a predominantly fresh water system as it was before it was drained. ▪ Increase and maintain a higher water level in the creek. ▪ Reduce the risk of acid discharges from low lying wetlands. ▪ Prevent water from the ring drain from entering the Palmers Island/Marshes and Palmers Island/Carrs drainage systems when levels are high.	Install a low level causeway/water retention structure in the lower section of the creek. Also raise the bed level in a small section of the upper creek or install floodgates on the pipes under Gardiners road to prevent over drainage in this direction.	▪ The creek would be restored to a predominantly freshwater system. ▪ Improved habitat for freshwater plants and bird species. ▪ Higher groundwater levels maintained in acid sulfate soils areas. ▪ Reduced risk of saline water affecting low lying cane lands in the Palmers Island/Marshes and Palmers Island/Carrs drainage systems.	▪ Agreement would have to be reached with all landowners in the area as to the specific design and location of works. ▪ Algal blooms would still be likely during warmer months of the year, but "stagnation" and odours may be reduced if higher water levels are maintained. ▪ Fish passage in the creek would be more restricted; however it would be similar to what it would have been prior to drainage works.

Reedy Creek management area

Description

Reedy Creek is approximately 7.3km long. It originally started in the northern Palmers Channel area and drained into the marshes behind Lake Wooloweyah. Prior to flood mitigation works this creek would have been a shallow series of fresh water holes during the drier months of the year. About half of the creek in the area north of Gardiners road is now highly modified and similar in appearance to most artificial cane drains. South of Gardiners road the creek is a shallow, predominantly fresh water creek that links to Taloumbi Radial drain No.1. It has a series of higher points in the creek bed that mostly exclude saline water from the radial drain from entering an extensive section of the creek. The freshwater section of the creek has a prolific growth of native freshwater plants and is habitat for a range of waterbirds.

Issues and Management Options

Salt occasionally water intrudes into the fresh water part of the creek via Radial drain No.1, when water levels in the ring drain are high. This kills the freshwater aquatic vegetation and causes the creek to stagnate.

Management Objectives	Options	Benefits	Potential problems, or obstacles
▪ Maintain the section of the creek below Gardiners Rd as a fresh water system. ▪ Prevent saline intrusion into this section of the creek.	Install floodgates on one of the existing crossings, or a low level causeway in the lower section of the creek. The exact details could be determined after consultation with landowners.	Part of the creek would be maintained as a freshwater system as it would have been prior to flood mitigation works in 1966.	▪ Agreement would have to be reached with all landowners in the area as to the specific design and location of works. ▪ Fish passage in the creek would be more restricted; however it would be similar to what it would have been prior to drainage works.

Palmers Channel/Marshes management area

Description

Palmers Island/Marshes drain is an artificial drainage system designed to drain cane lands in the Palmers Channel area. A winch and tidal gate have been fitted to the floodgates for the Palmers Channel Acid Remediation Project, and side drain structures constructed to prevent inundation of low lying cane lands. The structures are operated by local landowners to allow tidal exchange and flushing of the drains to improve water quality. This has been very beneficial and has reduced the number of algal blooms. It has also reduced the risk of fish kills, and provided fish habitat.

Issues and Management Options

The main issue on this creek system is low lying cane lands. The system needs to be managed carefully to avoid cane lands being inundated. In the western section of this area near the James Creek Road is a natural wetland that has been drained. This wetland is about 11ha in area, and would have originally been a shallow seasonally inundated wetland. It could be restored by the construction of a low bank and water retention structure.

Management Objectives	Options	Benefits	Potential problems, or obstacles
Maintain the existing program of tidal exchange	Continue current program of tidal exchange. Further works if required to prevent inundation of low lying cane lands.	▪ Improved water quality and neutralisation of any acid produced in the drainage system. ▪ Fish habitat	Low lying cane lands
Restore an over drained wetland near the James Creek Road.	Construction of a low bank and water retention structure.	▪ Improved habitat for freshwater plants and water bird species. ▪ Improved grazing productivity.	No foreseeable problems or obstacles.

Palmers Channel/Carrs management area

Description

Palmers Island/Carrs drain is a short natural estuarine creek system that drains into the northern end of Palmers Channel. An extensive system of private cane drains link to Carrs Creek. There is a small natural wetland at the top of Carrs Creek.

Issues and Management Options

The main issue on this creek system is the overtopping of creek banks and saline water getting onto low lying cane lands. This is thought to happen when water levels rise in the Wooloweyah ring drain, leading to an accumulation of water throughout the entire drainage system.

Management Objectives	Options	Benefits	Potential problems, or obstacles
Maintain the existing program of tidal exchange	▪ Continue current program of tidal exchange. ▪ Further works if required to prevent inundation of low lying cane lands. These may include installation of a structure in Little Reedy Creek, adjustment of the tidal gate, construction of low banks or levees on the creek banks adjacent to low lying cane lands installation of a side drain structure on Carrs creek, or a combination of these.	▪ Improved water quality and neutralisation of any acid produced in the drainage system. ▪ Fish habitat	Low lying cane lands.

Palmers Channel/Marshalls management area

Description

Palmers Island/Marshalls drain is a small artificial drainage system designed to drain cane lands. It has a small pipe and floodgate that is difficult to access, as the banks of Palmers Channel are steep where it is located.

Issues and Management Options

No issues or management options have been identified for this area. It is probably not worth considering any modifications to the floodgate to allow water exchange, due to the small size of the system and the difficulty in accessing and modifying the floodgate.