TUGGERAH LAKES ESTUARY PROCESS STUDY

February 2000

WYONG SHIRE COUNCIL

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EXECUTIVE SUMMARY

The Tuggerah Lakes are a series of three interconnected shallow coastal barrier lagoons that are open to the sea at The Entrance. An estuary process study was done as part of the NSW state governments estuary management program. The estuary process study was to describe the physical, chemical and biological patterns and processes operating within the estuary and identify management issues that would be the focus of the subsequent management study. In the past, community concerns about deteriorating environmental quality within the estuary have led to scientific studies and a number of management actions. Many of the studies were not done at appropriate spatial and/or temporal scales and were generally focused on issues surrounding the operation of the Munmorah Power Station and its effects on the estuary. The Tuggerah Lakes restoration program was a direct result of community and political pressure to do something about eutrophication within the estuary. The results of that particular management action have and continue to be questioned by the community and technical experts from various disciplines. The lakes restoration program may be considered a "bandaid solution" because it only treated the symptoms and not the actual cause of the problem.

which is (?)

The Tuggerah Lakes Estuary Process Study was to identify data gaps and key estuarine processes so that we had a clear understanding of how the estuary actually "worked". All the relevant scientific studies that had been done were examined so that a generalised description of the processes within the estuary could be used to assist with managing environmental issues. It became clear early in the study that many of the previous works were inadequate for describing estuary processes because appropriate spatial and or temporal scales were never examined. To help overcome this, a number of studies were done aimed at describing the estuary in terms of its important physical, chemical and biological components. Many of these studies are ongoing and are funded by Wyong Shire Council independent of external funding (e.g. water quality, macroalgae and phytoplankton monitoring). These programs will also be reported in annual state of the environment and technical reports and in the relevant scientific literature.

The estuary was formed some 5,000 years ago when sea levels rose after the last ice age. Most of the geomorphological features of the estuary are relic i.e. they are no longer active except for the river deltas of Wyong and Ourimbah Creeks and the tidal delta at The Entrance. Sedimentary processes within the estuary were found to be slow, with no evidence for depth changes since the early bathymetry studies in the 1970's. There were however small-scale changes with some places becoming shallower around inflows whereas other places had become deeper due to the effects of mine subsidence. The Tuggerah estuary is one of the slowest infilling estuaries along the NSW coast and at current rates would take over 1000 years to completely fill. The flushing and mixing characteristics of the estuary were examined and tidal flushing contributes very little to its circulation and mixing patterns. Overall the bottom sediments within the estuary were relatively "healthy" apart from some small-scale problems in some urbanised areas. Initial investigations on pollutants within the sediments indicated very low levels of pesticides whilst some heavy metals were found in Lake Budgewoi although these levels were well below levels found to cause adverse ecological effects. The sediments within the estuary had high nutrient concentrations and studies on sediment nutrient fluxes indicated positive flux rates. Ambient nutrient concentrations within the water column were found to be above the ANZECC guidelines and the estuary could be classed as mesotrophic (i.e. medium nutrient status).

Phytoplankton populations within the estuary were low with occasional blooms whilst macroalgae assemblages experience periodic small-scale blooms (generally around developed foreshores). Macroalgae blooms during the 1980's and early 1990's were consistent with the estuary being eutrophic. With projected increased population pressure in the Wyong catchment these macroalgae blooms could return if appropriate management action is not taken. One of the major ecological issues in the estuary has been the defragmentation and loss of up to 85% of fringing saltmarsh and wetland vegetation. Saltmarsh and fringing wetlands play an important role in nutrient recycling processes and their removal has probably altered the way seagrass and macroalgae wrack are recycled through the estuary. Ecologically sustainable foreshore management will need to be addressed as part of any management plan for the estuary. Contrary to public opinion there has been a significant decrease in the extent of seagrasses within the estuary by at least 50% since the 1960's, probably due to increased turbidity within the lakes and by physical disturbance. Descriptions of ecologically sensitive habitats that will need to be considered in the management plan are also included.

Estuary management issues were identified in conjunction with the Tuggerah Lakes Estuary Management Subcommittee workshops and through community consultation The following key issues will require further exploration in the estuary management study

- Ecologically sustainable management of estuarine beaches and foreshores

- Protection of ecologically sensitive habitats, eg Budgewoi Sandmass and Tuggerah Bay

- Managing potentially elevated nutrient and sediment loads to the estuary from increased urbanisation and development in the catchments

- Identification and management of those nutrients responsible for excessive aquatic plant growth

to now

still to addressed

- Implications of periodic dredging of rivers and the tidal delta at The Entrance

- Practical and ecological implications of a second entrance and/or break walls to alter existing estuarine mixing and flushing

- The management of both recreational and commercial fisheries

- Potential ecological effects of mine subsidence

- The feasibility of using "Bioindicators" to quantify whether management targets for the estuary are attained

Should all be answered prior to management plan

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1. INTRODUCTION

1.1. The Tuggerah Lakes Estuary

The Tuggerah Lakes catchment represents around 80% of the area of the Wyong Shire (Figure 1) The estuary is composed of three interconnected lakes, which are open to the sea at The Entrance The study area, located on the central coast of NSW, comprises three shallow coastal lagoons, Tuggerah Lake, Budgewoi Lake and Lake Munmorah (Figure 2) The process study was not limited to the three lakes but included their foreshores, adjacent lands and major tributary rivers and creeks Land in the catchment is used in a number of ways, ranging from residential, commercial, rural, industrial, forestry and natural bushland The Tuggerah Lakes estuary has always been important to the Shire in terms of its value to tourism, recreation and fisheries (Inter-Departmental Committee, 1979)

1.2. Catchment and Landuse

Wyong Shire is approximately 100 kilometres north of Sydney (Figure 1), bounded by Lake Macquarie in the north and Gosford in the south and is approximately 826 km^2 in total area (WSC, 1997, 1999) The eastern part of the shire is dominated by the Tuggerah Lakes, whilst the Wattagan Mountains dominate the western part of the shire (WSC, 1997) Wyong Shire experiences a mild temperate climate with an average temperature of 28°C during summer and 8°C during winter The average annual rainfall in the catchment is approximately 1200 mm The rainfall varies throughout the year, with March the wettest month (140 mm) and August the driest (70 mm) (WSC, 1997) During the winter months, the prevailing wind direction is from the south-west, whilst south-east winds prevail during spring and early summer In late summer, north-eastly sea breezes prevail The geology and soil landscapes of the region were described by Murphy (1993), and a summary of those pertaining to Wyong Shire can be found in Wyong Shire Councils state of the environment reports (WSC, 1997, 1999) Over the last 160 years the natural environment of the region has been modified with many different types of landuse (WSC, 1997) In general they have included forestry, residential, commercial, industrial and agriculture Approximately 3% of the area of the shire is comprised of National Park A description and breakdown of the various landuse in the shire and a summary of the major changes that have occurred can be found in the state of the environment reports (WSC, 1997, 1999) Wyong Shire Council's 1998/99 state of the environment report (WSC, 1999) explores the pressures that population growth and associated landuse activities have on the social, economic and environmental components of the region The central coast regional planning strategy is to focus on managing land development to achieve agreed economic, social and ecological goals (WSC, 1999)

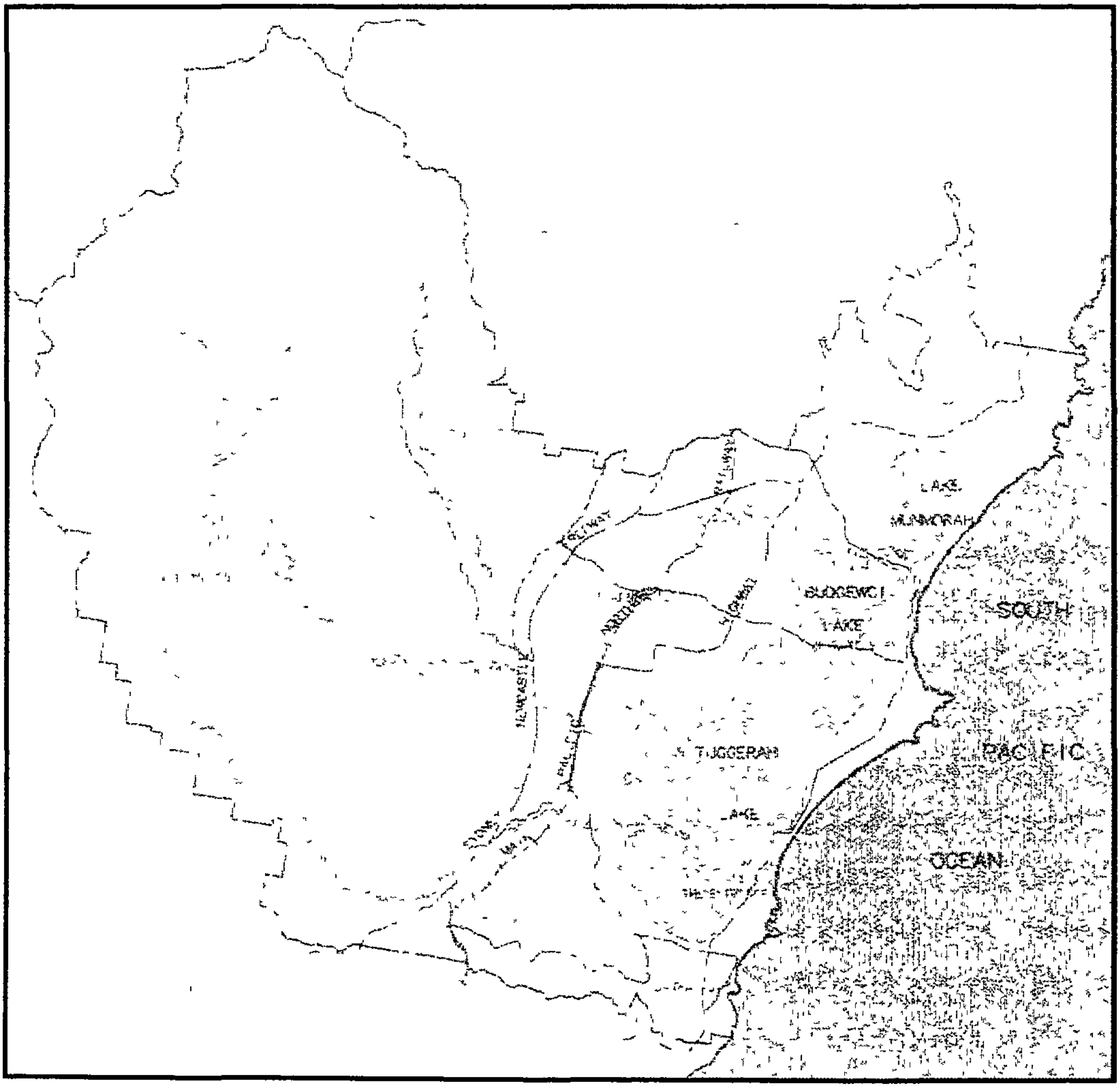

Figure 1. Wyong Shire on the Central Coast of NSW

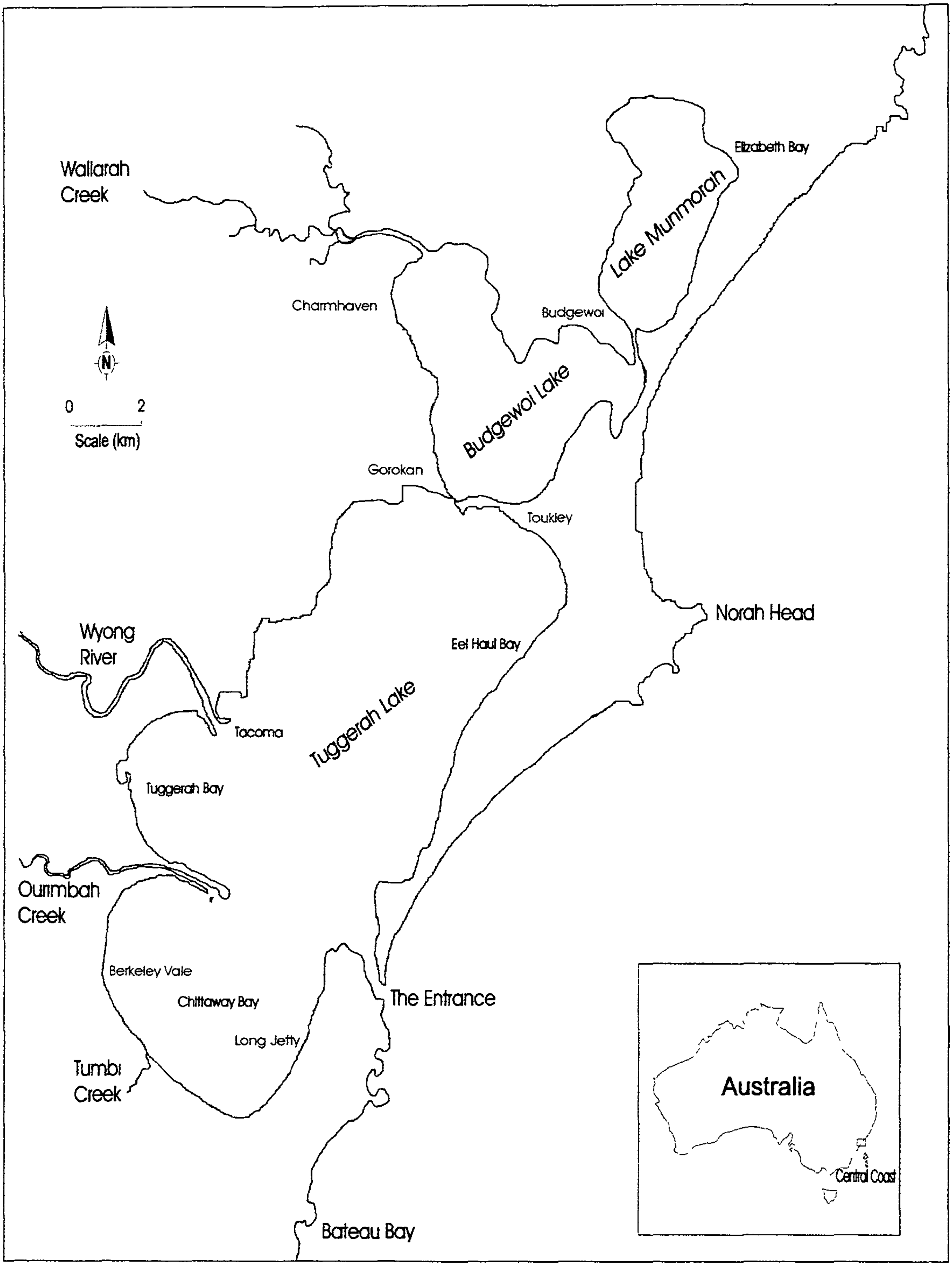

Figure 2. The Tuggerah Lakes Estuary

1.3. Framework for the Estuary Management Plan

The NSW state government's estuary management process required that a management plan for the Tuggerah Lakes estuary be prepared (Estuary Management Manual, 1992) An estuary management sub-committee was formed to assist in the formulation of this estuary management plan (Appendix 1) The estuary management committee's main objective was to promote ecologically sustainable development through the formulation of an estuary management plan, which accounted for all stake-holders

The process of formulating an estuary management plan is detailed in the Estuary Management Manual (1992), which outlines a process leading to the implementation of the plan based on principles of ecologically sustainable development and management of the catchment The first stage in the plan was to undertake a review of literature and to compile relevant data, these were, to some extent, done as part of the Adaptive Environmental Assessment and Management Program (AEAM) for Wyong Shire Council (WSC) The second stage, the process study, was to be followed by a management study and production of a plan of management for the estuary

The Estuary Process Study was to provide an overall appreciation of the various physical, chemical and biological interactions occurring in the estuary and to form the basis for a balanced, integrated managerial plan that includes issues relevant to all stake-holders The following issues were identified by the community as relevant to the estuary and its catchment and provided an initial focus for the study It should be recognised that, in preparing such a list, the inclusion and, in particular, the ranking of particular issues was subjective. Many of the issues were interactive and included the following

- Entrance conditions and their impact on tidal exchange and the flushing of nutrients
- A proposal for a second entrance
- Flooding of foreshores
- Water quality, especially adjacent to stormwater outlets
- Impact of heated water discharges from Lake Munmorah Power Station, especially on growth of seagrass and macroalgae
- The effects of seagrass and macroalgae growth on recreation
- Accretion of sediment at stormwater outlets and creeks
- Dredging of sediment, especially to evaluate the effects of past foreshore dredging and reclamation works

1.4. Adaptive Environmental Assessment and Management

The AEAM program developed by Macquarie Research Ltd, WSC and the Wyong community was used to help identify areas of research for management of the estuary and catchment within Wyong Shire The AEAM models were initially developed to provide a framework in which the bulk of the studies on the Tuggerah Lakes estuary were to be done The program was to develop a modeling tool that could offer potential management strategies to alleviate the effects of an increasing human population (Walkerden and Gilmour, 1996) The AEAM wokshop proceedings, aims, methods and recommendations are summarised in Walkerden and Gilmour (1996)

1.5. Peer Review and Community Consultation

The Tuggerah Lakes Estuary Management Sub-committee oversaw the formulation of the process study and was involved at all stages and with scoping of the issues (Appendix 1) All components of the process study were peer-reviewed by experts in estuarine ecology and environmental management, whilst a panel of technical experts consisting of leaders in their respective fields reviewed the final document and reports (Appendix 2)

1.6. Literature and Data Review

A great deal of the literature and data review for the Tuggerah Lakes system was done as part of the AEAM scoping and workshop programs. A three-volume report outlines much of this work (Walkerden and Gilmour, 1996) In 1970, the State Government set up a committee with representatives from various authorities with management responsibility for the estuary This committte was to closely examine the problems within the estuary and make recommendations to overcome them (Inter-Departmental Committee, 1979) The Murray-Darling Freshwater Research Centre and the CSIRO were commissioned to review the ecology of the Tuggerah Lakes system but its main focus was on the effects of power stations (CSIRO, 1990) Wyong Shire Council's, State of the Environment Reports, contained information and relevant literature on the catchment and estuary and were used to gain basic information and provided much of the background information required for the process study

1.7. Objectives of the Process Study

The main objectives of the process study were to develop a further understanding of a number of key issues including the following

- Hydrodynamic and sedimentary processes operating in the estuary
- Water quality variables of importance to the "health" of the estuary and their mixing and flushing behaviours
- Interactions between physical, chemical and biological processes
- Ecological and biological processes and characteristics of importance to the estuary
- Location and nature of significant natural, cultural, physical and scientific sites
- Extent to which human activities have modified or disturbed processes
- Additional data and studies necessary to aid in preparing the subsequent stages of the Estuary Management Study and Plan

1.8. Scope of the Process Study

The following issues were identified and considered important in affecting the long-term “health” of the Tuggerah Lakes estuary Final scoping of the patterns and processes involved provided the focus for undertaking the process study

- Monitoring key physical/chemical water quality variables
- Sediment/nutrient interactions with biota
- Biological indicators of lake and catchment health
- Nutrient sources and budget
- Annual sediment loads and characterisation
- Major catchment sources of pollutants and development of management options
- Management of non-point source pollution controls across a variety of land uses
- Management of stormwater treatment zones
- Ground water movement and its quality and quantity in the catchment
- Dredging operations and effects on water quality and biota
- Sediment/nutrient fluxes
- Spatial and temporal variation in seagrass and macroalgae
- Phytoplankton and zooplankton dynamics
- Lake hydrodynamics and flushing characteristics

1.9. Patterns and Processes in the Ecology of Estuaries

Simple models of how the physical, chemical and biological components of an estuary interact were used to scope the process study (Figure 3) Any scientific research program or study begins simply with observations, i e we describe the patterns or phenomena that are observed Observations are generally followed by the construction of one or several models or potential explanations of the observed phenomenon To be able to discriminate amongst several competing models that can be constructed to explain phenomena in nature, we must be able to make predictions and test these predictions in some measurable way This is fundamental to basic scientific procedure and describing patterns of variation is the first step (Underwood, 1997) This study is referred to as a process study, but it is really only a study of patterns To be able to interpret processes from observed patterns requires experimental tests of hypotheses derived from competing models (Underwood, 1997) When this study began, many significant gaps in our understanding of key estuarine patterns were identified, making predictions and descriptions of processes fundamentally weak Furthermore, the general ecology of estuaries is poorly understood when compared to other ecosystem types (Constable and Fairweather, 1999). It must be kept in mind that the formulation of an estuary management plan is supposed to be a dynamic process As new information and data become available, they are added to the process of management Natural systems undergo fluctuations at greater temporal scales than those usually accomodated in budgets for research and therefore patterns are often described at inappropriate scales

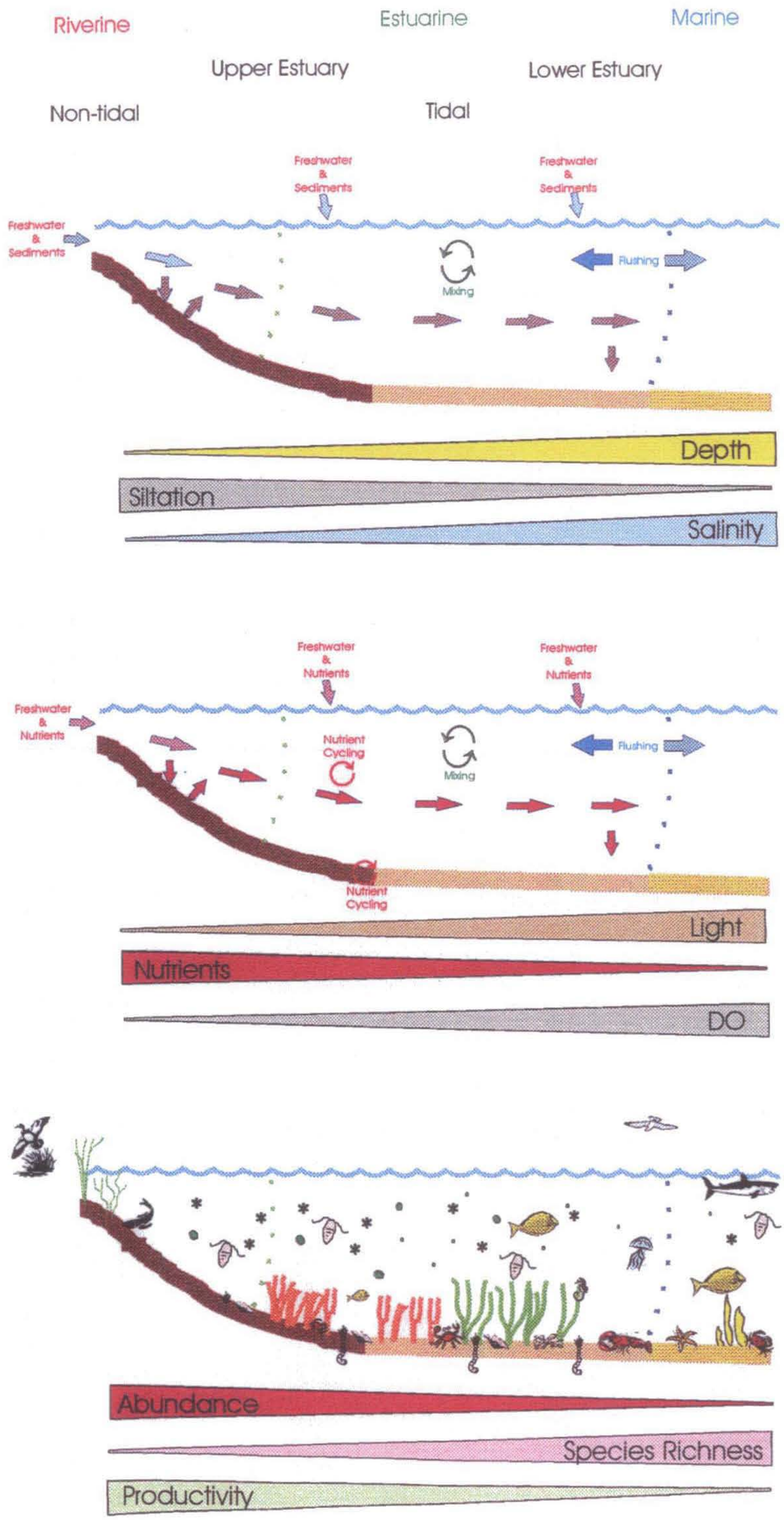

Figure 3. **Summary of physical, chemical and biological processes influencing an estuary**

2. PHYSICAL PATTERNS AND PROCESSES

2.1. Introduction

Estuaries are complex, dynamic and biologically rich environments largely dominated by physical forces The Tuggerah Lakes estuary is a series of three interconnected coastal lagoons, which open to the sea at The Entrance They include Tuggerah (the largest), Budgewoi and Munmorah (the smallest) Tuggerah Lake is approximately 5km wide and 13km long whist Budgewoi is 4km wide and 4km long, and Lake Munmorah is 2km wide and 4km long Large estuarine systems like the Tuggerah Lakes are most commonly found on low-relief coastal regions Estuaries have not been a common feature of the earth's geological history, and the two most recent geological epochs, collectively named the Holocene, are known as the age of the estuary (Day *et al*, 1989)

All present day estuaries are less than 5000 years old, which represents the time since sea level peaked near its present level following the last ice age Humans have flourished since this time, often exploiting the rich resources of estuaries Present day estuaries like the Tuggerah Lakes are geologically ephemeral coastal features, which formed during the last interglacial stage as sea level rose to 120m, almost 15,000 years ago These glaciation and deglaciation events have occurred regularly during the past few million years and shifts in the position of coastlines worldwide and locations of estuaries have changed accordingly

Once formed, estuaries tend to fill with sediments and eventually disappear The sediment sources within estuaries are generally from river-borne terrestrial materials eroded from the catchments, whilst sand sized materials are brought up from the continental shelf From a geological point of view, the time scale of this infill is extremely short and estuaries infill at different rates, so that they are at numerous stages of geological development

The type and rate of geological development of estuaries depends on many factors including, glaciation cycles, sediment supply, climatic variability, regional and local geology and variation in energy inputs Estuaries can be classified on their shape, history, tidal range and salinity regimes Barrier estuaries range in size up to 100km^2 and are characterised by narrow, elongated entrance channels, sometimes only intermittently open to the sea Away from the channels the estuary is generally shallow, low in energy, and supports vast seagrass communities When young, the shores of barrier estuaries are generally rocky and irregular, but over time they fill in and become smoother Eventually, deltas and mud flats develop, with long twisting channels and are quite often non-tidal in the upper reaches of the estuary

To understand the processes that contribute to the patterns occurring within an estuary it is insufficient to solely focus on chemical and biological interactions The physical nature or geomorphology of the estuary will have a great influence on basic hydrodynamics including water circulation, stratification, mixing and flushing rates The Tuggerah Lakes estuary can been classified as a barrier estuary, formed during the Holocene/Pleistocene period (Roy, 1984) Of all three lagoons, Tuggerah Lake is the largest (60km^2) and due to dredging, is continuously open to the sea The estuary is shallow with an estimated average depth of 1 6m, whilst eighty percent of its total area is situated between the depth contours of 2m and 3m (Roy and Peat, 1973)

2.2. Sedimentary Processes

There is the potential for large amounts of sediments to enter the Tuggerah Lakes estuary from the surrounding catchment These sedimentary processes occur naturally but, with increased urbanisation and development, increased rates could be expected Flow and sedimentary processes have probably been altered by anthropogenic disturbance including dredging, weirs and stormwater drains Therefore, it is necessary to provide a description of sediment type, patterns of distribution, rates of sediment accumulation, potential sources, and factors affecting the movement and deposition of sediment

Sediments within an estuary are principally derived from the erosion of land-based material (rock, soil, organic matter), which enters the estuary principally from rivers, creeks and the sea They can also enter estuaries from the surrounding catchment via wind and surface water runoff The composition of estuarine sediments varies from estuary to estuary and within an estuary

Within an estuary, there are a generally a number of sediment zones Areas of accumulation are places where fine materials are continuously deposited. These zones contain fine silts and clays with a high organic content Areas of transportation are where fine materials are deposited and then remobilised and result in a diverse range of sediments ranging from muds to sands Examples include tidal deltas such as The Entrance or river deltas such as at Chittaway Point in Tuggerah Lake Areas of erosion are places where there is little to no deposition of fine materials These areas are characterised by bare rock, gravels and sands, e g shoreline areas around the north-eastern part of Tuggerah Lake (Tuggerawong)

The grain size of sediment is proportional to the energy of the water flowing over the bottom Where energy is low, particles tend to be small (e g bottom of the estuary) Where energy is high, particles are larger, e g at the mouth an estuary The nature of the sediment will therefore depend heavily on associated variations in energy During periods of low energy, fine particles will settle out of the water column whilst during higher energy flows these fine particles are re-suspended in the water column and moved to other places Water velocities in estuaries vary over short and long periods and therefore variation in sediment deposition, erosion and transport occurs Large flood events (50 -100 year) have an important role in shifting material that would not otherwise have been moved by normal flow events Sediments are important components of the estuary because they are crucial to nutrient recycling and provide a habitat for a multitude of animals and plants

2.2.1. The Geomorphology of the Tuggerah Lakes Estuary

2.2.1.1. Introduction

The shoreline of the Tuggerah Lakes estuary can be categorised into three physiographic units, coastal sand dunes, bedrock hills and alluvial valleys The lakes have developed through the formation of coastal sand barriers linked by three bedrock highs at The Entrance, Norah Head and Wybung Head (see Figure 2) On the eastern side of Tuggerah Lake, a dunal system (North Entrance Peninsula) reaches heights of 45m These dunes support the well-developed red gum and blackbutt forests of the Wyrrabalong National Park The barriers adjacent to Budgewoi Lake and Lake Munmorah are less developed and have been modified in the past by mining

Marine barriers consisting of quartzose sand can be found deposited in nearshore, beach and dune environments These marine barriers link the three bedrock outcrops mentioned above and tend to widen towards the north Alluvial deposits infill the valleys of Wyong and Ourimbah, and the western side of the estuary where deltaic deposits occur The Tuggerah Lakes are classified as a barrier estuary, formed because longshore drift progressively deposited sand along the three main bedrock outcrops

2.2.1.2. Tuggerah Lake

Tuggerah Lake is shallow, generally less than 3m and flat-bottomed. The bottom beds are composed of soft black mud carried into the lake by creeks during floods and deposited from suspension The sides are generally formed of gently sloping sandy banks The eastern sides are shallow flat-topped banks, which are related to the dune barriers

In Tuggerah Lake, the bank adjacent to the north entrance peninsular expands opposite to the entrance into a broad tidal delta This tidal delta has been modified in recent years by dredging operations On the western side of Tuggerah Lake, fluvial deltas protrude around 1-2 km from Wyong River and Ourimbah Creeks (Figure 4) Elsewhere in the estuary, the peripheral sandbanks are composed of material eroded from the foreshores by wave action (Roy and Peat, 1973)

There are six distinct morphological zones within Tuggerah Lake (Roy and Peat, 1973) These include the lake-bed, two river deltas, a tidal delta at The Entrance, a barrier bank along the eastern foreshore, rocky foreshores on the western side of the lake, and two large embayments (Chittaway Bay and Tuggerah Bay)

The deltas of Wyong River and Ourimbah Creek on the western side of the lake are composed of sandy mud, with muddy lithic sands restricted to the distributary mouths The Wyong River delta protrudes around 1,000 m into the estuary whilst the Ourimbah Creek delta protrudes around 2,500m Between the deltas, sandy mud extends well into the estuary beyond the 2m contour (Roy and Peat, 1973)

The tidal delta at The Entrance is a large deposit of marine quartzose sand, derived from the open coast and deposited when current velocities decreased upon entering the estuary (Figure 4) The distribution of sand in the delta is complex due to natural dynamic processes and from maintenance dredging The tidal delta is no longer active because tidal velocities are too low to transport sand. Marine sand deposition is restricted to the seaward end of the channel and the surface of the delta is flat-topped and sandy Sandy-mud/muddy-sands accumulate after flooding along the slopes and in the channels The tidal delta extends around 1,200m into the estuary (Roy and Peat, 1973)

The barrier bank is located on the north eastern and northern sides of Tuggerah Lake from the tidal delta at the entrance to the Toukley Bridge (Figure 5) It is composed of aeolian quartzose sand derived from the North Entrance Peninsular barrier dunes Wave erosion at the base of the dunes has redistributed the sand to form a flat-topped, steep sided barrier bank This sand body is a relic feature and is no longer active with the bulk of the sand derived from the adjacent sand dunes Evidence is provided by the fact that the bank is not being eroded, and emergent macrophytes line the shoreline The barrier bank varies between 250 and 750m wide (Roy and Peat, 1973)

The rocky foreshores outcrop along the north-western shoreline, where the sides are steeply sloping The sediments adjacent to the rocky foreshores include an assemblage of lithic facies Isolated deposits of lithic sands occur in the heads of shallow embayments In deep water, narrow zones of muddy/lithic/sand and sandy/lithic/mud are juxtaposed and grade into muddy sediments (Roy and Peat, 1973)

Two large embayments (Tuggerah and Chittaway Bay) have formed due to delta progradation and are dominated by muddy sediments with a lithic sand fraction (Figure 5) On either side of Ourimbah Creek delta, the embayments are shallow and seagrass beds slow wave energy Sediments in the shallow zones are primarily mud and sandy mud with a high organic content (Roy and Peat, 1973)

2.2.1.3. Budgewoi Lake

Budgewoi Lake is connected to Tuggerah Lake at Toukley and to Lake Munmorah by a narrow channel in the north The lake has a flat bottom comprising around 80% of its area Fifty percent of Lake Budgewoi is deeper than 2m whilst the other 30% is shallower than 1m The slope between these areas is between 1 and 2m (Roy and Peat, 1973)

Four distinct morphological units occur, the bed of the lake, peripheral sandbanks, rocky shelves, and the eastern sand flat (Budgewoi sandmass) The bed of the lake is composed of soft, black to dark olive-green mud The source of the mud is from deposition of suspended material entering from Wallarah Creek (see Figure 2)

The peripheral sandbank is composed of lithic sands, which surround the lake They are mostly sandy mud, lithic muddy sand and clean lithic sand The clean lithic sand zone is located against the shore in less than 1m The banks reach a maximum width of 300m in the northern arm of the lake These banks are very narrow or absent at the southern end of Budgewoi Lake The eastern arm has an extensive bank of quartzose sand The lithic sands in Budgewoi Lake are texturally related to the rocky outcrops Gentle sloping rocky shelves to 200m occur off the rocky points in the north These outcrops extend laterally less than 300m, before sediments overlay them (Roy and Peat, 1973)

The eastern sand flat is composed of quartzose sands whilst soft black mud up to 1 5m thick occurs on its eastern side whilst the surface of the bank is comprised of clean sand colonised by seagrass On the eastern side of the bank, the water depths are less than 15cm and bare sand is exposed at times of low lake level Muddy sands and sandy mud are found along the northern edge of the channel This sand body is a relic Pleistocene tidal delta formed at the mouth of an entrance channel, which once connected Budgewoi to the sea approximately 1-2000 years ago (Figure 6)

2.2.1.4. Lake Munmorah

Lake Munmorah is the deepest of all three lagoons and has four distinct morphological units, the flat lake bottom, the western peripheral sandbank, the eastern peripheral sandbank and the crescent shaped bank (Figure 6) The flat bed of the lake is composed of soft, black to dark olive-green mud derived from Colongra Creek during floods and from Budgewoi Lake Deep holes occur in the lake up to 3 5m in places whilst the bed of the lake occupies 70% of the total area The western peripheral bank is composed of muddy and clean lithic sands The lithic sands are less muddy in the south than in the north, and the lithic sediments possess a course fraction, which is poorly sorted These sediments are related to the onshore outcrops of Munmorah Conglomerate eroded by wave action Colongra Creek is no longer active because of the Munmorah Power station commissioned in 1969 The eastern barrier bank is comprised of clean quartzose sands of aeolian origin (coastal sand barrier) Lithic sands to the south-west merge with quartzose sands to the north There is a narrow zone of muddy sand and sandy mud, which occurs on the steeply sloping edges Water turbulence on the surface of the bank prevents accumulation of mud These submarine barrier banks were formed by waves eroding the inner edge of the coastal dunes These deposits are considered relic features with little active deposition The crescent shaped bank abuts the shoreline near Elizabeth Bay at the northern end of lake It is composed of clean quartzose-aeolian sand and merges with the barrier bank on its eastern side and facies into lithic sediments on its western side Its top is composed of clean quartzose sand down to sandy mud and mud at its base It is probably a modified relic of a former coastal dune system from the Pleistocene age (Roy and Peat, 1973)

Figure 4. Delta at the mouth of Wyong River (Top) and the tidal delta at The Entrance (bottom)

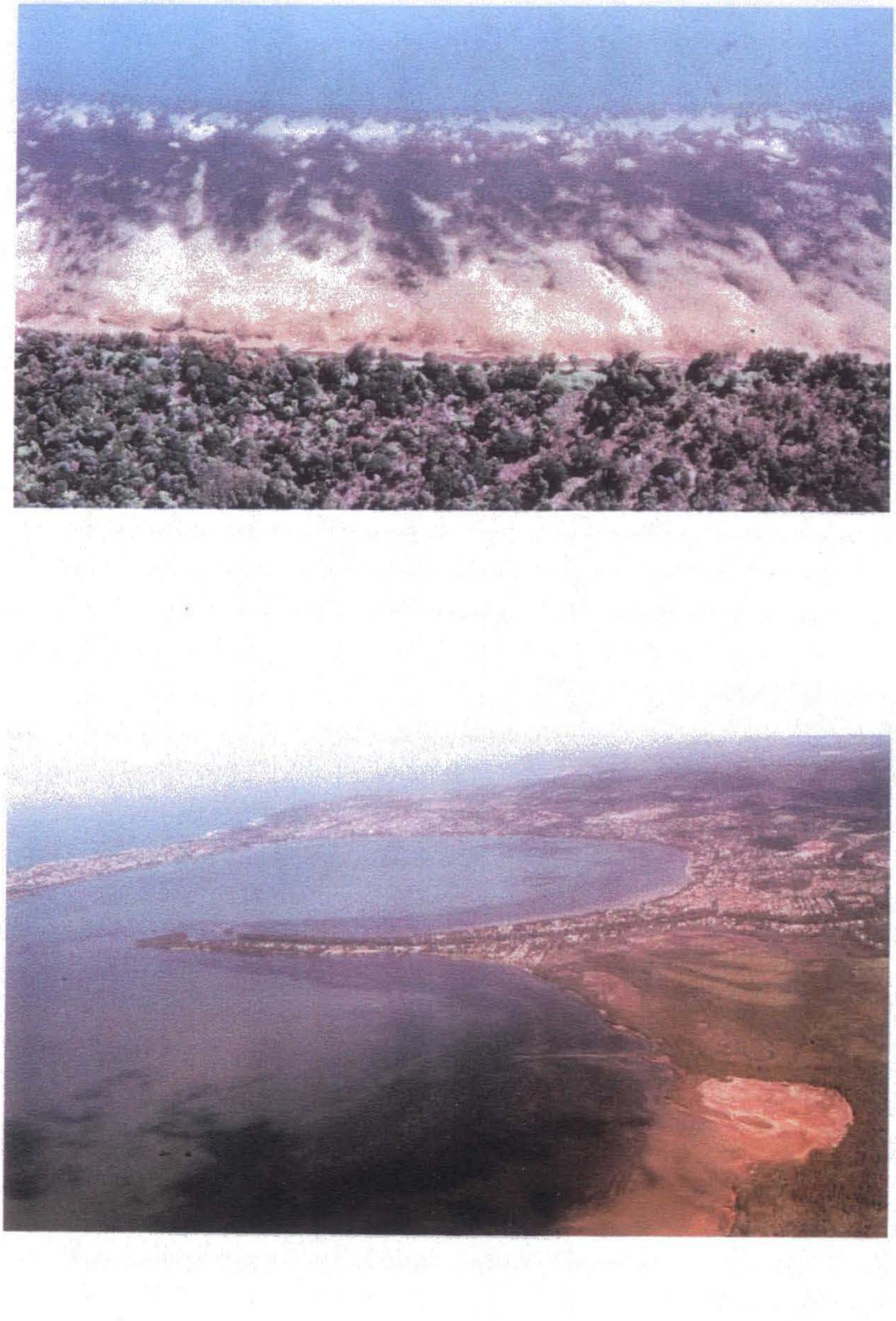

Figure 5. Barrier bank along eastern shoreline (Top) and Tuggerah Bay and Chittaway Bay (Bottom)

Figure 6. Budgewoi sandmass (Top) and Lake Munmorah (Bottom)

2.2.2. Distribution of Sediments in the Tuggerah Lakes Estuary

2.2.2.1. Introduction

The bottom sediments in an estuary provide one of the major habitats from which many significant ecological interactions occur The interections that occur between the biota and their environment and knowledge of the characteristics and distribution of the sediments is essential to understanding these processes Estuarine sediments strongly interact with the over-lying surface waters and can modify physical, chemical and biological processes They are derived principally from riverine sources although in some estuaries the sea also provides sandy material brought in during storms and by strong tidal currents The characteristics of bottom sediments are generally described by their particle size distribution and for Tuggerah were first examined by Roy and Peat (1973) To be able to generalise about sedimentary processes within the Tuggerah Lakes estuary, Dickinson (1997) examined the sediments at various spatial scales and earlier studies were used to assess potential changes to sediment composition and distribution (Dickinson and Roberts, 1999)

2.2.2.2. Methods

The sediments within the estuary were originally mapped by Roy and Peat (1973) and reproduced in the report by the Inter-Departmental Committee (1979) (Figure 7) In the present study, the estuary was arbitrarily divided into six locations based on its flushing characteristics to determine if there were large-scale spatial variations in the composition of sediments (Figure 8) Within each location, two random sites were examined and within each site four zones were sampled, three from within seagrass and one from within the deeper open water habitat This was done to examine whether any pattern of zonation occurred from the shore Within each of these zones, three random cores were collected The samples were obtained using a 50mm diameter core made of polycarbonate, which was inserted to a maximum depth of 300mm The top 10cm of the sample was removed and homogenised before being transferred to a container The sample was frozen to minimise further biological or chemical activity The sediment samples were washed through a 500mm sieve to remove the larger material, which could damage the instrument used to analyse particle size Each sample was further homogenised to ensure that the effects of settling were removed A random portion of the homogenised sample was dosed with a chemical dispersent to remove inter-particle forces

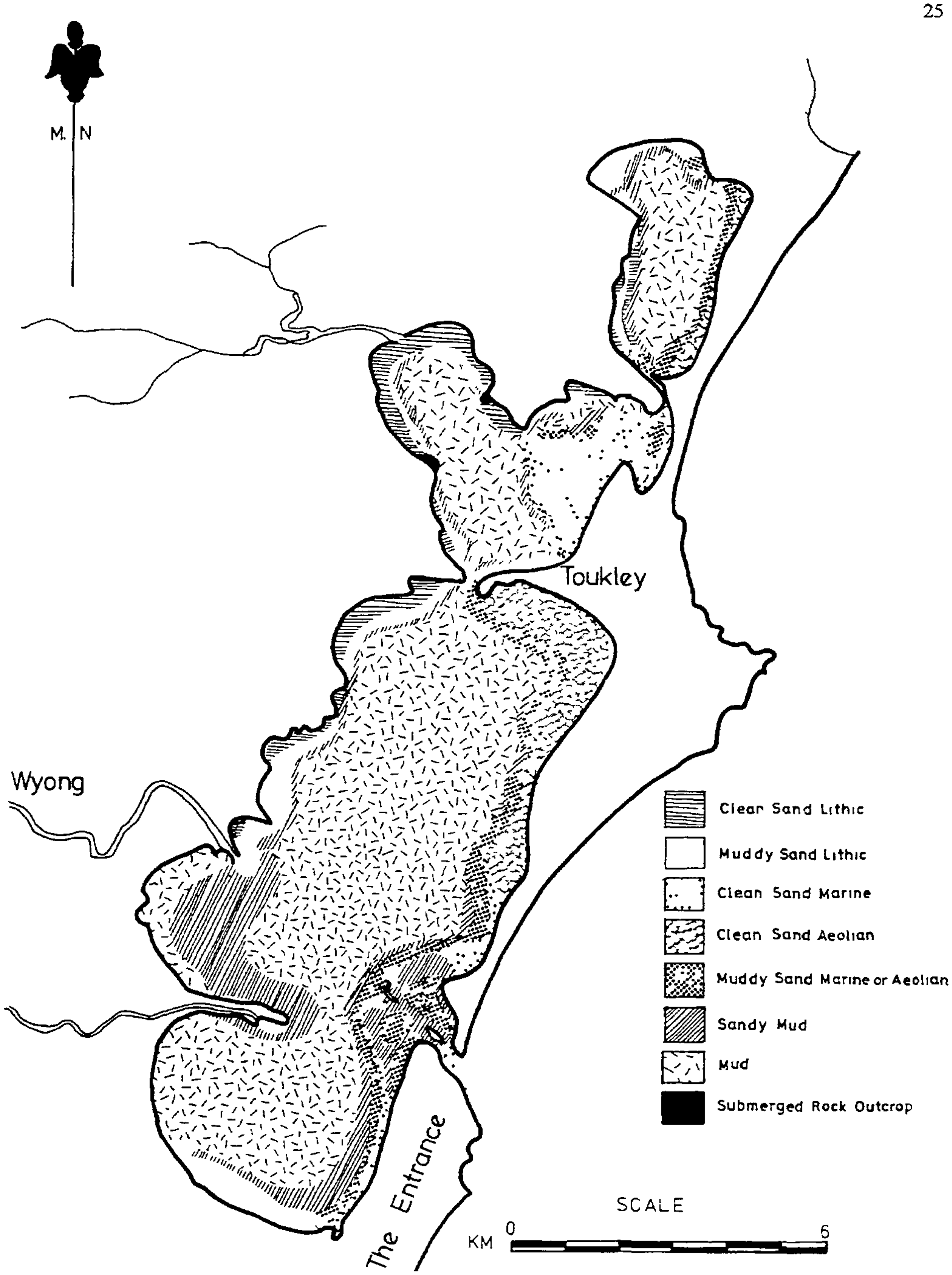

Figure 7. Bottom sediment types of the estuary (After Inter-Departmental Committee, 1979)

The sediment samples were analysed based on the diameters of the particles within the sediment using a MALVERN® Laser Particle Size Analyser. The output from this analysis provided information on the d_{10}, d_{50} and d_{90} particle size distributions (Dickinson, 1997), which refer to the percentage of material found below the reported diameter Analysis of variance (ANOVA) was used to determine differences in sediment particle size between locations, sites and zones (Dickinson, 1997)

2.2.2.3. Results and Discussion

Dickinson (1997) found that for each of the three derived particle sizes, d_{10}, d_{50} and d_{90}, no significant differences could be found between the six locations. There were significant differences between sites nested within locations with open water sediments consistently having smaller particle sizes than sediments within seagrass habitats This pattern was different in Lake Munmorah, where the shallow sediments were as fine as the deeper sediments (Dickinson, 1997) There were no patterns of zonation in sediment particle size within any of the seagrass habitats (Dickinson, 1997)

The particle sizes of sediments within seagrass habitats were generally uniform in their distribution but generally larger than those found within the open water habitats (Dickinson, 1997) There were significant differences between sites within a location, reflecting the changing geomorphological characteristic at these small spatial scales Submersed aquatic vegetation (seagrasses, macroalgae and emergent macrophytes) can slow water movement allowing suspended particles to settle The pattern of sediments at a particular place in the estuary reflected its past and present geomorphology and the rates at which active sedimentary processes were occurring The flow of water between the seagrass habitats and open water in the estuary are not well understood and further work on this is being done

Stormwater can carry various quantities of sediments into the estuary depending on the size and level of disturbance within individual catchments The sediments close to stormwater and other inflows should reflect the characteristics of these catchments Catchments soils, which are predominantly clay and silt, are more likely to produce finer sediments in the near vicinity of their discharge points compared with those where there are sandy clay soils

Coarse sediment being conveyed in stormwater will not encounter sufficient velocity in the nearshore zones to transport it to the deep areas of the lake That is, the nearshore zones act as an efficient sediment trap The only sediments capable of moving through and past the nearshore zones are those with very low settling velocities (fine sediments). It is reasonable to assume that the nearshore zones will receive coarse sediment and the deep zones receive the fine sediments from a given stormwater load. This explanation fits with both the flow and sedimentation patterns known to exist in the lake.

Lake Munmorah is the deepest of the three lakes with the majority of the open water between 2.5 and 3.5 metres in depth (Dickinson, 1997). The shallow sand banks are not established as shelves, as they are in the other two lakes, i.e. the floor slopes more gradually from shallow to deep allowing better mixing. In Lake Munmorah, the system takes advantage of both gravitational settling and velocity settling. The gravitational settling will tend to support the sediment migrating from nearshore to deep areas given the more significant slope. Gravitational settling in the other lakes is negated by the presence of the almost horizontal nearshore shelves.

Detailed sediment surveys were done by Roy and Peat (1973), and comparisons with this study provided a long-term assessment of changes in sediment distribution. The same classification scheme used by Roy and Peat (1973) was used in the comparison. Both large and small-scale patterns of change were evident with most nearshore sites around the estuary becoming muddier since 1973 (Figure 8). This trend was also apparent in areas where no development had occurred in the catchment (eg. the eastern side of Tuggerah Lake, Wyrrabalong National Park). The action of wind currents in the resuspension of the floor sediments of the estuary may be responsible for these patterns. Once these fine particles (with very slow settling velocities) are resuspended, they will only settle out in areas with slow water velocities, i.e. seagrass habitats.

The sediments within some seagrass habitats have become coarser over time and these can largely be related to localised disturbance, e.g. Chittaway Bay. This may be due to activities associated with the Tuggerah Lakes Restoration Project, where large amounts of silty deposits were removed and replaced with sand. These works involved the large-scale importation of sand, reshaping the shallow areas into a gradual slope and removal of seagrass beds.

Two anomalies in changes to the nearshore sediments were found in Tuggerah Bay and on the northern shore of Ourimbah Creek. The Tuggerah Bay site recorded increasec fine sediments near the shore and increased coarse material towards the outer edges. The northern shore of Ourimbah Creek also recorded an increase in sandy material. These patterns do not fit with previous discussions relating to flow and landuse (Tuggerah Bay is almost completely untouched and the other site has not undergone development since the

1973 study) Further work on establishing the source of these sediments would be required to isolate the reasons

Two deep sites off the North Entrance peninsula have become sandier since 1973 As part of the Tuggerah Lakes Restoration Project, an existing but relatively inactive channel was dredged, linking the deep-water sites directly with ocean water exchange at The Entrance The two sites are in line with this channel and would receive flow and corresponding sandier sediment loads from The Entrance channel Also, there is constant erosion of both the large tidal delta (relic for thousands of years) and the foreshore of North Entrance peninsula Both these geological features are sand dominated and wind wave action can reasonably be expected to produce gradual erosion These processes (as well as the local influence of the Canton Beach restoration work) may be responsible for producing sandier sediments at these sites

The Munmorah Power Station (active since the late 1960's) reversed natural flow between Budgewoi Lake and Lake Munmorah, such that water was extracted from Munmorah and pumped into Budgewoi This action is responsible for relatively fast flow (in terms of normal lake velocities) past the Budgewoi sandmass and into Lake Munmorah This process could be expected to erode the sandmass and transport the sandy material to the next point of slow flow in Lake Munmorah The result of the interaction of these processes is a deposition of coarser sediment into Lake Munmorah's southern deep-water areas

A number of generalisations can be made regarding the spatial distribution of sediments in the Tuggerah Lakes estuary

- Sediments in seagrass habitats are much sandier than in deep habitats
- Considerable spatial variation occurs within a location due to catchment input
- No significant differences were found in particle size of sediments between locations

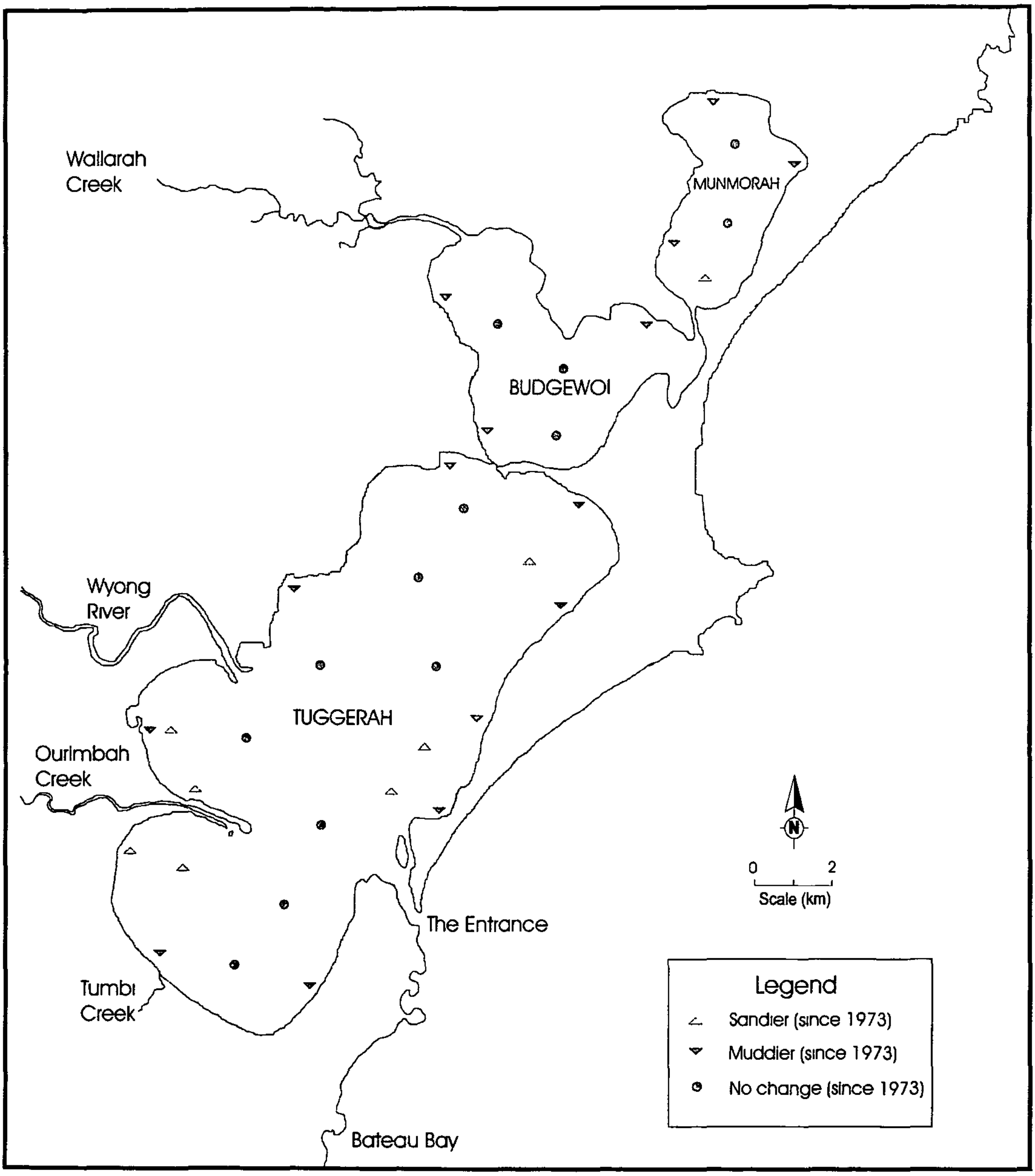

Figure 8 Changes to particle size distribution in the estuary

2.2.3. Sediment Dynamics within the Tuggerah Lakes Estuary

2.2.3.1. Introduction

Estuaries generally act as a sink for sediments that are eroded from the catchment There have been many statements made about increased sedimentation causing the infilling of the Tuggerah estuary and public opinion is that the estuary is much shallower than it was 20 years ago In 1975, the NSW Department of Public Works (PWD) undertook a bathymetric survey of the Tuggerah estuary in 1975 (Figure 9) and compared it with earlier surveys to establish rates of sedimentation (Inter-Departmental Committee, 1979) Estimates of the total amount of sedimentation over the last 25 years were made by repeating the survey and contrasting it with those done in 1975 (Dickinson and Roberts, 1999) to identify areas of sediment accretion and erosion, and determine sedimentation rates (+ve or -ve)

2.2.3.2. Methods

The bathymetry of the estuary was establsihed using depth soundings recorded using a RATHYEON® DEMKII echo sounder (Dickinson and Roberts, 1999) The unit consisted of a transducer and trace recorder, which was calibrated at various stages throughout the survey The estuary was surveyed by running parallel transects in a north-west to south-east direction with each transect beginning in shallow water generally at the edge of the seagrass meadow At the start of each transect, a Global Positioning System (GPS) fix was recorded, to locate its position The surveys were done maintaining an approximate groundspeed of four knots to ensure good resolution on the trace The trace recordings were analysed to find points where the recording crossed recognised depth marks on the plot The resultant data were entered into a Geographic Information System (GIS) GENEMAP, which enabled the position of the depths to be plotted on a map of the estuary

Natural variation in the depth of an estuary occurs over geological time scales and smaller time scales affected by climatic events These events (generally wind, river flow and tidal flux) have the potential to influence the estuary on a daily basis For this reason, the recorded levels were adjusted to a base level of 0 2m AHD averaged over the last 5 years This was also the value used in the 1975 survey Hourly records of depth were obtained from Manly Hydraulic Laboratory (MHL) from gauging stations at Toukley and Wallarah Creek and adjusted appropriately The error associated with the depths in the survey was ± 0 05m, whilst the positional error was ± 100m The error associated with comparing the two depths was ± 0 15m For this reason, areas that accumulated sediment (since 1975) at a rate of less than 6mm/yr were not reported as areas of significant change

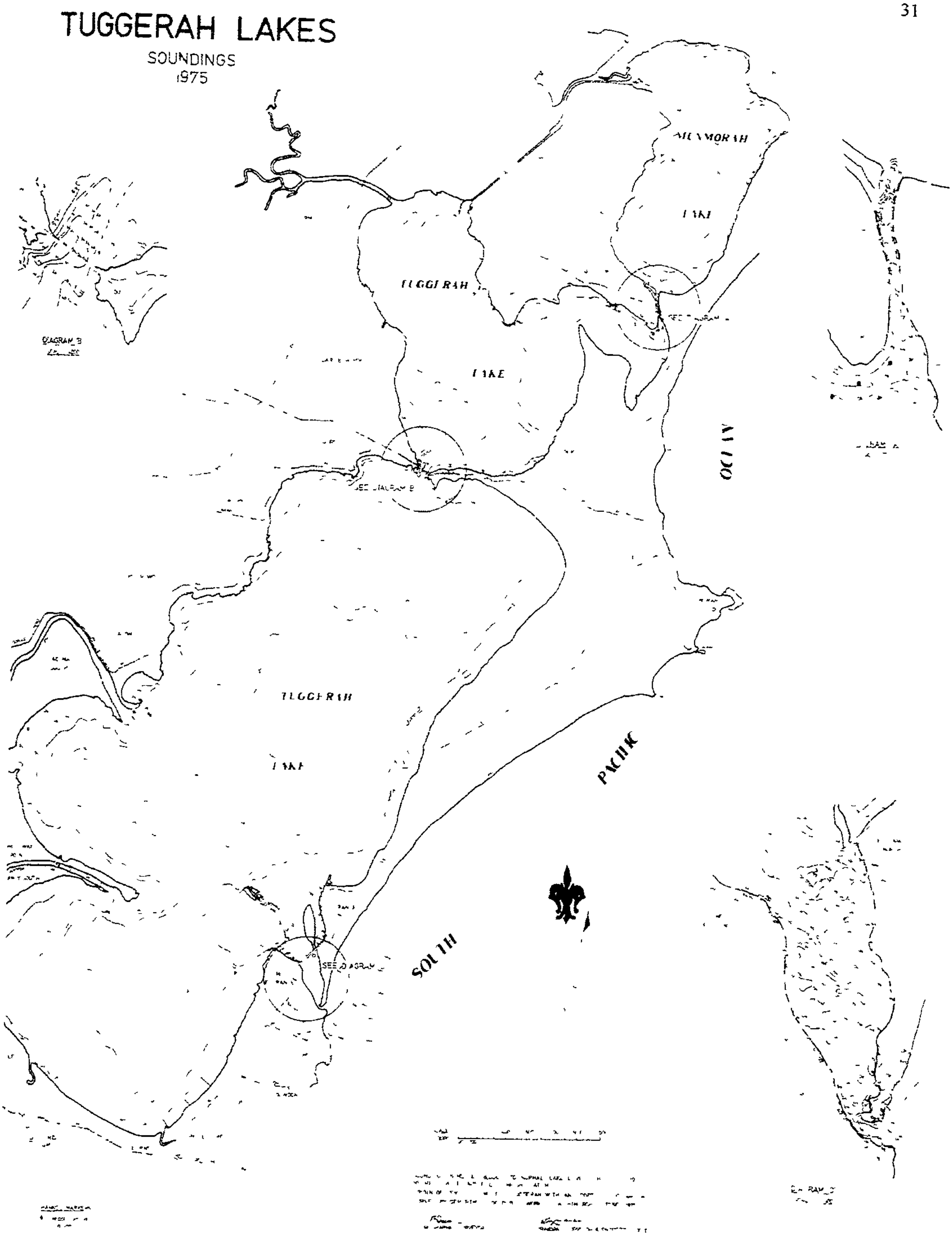

Figure 9. Bathymetry of the estuary in 1975 (after Inter-Departmental Committee, 1975)

2.2.3.3. Results and Discussion

Sediment accretion of 0 5m over 30 years was reported in the earlier bathymetric studies (Inter-Departmental Committee, 1979), however there was little evidence of infilling of sediments in the estuary based on the recent bathymetric survey Some areas of deposition were found at the entrance to Lake Munmorah, within Tuggerah Bay and below Pelican Island in the southern most part of Tuggerah (Figure 10) Small-scale scouring has occurred at various places including Budgewoi Channel, Munmorah Power Station inlet, Buff Point, Budgewoi Sandmass, north of Terilbah Channel and off Ourimbah Creek delta This scouring varies in magnitude from approximately 1m near the sandmass to 0 3m just north of Budgewoi Channel Significant increases in depth occurred in the northern area of Lake Munmorah (approximately 1m) and in the north-west section of Budgewoi Lake (approximately 0 5m) since 1975 (Figure 10)

The primary aim here was to quantify the amount of sediment being introduced to the Tuggerah Lakes estuary It was thought that there would be an overall decrease in the depth of the estuary over the past 25 years given the results provided with the Inter-Departmental Committee (1979) report however the pattern of an overall reduction in the depth of the estuary was not found The most significant changes were those of increased depth in both Lake Munmorah and Budgewoi Lake, which may be due to subsidence caused by coal mining activities

There were two areas in the estuary where depths had decreased since 1975, both in Tuggerah Lake Tuggerah Bay decreased in depth by 0 3 - 0 5m with a calculated sedimentation rate of between 13 - 22mm/year This may be due to its close proximity to the active river deltas of Wyong River and Ourimbah Creek (Dickinson and Roberts, 1999). Tidal flow from the entrance could also provide a source of sediments for Tuggerah Bay Extensive seagrass meadows occur in Tuggerah Bay, which could also cause entrained material to settle as water velocities decreased

A decrease in depth of approximately 0 5 ± 0 15m was found to the south of the Ourimbah Creek delta, within Chittaway Bay which equates to a sedimentation rate of approximately 22mm/year The interaction of flow from both Ourimbah Creek and The Entrance could be expected to produce a circulating flow pattern Water flows from the entrance channel to the south (past Picnic Point) and continues out into Chittaway Bay, whilst the flow from Ourimbah Creek is also south Both of these inflows would produce a current around the edge of the system, which would make central parts of this area of the estuary much slower and therefore more conducive to sedimentation

Erosion due to scour and dredging activities was evident at a number of areas around the estuary. There were significant increases in depth along the Terilbah Island channel due to dredging. Sediment erosion occurred along the northern shore of the large tidal delta at The Entrance, west of Terilbah Channel whilst scouring occurred at the mouth of Wallarah Creek and at the Munmorah Power Station inlet. The inlet in Lake Munmorah has been dredged to ensure that appropriate flow conditions are maintained for the power station. A small area at the mouth of Wallarah Creek has increased in depth since 1975, due to dredging. Areas around Budgewoi sandmass have increased in depth as a result of increased (above natural levels and direction) velocities moving through these areas. The channel running along the north-western shore of the sandmass has increased in depth by 0.8 ± 0.15m. The increased depth on the northern edge of Budgewoi Channel of 0.3 ± 0.15m is also linked to both the reversal and increased flows from the power station. The same jet like depositional process which may have produced the Pelican Island sedimentation area is likely to have resulted in the 0.5 ± 0.15m decrease in depth at the southern end of Lake Munmorah. Flow from Budgewoi Channel moves into a greater flow area, which will slow the velocity and aid sedimentation. The material being deposited is likely to be sediment eroded from the sandmass.

It is unlikely that the depths in the open water sections of the estuary would change because of development and corresponding stormwater runoff. Coarse (and therefore high volume) sediments readily settle under slow flow conditions whilst finer material will also settle in slower flow, though not as quickly. For this reason, sediments conveyed in stormwater are likely to be contained within the shallow seagrass meadows. Dickinson (1997) suggested that these habitats might be responsible for the deposition of fine material resuspended from the open water by wind action.

In summary, The Tuggerah Lakes estuary does not appear to be experiencing significant sedimentation. The areas of deposition are limited to the southern areas of Tuggerah Lake and are likely to be related to flow conditions and proximity to sediment sources (tidal and river deltas). Flows from the entrance channel, Ourimbah Creek and Wyong River are thought to interact and produce conditions that support deposition in some areas. These processes may be producing the depositional areas in Tuggerah Bay and south of Pelican Island. There has been some scouring in areas around the estuary, which can be related to localised processes. Depth increases near the Budgewoi Sandmass, Budgewoi Channel and Munmorah inlet are attributable to the power station. The influence of development and resultant sedimentation is probably limited to shallow-seagrass habitats. The effects of stormwater on these shallow habitats will be the focus of ongoing work on sedimentation.

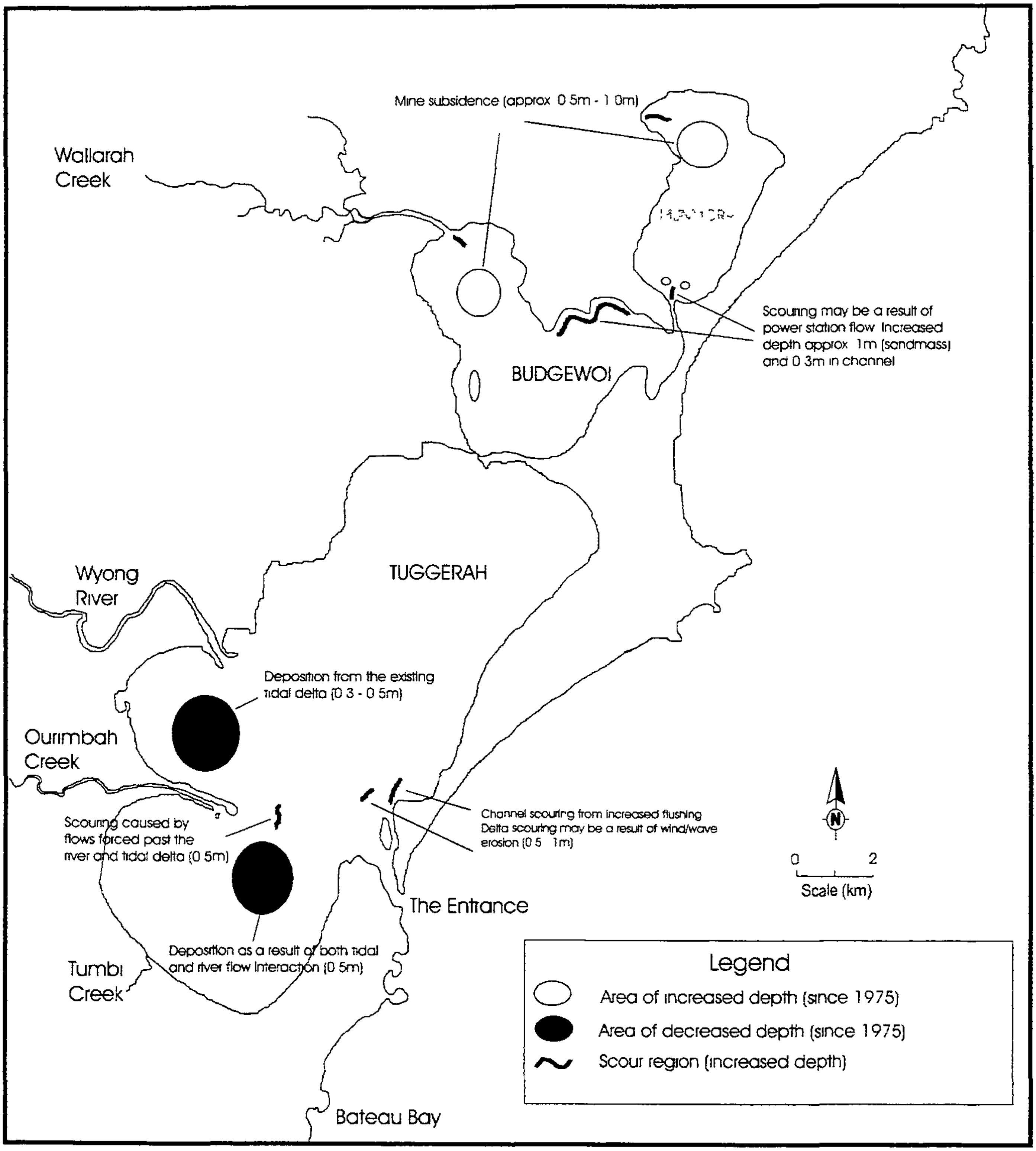

Figure 10. Changes to the bathymetry of the Tuggerah Lakes estuary since 1975

2.3. Hydrodynamics

2.3.1. The Circulation of Water in the Estuary

Water circulation is a physical process that plays an important role in the ecology of an estuary Estuarine circulation is generally thought of as the 'average' flow patterns in an estuary implying that the short-term motions such as turbulence and sporadic flood-induced flows occur in addition to this average circulation The short- term turbulent motions are also important, as the intensity of these motions determines the degree of mixing between adjacent water patches that are moving with the circulation Computation of material fluxes (eg nutrients, pollutants, salinity etc) requires an understanding of the water circulation and mixing characteristics within an estuary

Circulation can never be determined from a single set of instantaneous measurements but represents a calculated quantity that requires systematic measurements over a number of temporal scales (Kjerfve, 1979) The time-averaged currents that contribute to estuarine circulation also vary depending on the location in the estuary and the depth at which an estimate is made These include, tidal currents, tidal residuals, gravitational currents, wind driven currents and non-tidal flows (Day *et al.*, 1989)

The water circulation and mixing characteristics determine the residence time of a given parcel of water The residence time provides a useful measure of the effects of circulation and mixing and can be readily compared to the bio-geochemical time scales The ratio of the residence time of the water to the bio-geochemical turnover rates provides an indication of the degree to which the hydrodynamics (circulation and mixing) influence the water quality and biotic response of the system (Day *et al* , 1989) This ratio will typically vary both in both space and time At locations where the ratio is small (residence time shorter than the bio-geochemical turnover rates) there is generally good flushing and hence little chance for accumulation of dissolved substances Conversely where the ratio is large (residence time longer than the bio-geochemical turnover rates) there exists good potential for the accumulation of dissolved substances and the associated trophic response

As part of the adaptive environmental assessment and management program, Hunter (1996) used a hydrodynamic numerical model to simulate the flows resulting from a range of forcing inputs Simulation results for steady-state wind driven circulation for different wind speeds and directions, as well as time dependent flows due to the tides were produced In addition a "particle tracking" algorithm was used to illustrate the dispersive characteristics of the tidal flows The results demonstrated the complex nature of the flow patterns and circulation in the system The steady state flow patterns were achieved only after a considerable spin-up time (weeks) of constant wind, implying that the wind driven circulation rarely attains a steady state because the winds are changing over shorter time scales (days) Furthermore the circulation will be a dynamic feature that is continually changing in response to changes in wind speed and direction and the tidal currents

2.3.1.1. Types of Estuarine Circulation

External energy sources must be applied to the water to cause water movement The energy that drives estuarine circulation is derived from solar heating, astronomical tides, wind and fresh water inputs Solar heating differentials and fresh water inflows can cause horizontal variability in the water temperature and salinity resulting in water density gradients that cause flow adjustments known as gravitational flows Rainfall effects estuaries by the energy and mass associated with fresh water inflows from rivers Wind stress on the water surface causes a range of flows and the tides cause periodic motions all of which contribute to the general circulation (Day *et al*, 1989)

The geometry and bathymetry of the estuary are also important for modifying the circulation patterns, however they are considered passive processes (Kjerfve, 1979) Human activities that may affect circulation patterns include dredging, channel diversion, breakwaters and regulation of the rivers and creeks entering the estuary The three main driving forces for water circulation in an estuary are gravitational (density differences between fresh and salt water due to heating or freshwater inflows), tidal (regular rise and fall), and wind (large expanses of water, shallow depth, small tidal range and low freshwater inflow) In the Tuggerah Lake estuary, long period oceanic water level oscillations may also form an important contribution to exchange with the ocean The resultant flows due to the forcing inputs interact to form complex circulation patterns at various spatial and temporal scales The flow patterns produced by each of these inputs is discussed below in relation to the Tuggerah Lakes estuary

2.3.1.2. Gravitational Circulation

Gravitational circulation patterns are caused by horizontal density differences resulting from freshwater runoff entering saline waters and/or temperature differences caused by spatially variable rates of heating (eg shallow waters heat quicker and hence become warmer than deeper waters) In the absence of mixing, fresh water will remain as a surface layer because lighter fresh water will float on heavier saltwater resulting in a stable vertical stratification Similarly, warmer water is lighter and floats over colder water Turbulence generated by tidal and wind driven currents causes mixing of the water column, resulting in vertical exchange between surface and bottom waters Gravitational circulation in an estuary is therefore primarily related to its salinity and temperature characteristics Gravitational circulation within the Tuggerah estuary may therefore be important in summer when temperatures are high or immediately after rainfall events (van Senden, 1997) Further, the gravitational circulation varies in space and time and hence this type of flow is probably important for water exchange between the following areas

- shallow fringing areas and deeper central basins,
- between the rivers and the estuary during low river flow, and
- between the major basins and ocean following large freshwater inputs

2.3.1.3. Tidal Circulation

In the absence of density gradients and wind stress, tidal currents (tidal pumping) can dominate the circulation patterns The complex interaction between tidal currents and bathymetry produces non-tidal flows that may remain well beyond the tidal period (Day *et al*, 1989) Bathymetric variations interact with the tidal currents such that the ebb flow patterns are different to the flood flow patterns (both horizontal and vertical patterns) and this asymmetry of the tidal flows results in mixing and exchange This type of circulation is highly pronounced in estuaries that are shallow with large tidal ranges

In the Tuggerah estuary the flow through the entrance channel is driven by tides, longer period oscillations and density currents (van Senden, 1997) The flood tide brings heavier saline water into the estuary, which forms a density current that flows into the deeper parts of Tuggerah Lake (van Senden, 1997) During the subsequent ebb tide, only waters located near to the entrance are ejected and hence this effect is quite efficient at causing exchange Even though this effect is quite efficient, the low tidal range in the estuary (2-3 cm) and its large volume mean that it takes a large number of tidal cycles to exchange the estuary volume

2.3.1.4. Wind-Driven Circulation

Large expanses of open water, shallow depths, small tidal ranges and low freshwater inflows favour wind-driven circulation Wind driven circulation is often masked by gravitational and tidal circulation Wind is highly variable and can change on scales from minutes, days, weeks and seasons Where winds are steady and tend to blow along-estuary, wind stress will generate significant currents Hunter (1996) found that in the Tuggerah estuary, the current tended to flow in the direction of the wind in shallow water and against the wind in deeper water Furthermore, circulation was found to be dominated by horizontal movements however overturning was also quite important Wind driven currents would mix the estuary within about 12 days with a vertical mixing time of around 3 hours

The wind driven circulation of in the Tuggerah estuary seldom achieves a steady state because of the complex temporal and spatial variations and the relatively long response time of the estuary to changes in the wind field Alterations from one type of circulation pattern to another will change with variations in wind stress, river discharge rates, tidal ranges and slow changes to mean sea levels brought on by meteorological forcing of coastal waters by atmospheric pressure systems

2.3.2. Mixing within the Estuary

Mixing is the process whereby neighbouring water masses tend to coalesce or dilute each other (Day *et al*, 1989) There are two types of mixing (1) advective (long-term) due to general circulation patterns and (2) dispersive (short-term) due to turbulent motions Salinity is the most commonly used indicator of mixing in an estuary because it is easy and inexpensive to measure and it is conservative and is not changed by bio-geochemical processes The energy required to mix estuaries is derived from several sources, tidal forcing, wind stress, wave motion and river runoff Tidal forcing is the most important as interactions between tidal currents and estuarine boundaries generate significant turbulence on a regular basis In the Tuggerah estuary, wind stress, at times of moderate to strong winds, will be more important than the relatively small tidal flows, as the estuary surface area is large and shallow and hence a well developed sea state occurs with waves and white caps producing turbulence

Density differences in an estuary can play two important roles, (1) the horizontal gradients cause gravitational flows and (2) vertical stratification inhibits mixing and exchange because the turbulent motions must overcome the potential energy of the stratification to cause overturning The degree of mixing in an estuary is dynamic and important to ecological interactions In the main basin of the Tuggerah Lake, the estuary may be classed as being well mixed, whilst in the riverine portions the estuarine waters are partially mixed

2.3.3. Flushing of the Tuggerah Lakes Estuary

To be able to determine the flushing characteristics of an estuary, information on its circulation and mixing is required. The flushing characteristics of the Tuggerah estuary were assessed and the mechanisms causing water exchange described over a number of spatial scales (van Senden, 1997). Estimates of flushing in the estuary were derived from salinity data, collected by Wyong Shire Council (Figure 11), and found to vary over a number of spatial scales.

For the shallow fringing areas, the important mechanisms for flushing were diurnal heating and cooling cycles and freshwater inflow from local catchments (including stormwater drains) that caused gravitational flows. The tidal and wind driven flows were also likely to be important, but there were few data collected that could be used to assess their relative importance. These dynamic features generate very small currents but still produce significant mass transport and exchange between the shallow fringing areas and the deeper waters. Flushing times for the shallow fringing areas were estimated to be around 5 to 10 days.

Flushing of the entire volume of the estuary by exchange between the lakes and the ocean is dominated by the combined effects of river inputs and the subsequent gravitational flows following large runoff events, tidal motions and longer period oceanic oscillations. The combined effects give a flushing time of between 60 and 100 days. Flushing between the three main basins is predominantly wind driven with an average flushing time of about 12 days.

During low flow periods, the lower parts of the rivers where deep holes occurred, there was some evidence of sustained periods of vertical stratification and the associated effects on water quality (low dissolved oxygen and higher nutrient concentrations). These observations indicated that the residence time of deeper water in these deep holes is longer than the bio-geochemical turnover rates. The actual volume of water subjected to these processes is relatively small when compared to the estuary and hence the occurrence of poor water quality confined to the localised areas in the lower rivers.

under various
conditions.

Flushing
Map
indication of
flushing efficiency due
to tides under a
number of entrance
conditions
& Exchange Vol. with ocean

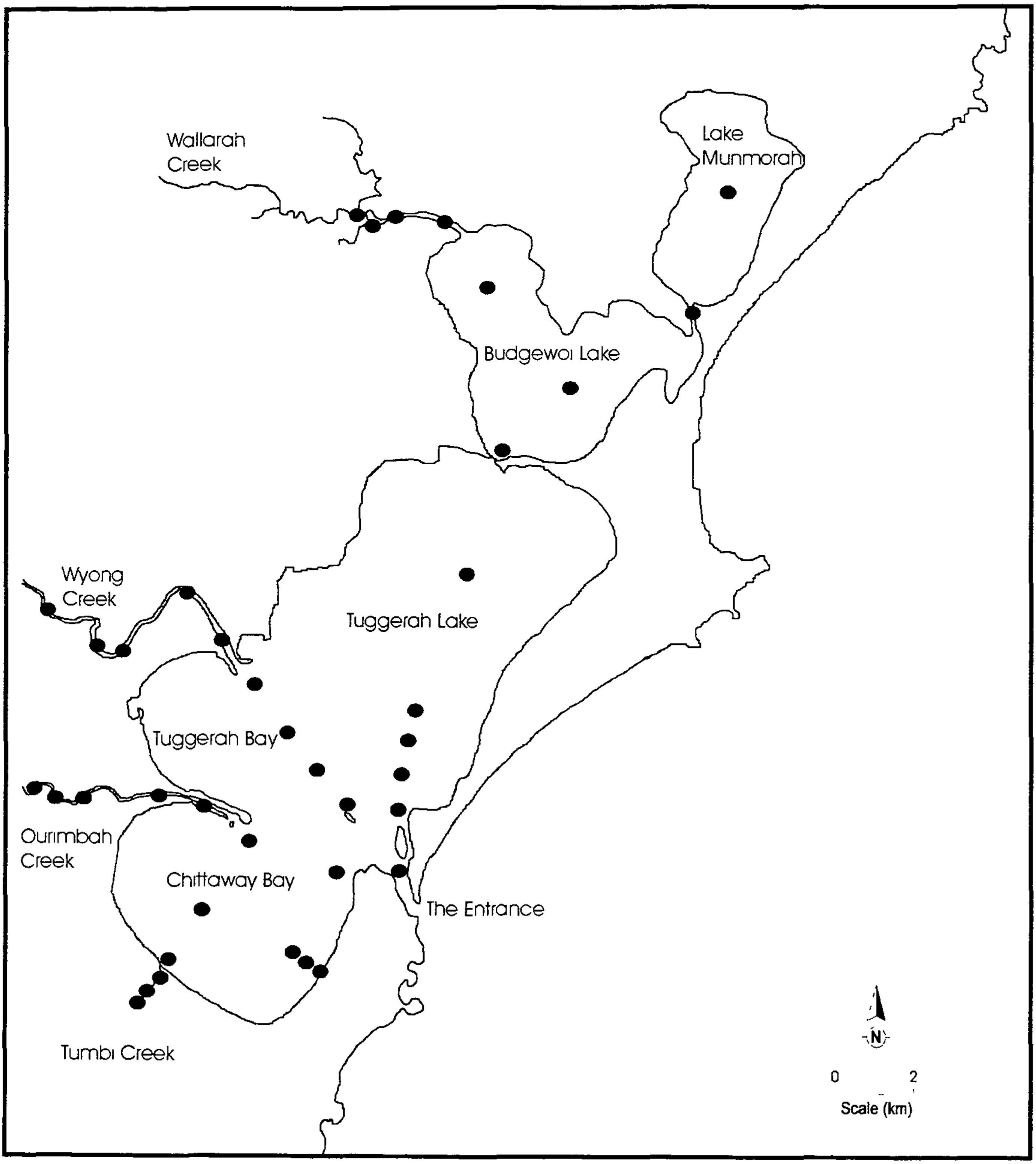

Figure 11 Location of water sampling sites used to determine flushing characterisics

2.3.4. The Behaviour of Floods in the Estuary

The Tuggerah Lakes estuary has a water surface area of approximately 75 square kilometres and receives approximately 95% of the catchment's runoff whilst the remaining 5% drains into Lake Macquarie (WSC, 1997) The Tuggerah Lakes estuary has a history of floods, which have been recorded either in Tuggerah Lake or in the Wyong River

The amount of rainfall from the upper catchment is a primary determinant of the peak height of floods in the estuary Manual records of rainfall events at Wyong have been kept since 1885 The first automatic continuous rainfall recorder was installed at Bateau Bay in 1980 There are now approximately twenty automatic rain gauges and water level gauges in the catchment Rainfall data is collected on a daily basis from stations located in and around the catchment, controlled by the Bureau of Meteorology, NSW Public Works, Wyong Shire Council and the Department of Land and Water Conservation Since the 1880's, significant floods have occurred during every month of the year except September Monthly rainfall and the occurrence of floods have always been greater between January and June (Table 1)

Table 1. Seasonal variation in rainfall and floods at Wyong

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	WHOLE YEAR
NO OF FLOODS SINCE 1888	1	3	4	5	4	6	1	2	0	1	2	1	---
AVERAGE RAINFALL SINCE 1885 (mm)	112	117	137	115	107	116	84	69	69	72	83	99	1196

In the case of a one-percent, annual exceedance probability (AEP) flood, there would be approximately 1800 residential floors flooded in the near vicinity of the estuary which does not include areas upstream on the Wyong River and other creeks For each additional centimetre of depth, approximately twenty additional floors would be flooded (1995 - 97 surveys of floor levels within the floodplain) Estimated flow rates for the entrance and Wyong River have been calculated for a 1% and 5% flood (Table 2)

Table 2 Estimated flow for The Entrance and Wyong River during 1 and 5 % floods

LOCATION	1 IN 100 YEAR FLOOD FLOW RATE 1% FLOW	1 IN 20 YEAR FLOOD FLOW RATE 5% FLOW
THE ENTRANCE CHANNEL	1500 cu m/sec (Lawson and Treloar, 1994)	1200 cu m/sec (WSC, 1992)
WYONG RIVER AT WYONG	2200 cu m/sec (Webb, McKeown & Associates, 1991)	1400 cu m/sec (WSC, 1992)

The major floods since 1927 (Table 3), have ranged in height from 0 4 - 2 1m above Australian Height Datum (AHD) During normal dry weather, the level of the estuary is approximately 0.2 metres AHD The level varies by approximately 0 05m due to daily tides, however it can range from 0 - 0 3 m AHD throughout the year depending on variations in ocean tides (WSC, 1994)

Table 3. Estimated 1% flood levels for various urban localities in Wyong Shire

LOCATION	1% FLOOD LEVEL
Tuggerah Lake, Budgewoi Lake, Lake Munmorah	2 2m AHD
Lake Macquarie	1 38m AHD
Tumbi Creek downstream of Wyong Road	2 72m AHD
Ourimbah Creek Downstream of Wyong Road	4 75m AHD
Wyong downstream of the railway	4 05m AHD
Wyong upstream of the Pacific Highway, Wyong	5 3m AHD
Wallarah Creek at Spring Creek Junction	2 2m AHD
Bangalow Creek at Brush Road, Ourimbah	16 9m AHD

Most historical references to floods around the Tuggerah Lakes estuary have been obtained from newspaper articles and from interviews with long-term residents Photographic evidence collected from long-term residents in the area covers flooding history from 1929 - 1949 This information was used for flood studies in the areas of Wyong River and Tuggerah Lake The most severe flooding occurred during the years 1889, 1927, 1946 and 1964

The size of floods of various dates is known to be different at different locations because of the non-uniform amount of rainfall, which occurs across the catchment during any given event For example, lower Ourimbah Creek was moderately flooded during 1992, whereas that particular storm event was not recorded elsewhere in the Shire Severe storm events at Wyong generally result in severe flooding events in the estuary, because Wyong River valley constitutes a large proportion of the area draining into the estuary

Flood studies were done during 1978-94 to determine the extent of flooding within the major catchments close to the estuary Upstream areas, such as the rural parts of Ourimbah Creek and Wyong River were not included in studies up to 1994 A study was completed for upper Ourimbah Creek, and an extensive study of Wyong and Jilliby Valleys commenced in 1996 by COAL Pty Ltd All previous studies were done by Wyong Shire Council or the NSW Government

2.3.4.1. Entrance Tidal Exchange and Flooding

The connection to the sea at The Entrance is believed to be an important factor controlling the behaviour of floods in Tuggerah Lake. Under normal climatic conditions, the entrance to the sea develops near the southern headland where the depth of potential erosion is restricted due to the bedrock formation. During floods, the sand barrier is scoured both vertically and horizontally. With a flood tide, the channel fills with an influx of marine sands, which leads to a gradual closure. Without dredging, this closure can last from several months to a year (WSC, 1993). The difference between peak flood heights with the entrance channel partially opened or fully closed would be small.

2.3.4.2. Flood Forecasting System

Wyong Council has established a flood forecasting system that uses data collected from ten automated stations around the catchment, as well as ocean tide data. The system uses a computer model to predict flood heights by approximately 12 hours in Tuggerah Lake, Wyong River and Ourimbah Creek. The Bureau of Meteorology system and Council's system would be utilised to assist the State of Emergency Services to plan any operational tasks during a flood event. Some instruments are programmed to automatically send warnings to the State Emergency Services in case of a flood.

The rivers and creeks within the Shire tend to flood differently compared with the estuary. Close to the estuary, the State Emergency Services would have sufficient time to be able to predict the flood level for all properties. During flooding, up to 5000 properties could be affected to varying degrees. The duration of the flood may last up to one week, however there would be almost no velocity of flow and the immediate danger to people would be low. The major problems associated with flooding of the estuary would be waves caused by winds or by the wake of vehicles, closure of local roads and lack of amenity as sewer systems became inundated and overflowed. A further investigation into the management of public health during these times is required. Flooding in the rivers and creeks could be more serious as water levels could rise in hours rather than days, and warning times for evacuation would be much less compared with the estuary.

History of closure?!

what sort of entrance do we get between low flow & hi flow conditions?

3. CHEMICAL PROCESSES AND INTERACTIONS

The existence and rate of activity of biological communities in estuaries can be largely influenced by the physical and chemical processes that transport and transform materials and energy between and within individual organisms Sunlight is transformed into organic rich substances by photosynthetic and chemosynthetic processes This organic matter is the fuel for biological activity and as the energy in these substances is used, it is dissipated as heat As this occurs the chemicals (or building blocks) are taken up and released as organic matter, and changed from one form to another Therefore, energy tends to flow through an estuarine ecosystem from sulight, to organic matter, to heat, while the chemical constituents of organisms are continually recycled through the water, sediments and atmosphere The compositon of fresh water (in terms of its species and dissolved substances) varies considerably, whilst seawater is quite uniform in its basic constituents When river water mixes with seawater the constituents are changed by dilution or they undergo transformations in response to physical, chemical and biological processes Water and sediments are the mediums in which most of these processes occur

3.1. Water Quality

Estuaries are complex ecosystems because they are the place where fresh water mixes with seawater Floods can deliver large amounts of organic and inorganic material to the receiving waters of an estuary, and where there is little water exchange with the ocean the estuary can become a sink for these materials (Harris, 1996, Scanes *et al*, 1997) Rural and urban development activities have increased sediment and nutrient loads entering coastal waters however, it has been shown that these catchment contributions are mainly episodic, and as yet, poorly defined (Harris, 1996, Pritchard, 1997) Rainfall, which has El Nino Southern Oscillation (ENSO) as well as seasonal patterns, drives these catchment contributions, with ENSO typically responsible for up to 40% of the variance in eastern Australian rainfall (Partridge, 1994) Flow regulation (water extraction, impoundment and changes to flow regimes) further alters the variation in freshwater inputs, impacting processes and altering the balance of external versus internal loads and diffuse versus point sources of nutrients (Harris, 1996)

Nitrogen and phosphorous are considered key nutrients responsible for plant growth and the degree to which they are modified is largely determined by factors such as depth, flushing time, river flow, dissolved oxygen and a number of biological interactions at a number of scales (Boynton *et al.*, 1997). In shallow (< 20m) enclosed-systems, a large fraction of the incoming nutrients will be deposited to bottom sediments where they may become stored, transformed or recycled depending on sediment processes (Boynton *et al.*, 1997). Nitrogen cycling is more complex than phosphorous, with transformations occurring between the different nitrogen species (Eyre and Twigg, 1997). If there are surplus nutrients entering from the catchment, an estuary has the potential to become eutrophic (nutrient enriched) and develop plant biomass (usually algae) that can severely alter ecosystem structure and function (Boynton *et al.*, 1995). As well as the ecological consequences, reductions to commercial fisheries, diminished recreational amenity, and costs associated with nutrient removal can result in large economic impacts at local and regional scales (Fisher *et al.*, 1992; Boynton, 1997).

To preserve the health and integrity of the Tuggerah Lakes estuary, management strategies need to be developed to mitigate the potential effects of increasing human activities (Walkerden and Gilmour, 1996; Boynton, 1997). To be effective, strategies need to be based on a sound understanding of the key processes operating within the system, relative to perceived disturbances such as nutrient enrichment, increased levels of suspended particulate materials and flow regulation (Harris, 1996; Scanes *et al.*, 1997). Furthermore, they must pre-empt and proactively manage potential impacts to the system (Abal *et al.*, 1998). The determination of the water quality, particularly its nutrient status, is an important aspect of any estuary management program (Coade, 1997). Water quality in the Wyong Shire has been measured in the past for a variety of reasons, including water supply and environmental quality.

3.1.1. Summary of Catchment Water Quality

There have been a number of studies done on the water quality within the Wyong catchment's rivers and creeks (Jones, 1993, Boake, 1991, Martin and Arago, 1997, Towell, 1999). Boake (1991) found high concentrations of nutrients in Burning Creek, Springs Road (Ourimbah) and Durren Road (Jilliby). High levels of nitrogen at Springs Road were attributed to intensive market gardening in the area. Apart from market gardening in the upper reaches of Ourimbah Creek, no link could be established between landuse and levels of nutrients in the water. Boake (1991) suggested that phosphorus was the main limiting nutrient within the creeks. Martin and Arago (1997) examined the effects of turf farming in the Wyong River and reported large-scale variability that would be expected in rivers due to changes in flow, runoff and other factors (The Ecology Lab, 1999). Towell (1999) examined the water quality and instream ecology of Tumbi Creek, Ourimbah Creek, Wyong River, Wallarah Creek and Spring Creek with the aim of quantifying the condition of Wallarah Creek prior to major development in its catchment. Concentrations of total nitrogen and NOx were relatively high in Ourimbah Creek whilst phosphorus levels were low at all sites compared to Tumbi Creek. Wyong Shire Council has been collecting water quality data within the rivers and creeks in the upper catchments since 1988. The Ecology Lab reviewed these data and other reports to document spatial and temporal variability in water quality variables among sites sampled within the Ourimbah and Wyong catchments. The Wyong Shire Council data included physico-chemical measurements and concentrations of total phosphate, orthophosphate and total oxidisable nitrogen (The Ecology Lab, 1999). The data revealed three major flaws in that samples were unreplicated, many of the sites were not sampled on the same occasion and not all water quality variables were measured on each occasion. The flaws in the data restricted the types of analyses that could be applied (The Ecology Lab, 1999). The review of the data suggested that there were potential problems with elevated nitrogen (Nox) in Ourimbah Creek and phosphorus (TP and OP) in Wyong River (The Ecology Lab, 1999). It was highly recommended that the existing monitoring program be re-designed to incorporate current management objectives and that they be integrated with other sampling programs of stream flow, rainfall and instream ecology (The Ecology Lab, 1999). Water quality monitoring within the major tributaries creeks is now done at the same temporal scales as that done in the estuary

3.1.2. Summary of Water Quality in the Estuary (1963-1997)

Data on the quality of water in the Tuggerah Lakes estuary has been collected since 1963 The results presented here are from surface water measurements only and have been compiled from various sources, primarily King and Hodgson (1995) The data from 1963-66 were compiled from Higginson (1971), whilst the data collected by Pacific Power (formerly the Electricity Commission of NSW), as a result of its power station operations on Lake Munmorah and Budgewoi Lake, covered the period from 1973-91 The 1993-94 period, was summarised from Cheng (1996), whilst the 1995-97 period, was summarised from data collected by Wyong Shire Council It must be kept in mind that prior to 1997, most of these data were collected without any estimates of spatial or temporal error and therefore caution is advised interpreting these results

Average water temperatures in the estuary have fluctuated since 1963, with a general trend of increasing temperature in all three lakes (Figure 12) Budgewoi Lake appeared to undergo greater temporal changes in surface water temperature, probably because of power station operations King and Hodgson (1995) reported average surface water temperatures of around 12°C, whilst in summer they were as high as 28°C The temperature of water at the bottom ranged from 13°C to 27°C respectively The cooling water discharged from the Munmorah Power Station caused, on average, an increase of 7°C in the receiving waters The average water temperature for all three lakes has been around 20°C over the last few years (Figure 12) The pH of the water in the estuary increased from 7 9 to 8 1 over the 1963 to 1997 period (Figure 12) This increase is relatively small and not considered to be of any concern to the ecology of the estuary Significant changes to the pH of water can be detrimental to aquatic organisms, however these values were within the guidelines recommended by ANZECC (1992)

Long-term and large-scale fluctuations in salinity have occurred within the estuary since 1963 (Figure 12) During the 1963 to 1966 period, the salinity in the estuary was approximately 30ppt (seawater is approximately 32ppt – parts per thousand) In the 1973-1979 period the salinity decreased to an average of 20ppt Over the next few years it rose and fell in response to the rainfall characteristics of each period. In general, the salinity has remained around 30ppt since 1993 Large fluctuations in salinity can adversely affect aquatic organisms through direct toxicity and by modifying the structure and dynamics in the assemblages of plants and animals Long periods of relatively constant salinity within an estuary will tend to suit many estuarine organisms When floods occur, and salinity is reduced, significant reductions in assemblages of many organisms may occur

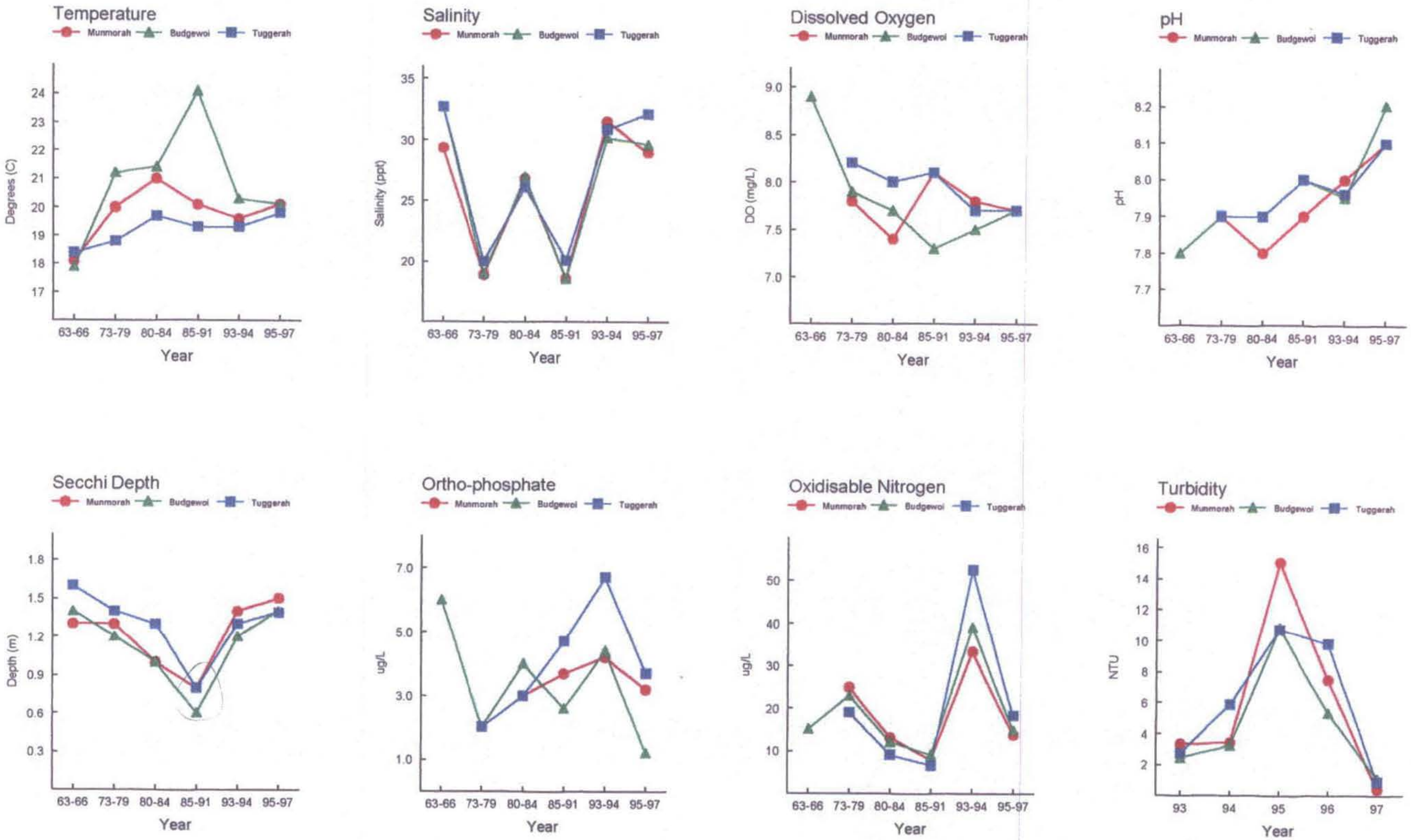

Figure 12. Summary of water quality in the estuary (1963-97)

There were significant spatial differences for dissolved oxygen (DO) concentrations within the three lakes and through time (Figure 12). The concentration of DO in the water is dependent on biological activity, atmospheric exchanges, salinity and temperature. Phytoplankton, macroalgae and seagrasses all produce oxygen during the day and remove it at night, which can result in considerable fluctuations in the amount of DO in the water over a 24 hour period. Due to these significant small-scale temporal interactions, single or spot measurements of dissolved oxygen in water are not that useful (ANZECC, 1992).

The amount of available light for the primary producers is an important limiting factor in the ecology of any estuary. Estimates of the euphotic zone or the depth to which plants can grow can be a very useful management tool. In Australia, over 45,000 ha of seagrass meadows have been lost as a direct result of decreased light availability associated with increased turbidity, eutrophication and epiphytic algal growth (Walker and McComb, 1992). There is evidence to suggest that the seagrass meadows within the Tuggerah Lakes estuary have declined since 1963 (see Seagrass Section). The depth of light penetration, estimated using secchi disc transparency, decreased between 1963 and 1991 but since 1993, the average secchi depth in the estuary has increased to levels that were found prior to the 1980's (Figure 12). The processes causing these apparent fluctuations in light regime are not known, but are related to fluctuations in suspended matter in the water column. Whether reduced clarity (measured by secchi depth) was due to increased suspended silt or biological material such as phytoplankton is unknown. The salinity regime during 1985-1991 was generally much lower than previous years (~20ppt), so maybe there was more suspended material in the water column from freshwater inflows. The amount of suspended material in the water column is currently estimated using a turbidity meter. Since 1993, the turbidity in all three lakes, at any one time, has been generally similar, but there were significant changes through time (Figures 12). The turbidity can change by an order of magnitude from morning to afternoon and from one day to the next, through the action of wind mixing.

Nitrogen and phosphorus are essential plant nutrients however, when they are found in high concentrations they can cause (given other factors are not limiting) nuisance growth of aquatic plants. The measurement of the concentrations of these nutrients within the water enables some determination of whether the estuary may be suffering from "over fertilisation". Nitrogen occurs in a number of forms with nitrates, nitrites and ammonia being those forms commonly available to plants. Phosphorus also occurs in water in both its dissolved and particulate forms. Nitrogen is generally the limiting nutrient available for plants in marine waters, whereas phosphorus is usually the limiting nutrient in freshwaters. In highly variable estuarine systems, it follows that nutrient limitation can vary both spatially and temporally and between the different types of primary producer and different species. The question of which nutrient may be limiting the growth of macroalgae within the Tuggerah Lakes estuary is currently being investigated and will be reported in the management study.

The historical nutrient data for the estuary is limited to temporal comparisons of the concentration of oxidisable nitrogen and ortho-phosphate, which are both biologically available to the primary producers. Oxidisable nitrogen and ortho-phosphate concentrations have fluctuated in the estuary since 1963 (Figure 12). The measurement of both these forms of nutrients is problematic since they can change very quickly in response to biological activity. The concentrations of these nutrients do not indicate the total amount of nutrient within the system because of the complex interactions that occur between the biota, sediments and the water column. Changes in nutrient concentrations within the estuary will be dealt with fully in the next section.

3.1.3. Physico-chemical Water Quality Program

A twelve-month program of monitoring physico-chemical water quality in the four major tributary creeks and within the estuary began in 1996 (Figure 13), to collect data for the hydrodymamic study (van Senden, 1997). Every two weeks, at fixed sites in the creeks and estuary, measurements of the temperature, conductivity, salinity, dissolved oxygen, pH, and turbidity were recorded using a Yeokal 611 data logger. At each site a secchi depth reading was taken whilst physico-chemical variables were measured at 0.5m depth intervals until the bottom was reached. The surface water data (0.5m) from each of four sites in the creeks and from most of the estuarine sites were summarised so that small-scale patterns over an annual cycle could be examined.

The water temperature within the four tributaries did not vary, however there were considerable fluctuations over the year (Figure 14). The period between June and August 1996 were the lowest for all four tributaries. Water temperature has a substantial influence on the chemical reactions and physiology of biological organisms as significant changes can affect the growth, metabolism and reproductive status of some aquatic organisms. The water temperature changes within the estuarine sections of the tributaries were acceptable under the current ANZECC (1992) guidelines.

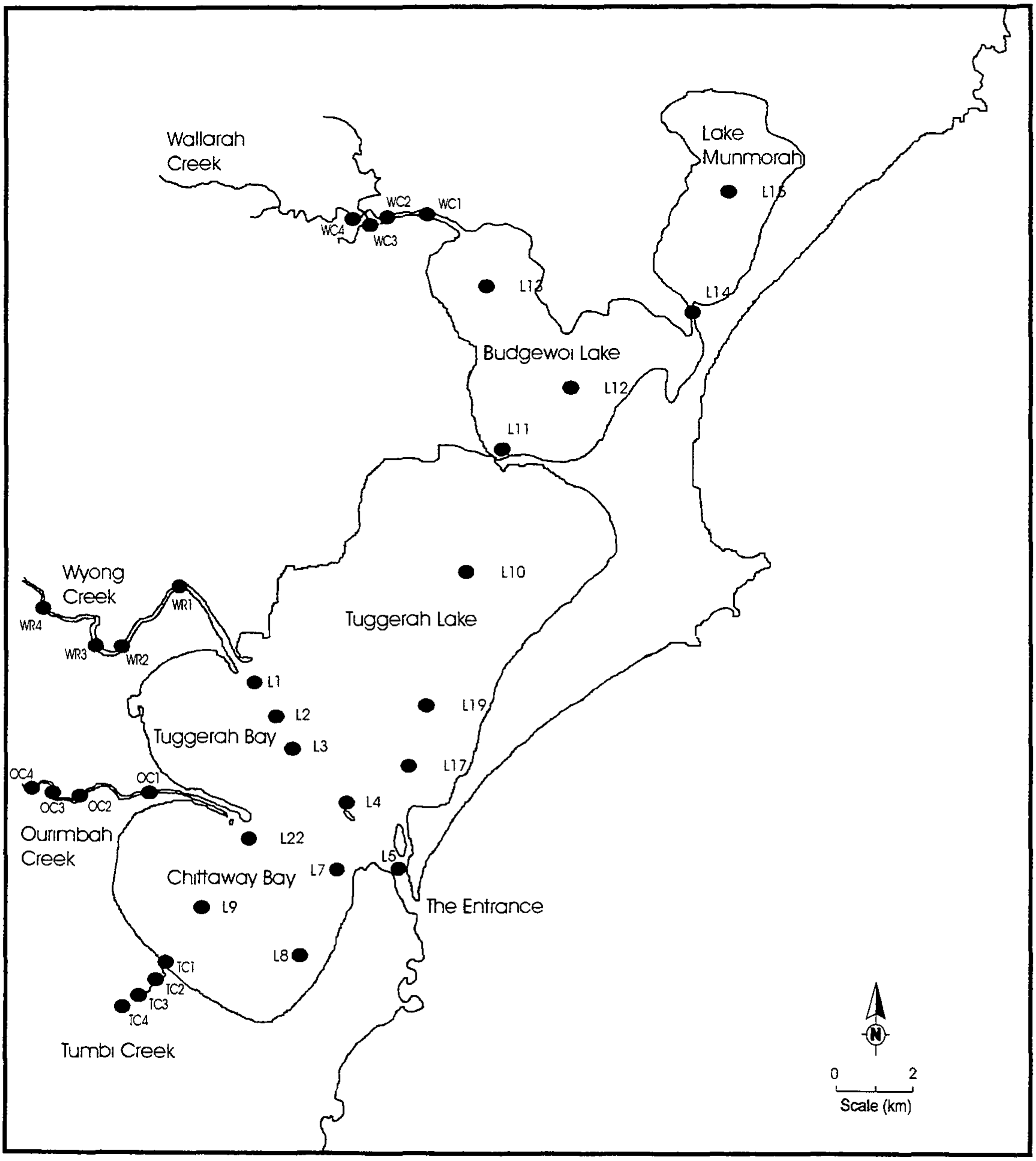

Figure 13. Location of physico-chemical water quality sampling sites (1996)

Conductivity and salinity were generally similar within the estuarine sections of each creek, however site 1 was generally higher during rainfall events because of its proximity to the estuary (Figure 14). Changes to the temporal patterns of these variables can be associated directly with large rainfall events in each of their catchments For example the salinity and conductivity in Tumbi Creek, Ourimbah Creek and Wyong River were reduced after rainfall in August and September 1996, however Wallarah Creek did not experience these events (i e the rainfall missed the catchment). All four tributaries experienced a rapid decline in salinity/conductivity due to heavy rainfall in December 1996 and January 1997 (Figure 14) The salinity and conductivity of water is important to aquatic organisms because many are stenohaline (i e they are tolerant to small variations in salinity), however estuarine organisms, including those found within the estuarine sections of the tributaries, are generally euryhaline and can tolerate wider salinity fluctuations

The concentration of dissolved oxygen (DO) in solution fluctuated within all four tributaries (Figure 15) In Wallarah Creek and Wyong River, the average DO concentration for the year was 6mg/L, whilst Ourimbah Creek and Tumbi Creek were on average slightly lower (5mg/L). The concentration of DO in the water can be reduced by the activity of aerobic bacteria which breakdown organic material Aquatic plants use and make oxygen during photosynthesis and changes to plant assemblages can cause oxygen concentrations to fluctuate at very small temporal scales, e g over a 24 hour diurnal cycle In general, dissolved oxygen concentrations should not fall below 6mg/L, determined over a number of diurnal cycles (ANZECC, 1992)

The pH of the water in each of the four tributaries was in the range 6-8 (Figure 15) In fresh water, a pH of 7 is normal, whilst in marine waters it is 8 2 The pH is controlled by the carbonate-bicarbonate buffer system and the buffering capacity of water is related to its alkalinity Marine waters are strongly buffered and small changes in pH can indicate problems The pH values that were recorded during the period were typical of lower estuarine tributaries, where freshwater is mixed with seawater (Figure 15)

The turbidity of the water within all four tributaries varied both spatially and temporally (Figure 15) Increased turbidity was generally correlated with heavy rainfall in each of the catchments The turbidity may increase when suspended sediments are washed in during rain events and because of the effects of mixing by local currents and wind Blooms of microscopic organisms within the water column can also influence the turbidity of water The ANZECC (1992) guidelines suggest that mean seasonal turbidity, measured by nephelometric turbidity units (NTU) should not change by more than 10%

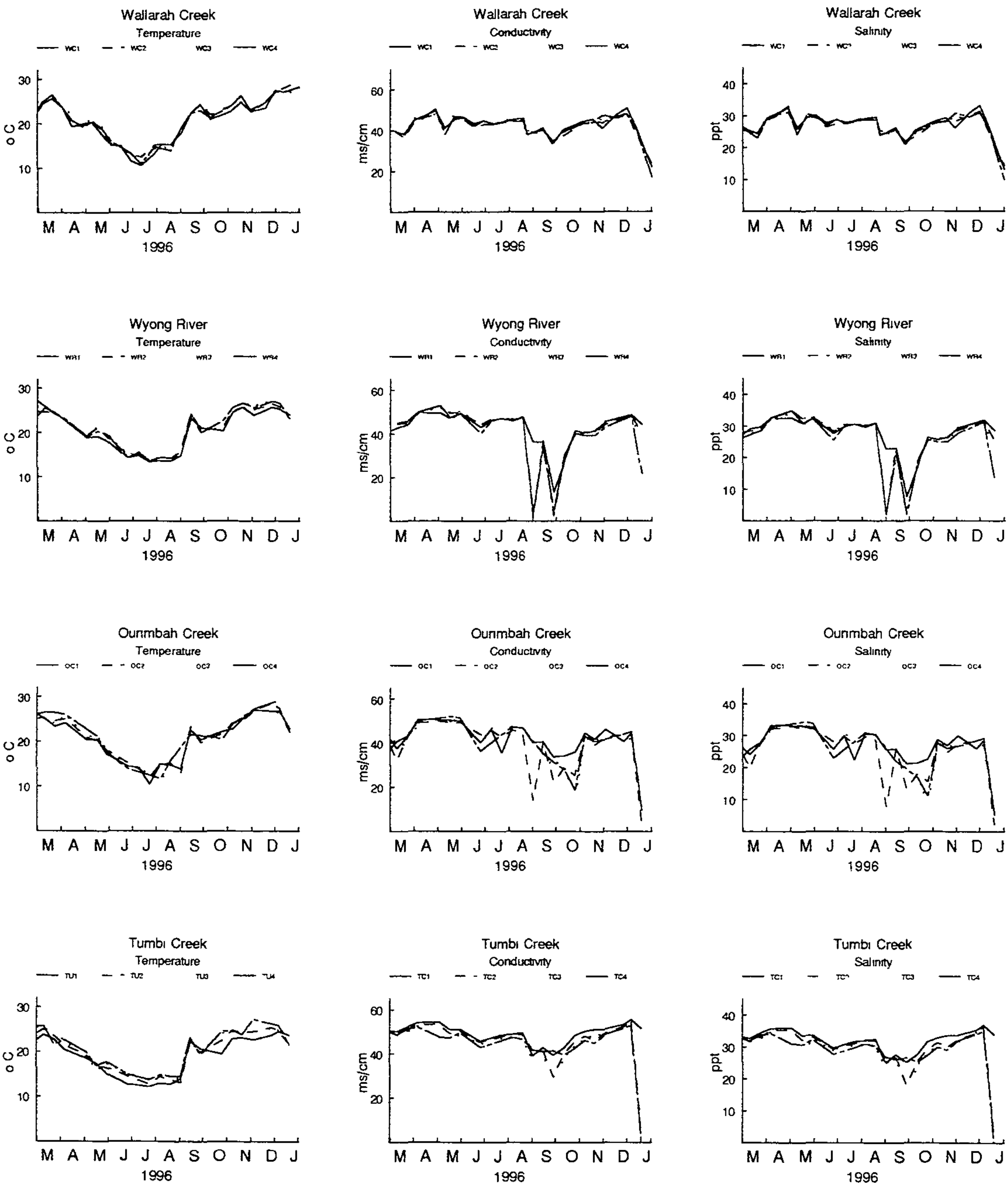

Figure 14. Temperature, conductivity and salinity in the estuarine tributaries (1996)

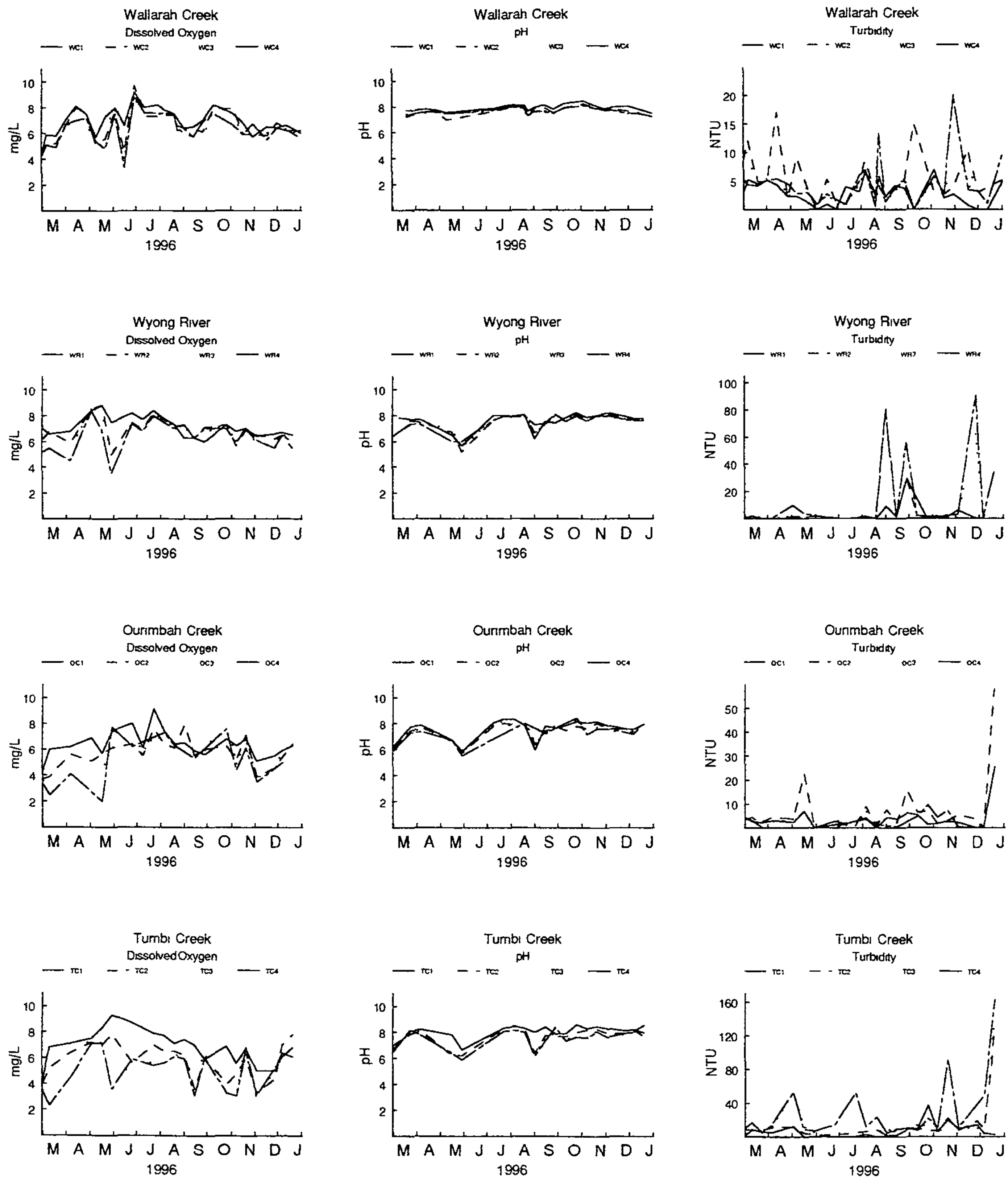

Figure 15. Dissolved oxygen, pH and turbidity in the estuarine tributaries (1996)

Within the estuary, surface water temperature fluctuated in response to air temperature and inflow of colder fresh water from the catchment and was similar at all sites with little variation (Figure 16) Temperature changes can occur naturally over diurnal and seasonal cycles or through changes brought about by anthropogenic disturbance The fluctuations that occurred to the surface water temperatures in the Tuggerah Lakes estuary are within normal ranges (ANZECC, 1992) The pH in the surface waters of the estuary (pH ~ 8) over the 1996 period showed little variation from one location to another or through time (Figure 16) This would be due to the buffering ability of the near seawater salinity concentrations in the estuary over this period (Figure 17) There were some reductions in salinity associated with fresh water inflows however these reductions were only for short periods of time (Figure 17)

Dissolved oxygen concentrations within the estuary fluctuated over the year however the DO between the different locations was fairly similar (Figure 18). DO concentrations in water are quite dynamic and as previousy mentioned can fluctuate widely over a diurnal cycle The turbidity in the estuary fluctuated significantly through time and probably represents small-scale temporal fluctuations on the scale of days rather than larger patterns associated with freshwater inflows of turbid water (Figure 18) However, the increased turbidity in December 1996 and January 1997 (Figure 18) was due to the large freshwater flow into the estuary at this time (see Figure 15)

In summary, the physico-chemical variables measured in the lower estuarine sections of the tributaries and the estuary fluctuated at various spatial and temporal scales, which were considered to be typical of waterways in temperate eastern NSW (ANZECC, 1992)

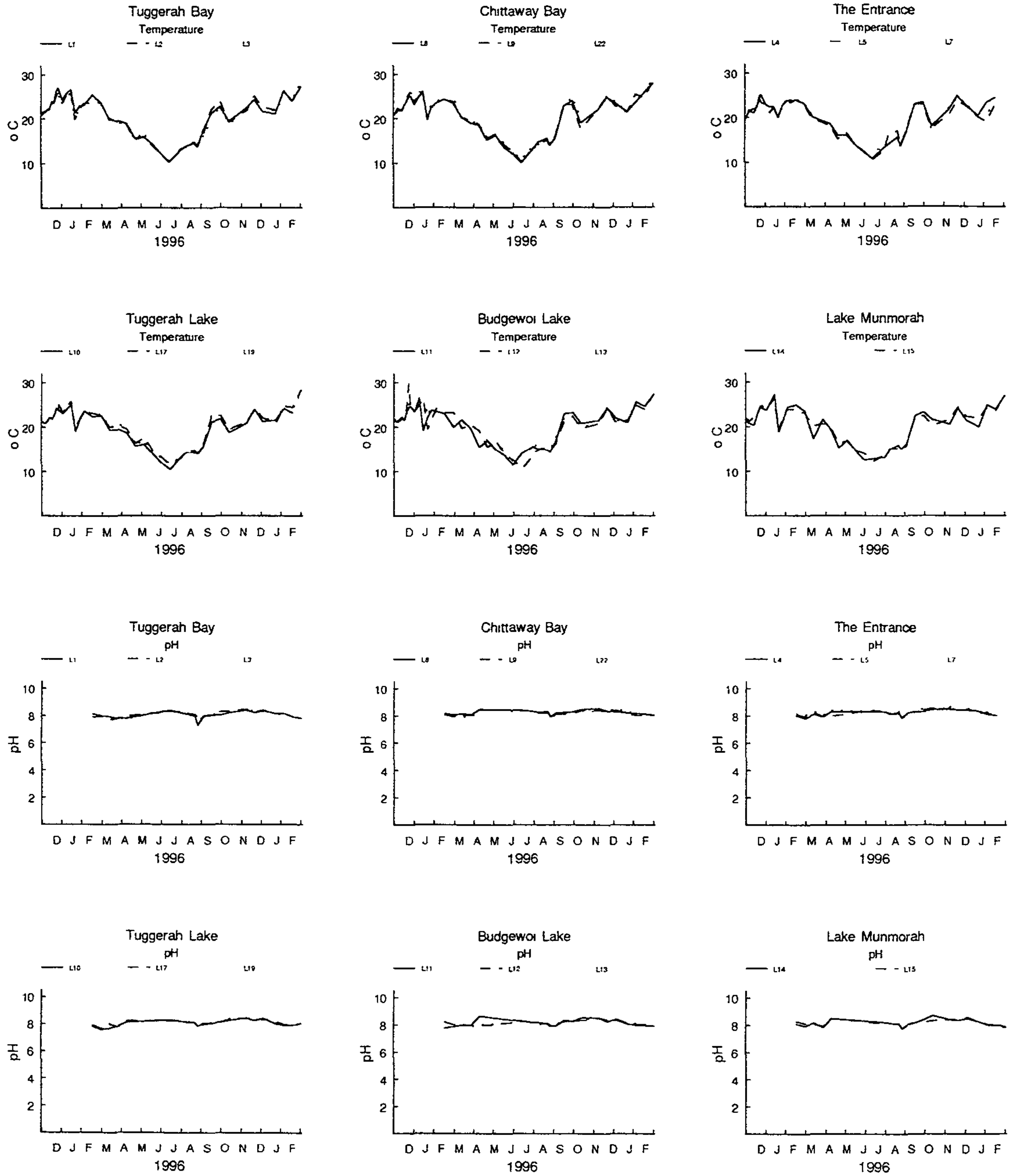

Figure 16 Water temperature and pH in the estuary during 1996

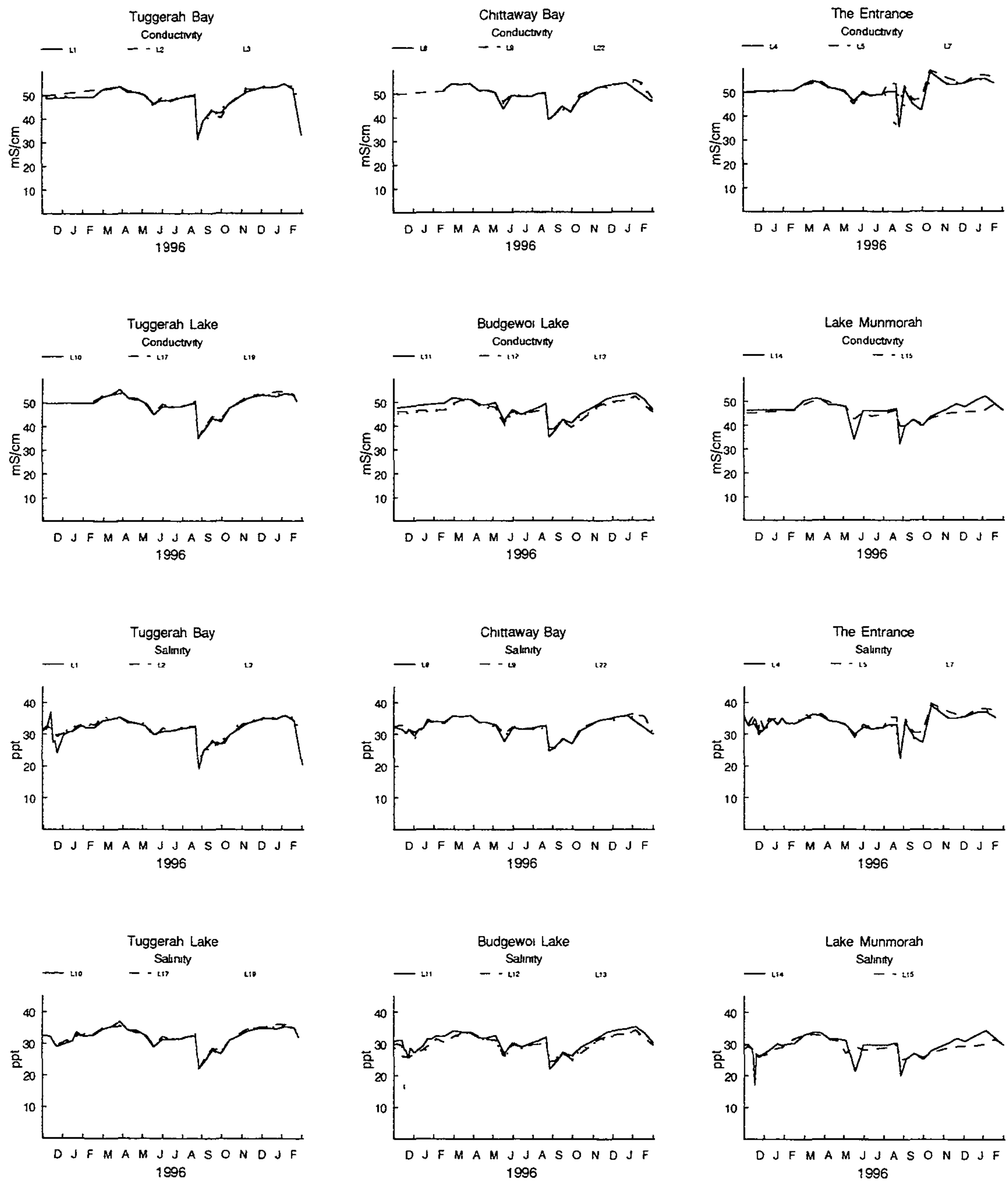

Figure 17 Salinity and conductivity in the estuary during 1996

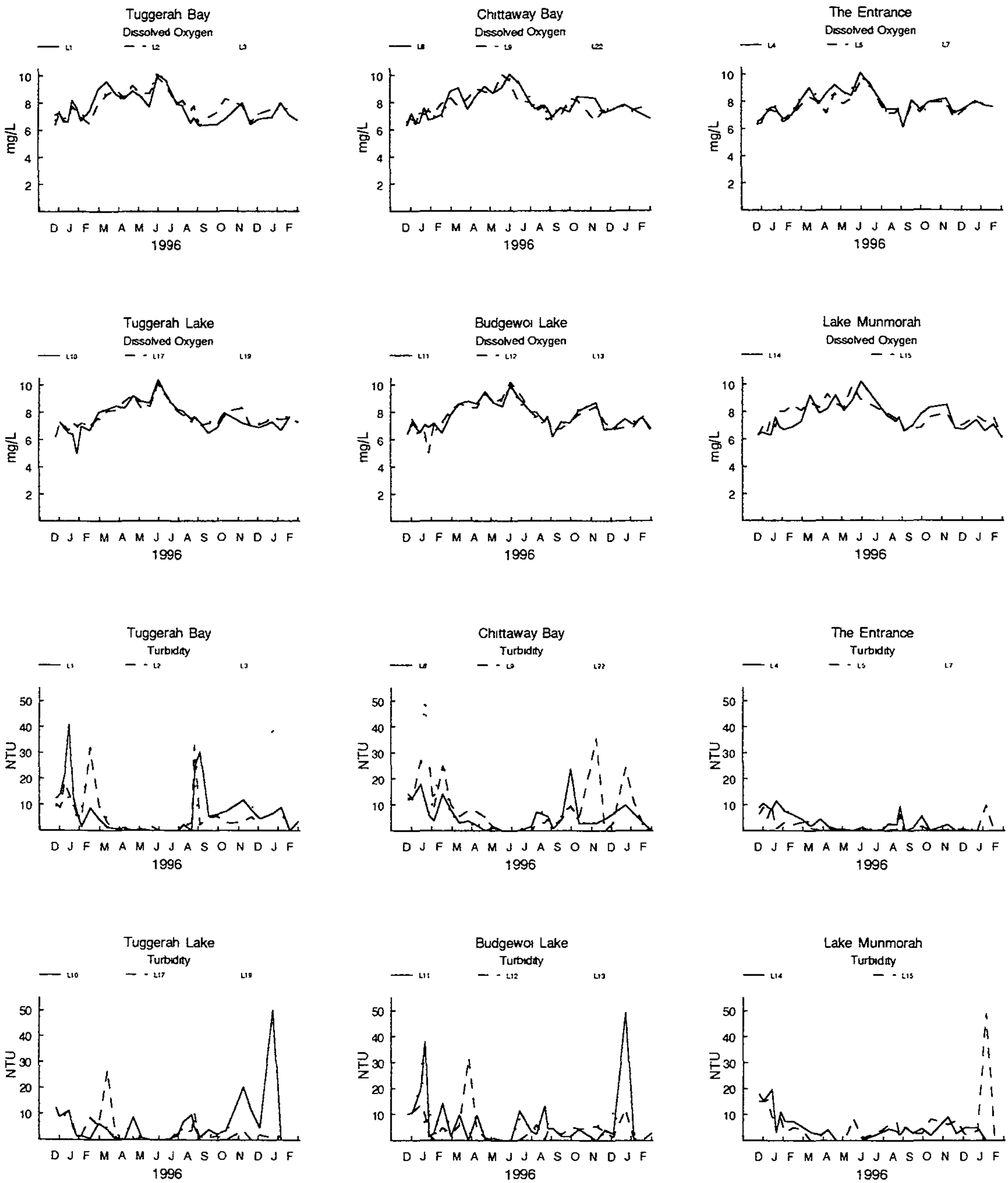

Figure 18. **Dissolved oxygen and turbidity in the estuary during 1996**

3.1.4. Water Quality Dynamics

Despite several studies, which have collected data on the quality of water in the Tuggerah Lakes estuary (Higginson, 1971, King and Hodgson, 1995, Cheng, 1996, WSC, 1995, 1997, van Senden, 1997), the quality of the data was considered to be limited (King and Hodgson, 1995) A rigourous program of monitoring was initiated in June 1997 to quantify spatial and temporal variability in the water quality at a number of scales (Cummins *et al*, 1999)

3.1.4.1. Methods

Spatial and temporal variability in the water quality of the estuary was measured by sampling randomly between June 1997 and June 1999 (Cummins *et al*, 1999) The estuary was divided into six locations (Figure 19) based on either the major contribution of flow from rainfall events in the catchment, or the flushing characteristics of individual locations Lake Munmorah (LM) and Budgewoi Lake (BW) were considered to be two independent locations whilst Tuggerah Lake was divided into four locations, Tuggerah Lake (TL), Tuggerah Bay (TB), The Entrance (TE), and Chittaway Bay (CB) Three sites were nested within each location and three replicate sub-surface water samples were collected for nutrient analysis using pre-rinsed 500mL PET bottles and then stored on ice Three replicate measurements of pH, temperature (°C), dissolved oxygen (mg/L), salinity (ppt) and turbidity (NTU) were also made at each site using a Yeokal-611 water quality instrument The four major tributaries entering the estuary were also sampled but at a reduced spatial scale Three replicate water samples and physico-chemical measurements were collected within the entrance to Wallarah Creek (WC), Wyong River (WR), Ourimbah Creek (OC) and Tumbi Creek (TC) at the same temporal scale as the estuary sampling (Figure 19)

Wyong Shire Council's Water & Sewage Laboratory analysed phosphorous species, whilst AWT EnSight analysed the nitrogen species Nutrient species, abbreviations and analytical procedures are summarized in Table 4 All results have been reported as concentrations of nitrogen or phosphorous in µg/L For data analyses, nutrient concentrations less than the detection limit were assigned a value equal to half the detection limit. Results can be converted to µM by dividing the concentration value by the appropriate atomic mass value (N = 14µg/µM, P = 31µg/µM)

Table 4. Nutrient forms, abbreviations and analytical procedures

Nutrient Form	Abbreviation	Method (Source APHA, AWWA & WPCF, 1989)
Total Phosphorous	TP	Persulphate digestion
Ortho-phosphorous	OP	Molybdate-blue
Total Kjeldahl Nitrogen	TKN	Mercuric oxide
Oxidised Nitrogen*	NOx	Cadmium reduction
Ammonium	NH_4	Phenol hypochlorite
Total Nitrogen	TN	TKN + Nox

* Oxidised nitrogen = nitrate + nitrite, hereafter referred to as NOx

The catchment is only partially gauged so freshwater inflow to the estuary could only be estimated Rainfall (Bureau of Meteorology) and 'height over weir' (Wyong Shire Council) data were examined to give an indication of the timing and nature of rainfall events, and the variation in freshwater inputs throughout the sampling period

Regression analysis was used to investigate the degree of linear association between selected nutrient forms and salinity, rainfall and 'height over weir' measurements TP, OP, TN, NOx, NH_4 and salinity data were analysed using analysis of variance (ANOVA) Differences between i) estuary locations, ii) tributary locations and iii) estuary vs tributary locations were examined For the estuary model, time was treated as a random factor, locations were fixed and sites were nested within time and locations For the tributaries model, time was treated as a random factor and locations (i e tributaries) were fixed To ensure a balanced model for the estuary vs tributary analyses, results from one site within each estuary location were selected randomly and then analysed with the data collected from the tributary locations Time was treated as a random factor whilst locations were fixed Prior to analysis, the data were examined for homogeneity of variances using Cochran's test (Winer, 1971) and where necessary were transformed (Underwood, 1981) Where the transformation was not successful in 'correcting' the inequality of the variances, analyses were performed using the raw data (Underwood, 1981)

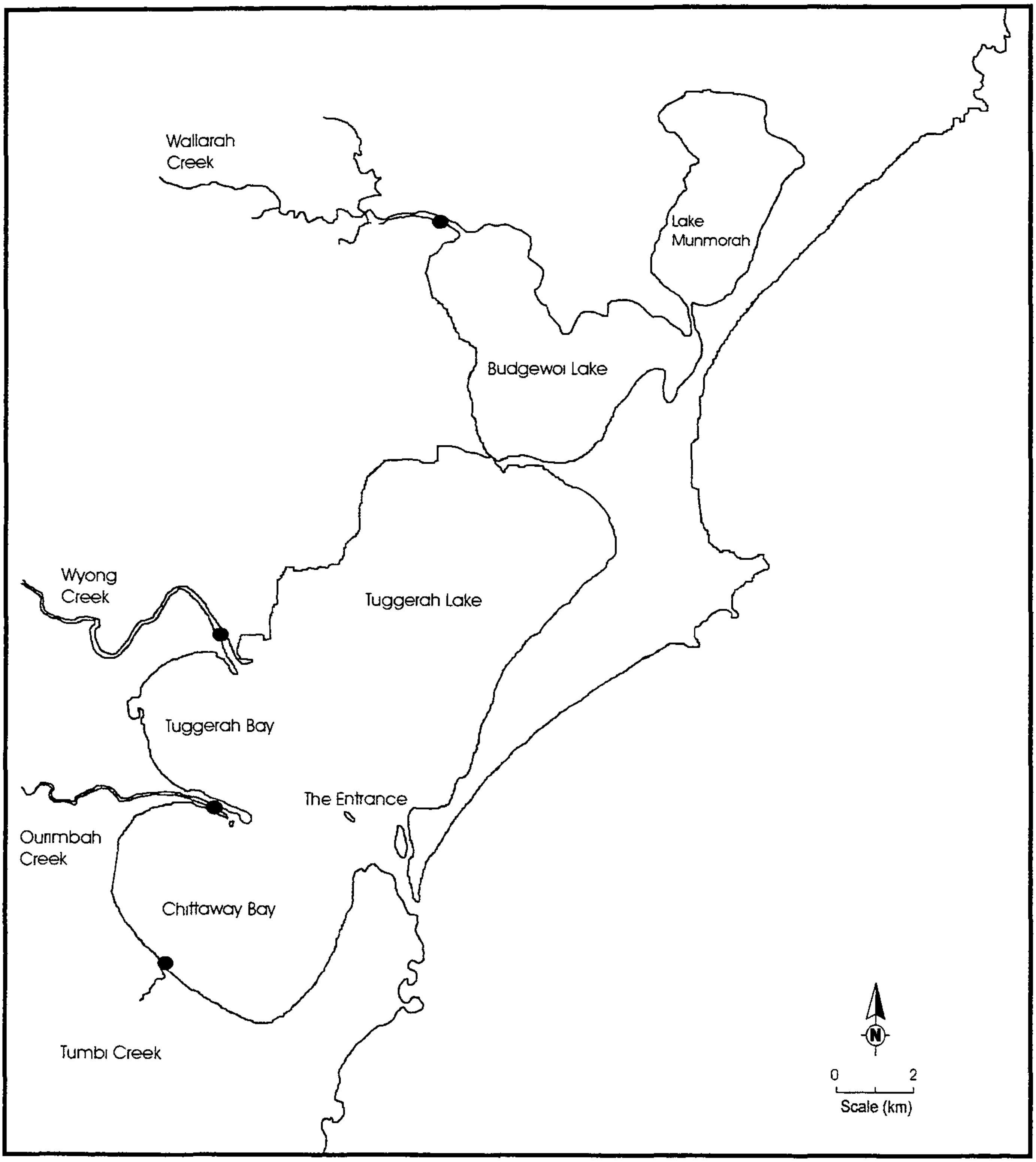

Figure 19. Water quality sampling locations in the tributaries and estuary

3.1.4.2. Results

There were temporal and spatial variations in many of the water quality variables measured within the Tuggerah Lakes estuary and its four major tributaries (Cummins *et al*, 1999) Rainfall measured at The Entrance averaged 4 4mm day^{-1} over the two-year sampling period whilst monthly averages were highest in May 1998 (12mm day^{-1}, total = 378), August 1998 (average = 13mm day^{-1}, total = 390mm) and April 1999 (average = 15mm day^{-1}, total = 447mm) Coastal rainfall values were comparable with those measured at stations at the top of the sub-catchment areas The 'height over weir' data indicated that between May 1995 and June 1999, there were no freshwater inflows from Wyong River and Ourimbah Creek for 60% and 25% of the time respectively (Cummins *et al*, 1999)

Temperature fluctuated through time with similar trends observed between locations (Figure 20) There were no significant differences in salinity concentrations between locations or through time (Figure 20) Salinity ranged between 16 and 38ppt with an average of 27 $\pm$ 0 6 ppt over the study period The Entrance location recorded the highest salinity (29 $\pm$1 8 ppt) due to tidal exchange, whereas Lake Munmorah (25 $\pm$ 1 7 ppt) and Budgewoi Lake (26 $\pm$ 1 7 ppt) recorded the lowest Salinity decreased with increased rainfall, reflecting freshwater input to the estuary (Figure 20)

Generally, surface waters were well oxygenated probably due to wind mixing of the water column (Figure 20) and oxygen concentrations were above saturation during the winter in 1998, probably because of photosynthetic activity by phytoplankton (see Cummins *et al*, 2000) The pH within the surface waters showed little variation, both among locations and through time (Figure 20) Turbidity varied spatially and temporally with levels highest in November 1998 (Figure 20) Chittaway Bay had the highest mean turbidity (12 7 $\pm$ 6), whilst Lake Munmorah had the lowest (4 7 $\pm$ 1)

There were significant time x location interactions for total nitrogen concentrations, which were highest in June and August 1997 (Figure 21) Overall, Lake Munmorah had consistently higher TN concentrations (578 $\pm$ 98 µg/L) compared to the other locations, whilst The Entrance had the lowest (375 $\pm$ 41 µg/L) (Figure 21) A significant time x location interaction was found for NOx and NH_4 (Figure 21) Generally, NOx concentrations were below the detection limit (≤10µg/L) however concentrations were elevated in Lake Munmorah in June 1998 (15 6 $\pm$ 1 9 µg/L) and in Tuggerah Bay in August 1998 (27 8 $\pm$ 9 5 µg/L) (Figure 21) Ammonium concentrations were much more variable than TN and NOx, with levels being particularly high in all locations in January 1998 (Figure 21) These concentrations did not appear to be due to rainfall Lake Munmorah had significantly higher concentrations of NH_4 (74 4 ± 1 9 µg/L) than all other locations during June 1998 (Figure 21)

Significant time x location interactions were detected for TP and OP concentrations throughout the estuary (Cummins *et al*, 1999) The concentration of TP ranged from 2 ± 0 3 µg/L to 41 ± 2 µg/L over the two-year period (Figure 21) with no consistent seasonal or rainfall related patterns SNK tests revealed that OP concentrations were significantly higher in January 1998, compared to all other times (except August 1998) Concentrations were generally low, ranging between 0 3 ± 0 2 µg/L and 11 ± 10 1 µg/L (Figure 21)

Average water temperatures fluctuated seasonally, with general trends being similar within each of the four creeks (Figure 22) There was significant time x location interactions found for salinity, with levels being considerably lower during winter 1998 (Figure 22) SNK tests revealed that concentrations within Wyong River (11 3 ± 3 1 ppt) were significantly lower in August 1998 than in Tumbi Creek, Wallarah Creek and Ourimbah Creek, reflecting considerable freshwater input from the sub-catchment (Cummins *et al*, 1999)

Concentrations of dissolved oxygen varied between tributaries, depending on the time they were examined (Figure 22) Dissolved oxygen fell below saturation (6 mg/L or 80-90%) in Tumbi Creek in January 1998 and April 1999 and in Wallarah Creek in February 1999 The pH in Wyong River dropped considerably in August 1998 (Figure 22), whilst turbidity maxima (34 8 ± 16 8, 43 ± 4 5 and 40 2 ± 18 0) were recorded in Tumbi Creek in January and November 1998 and February 1999 respectively (Figure 22)

Significant time x location interactions were detected for all nutrients examined within the tributaries (Figure 23) SNK tests revealed that TN concentrations (1735 ± 349 5 µg/L) in Wyong River were significantly higher than all locations (Cummins *et al*, 1999) Oxidised nitrogen concentrations were generally below detection limits (<10µg/L) however, levels were significantly higher in Ourimbah Creek in August 1998 compared to other times (Figure 23). These concentrations were coincident with increased freshwater input from the sub-catchments (Cummins *et al*, 1999) There were considerable variations in NH_4 concentrations, however levels were found to be significantly higher for all creeks in June 1997 (Figure 23) Also notable were the high values measured in the creeks in January 1998 (Figure 23) Both TP and OP concentrations showed considerable variation between tributaries and through time (Figure 23) Phosphorous concentrations were significantly highest in Ourimbah Creek for both TP (99 ± 1 8 µg/L) and OP (67 3 ± 2 7 µg/L) in January 1998 (Figure 23)

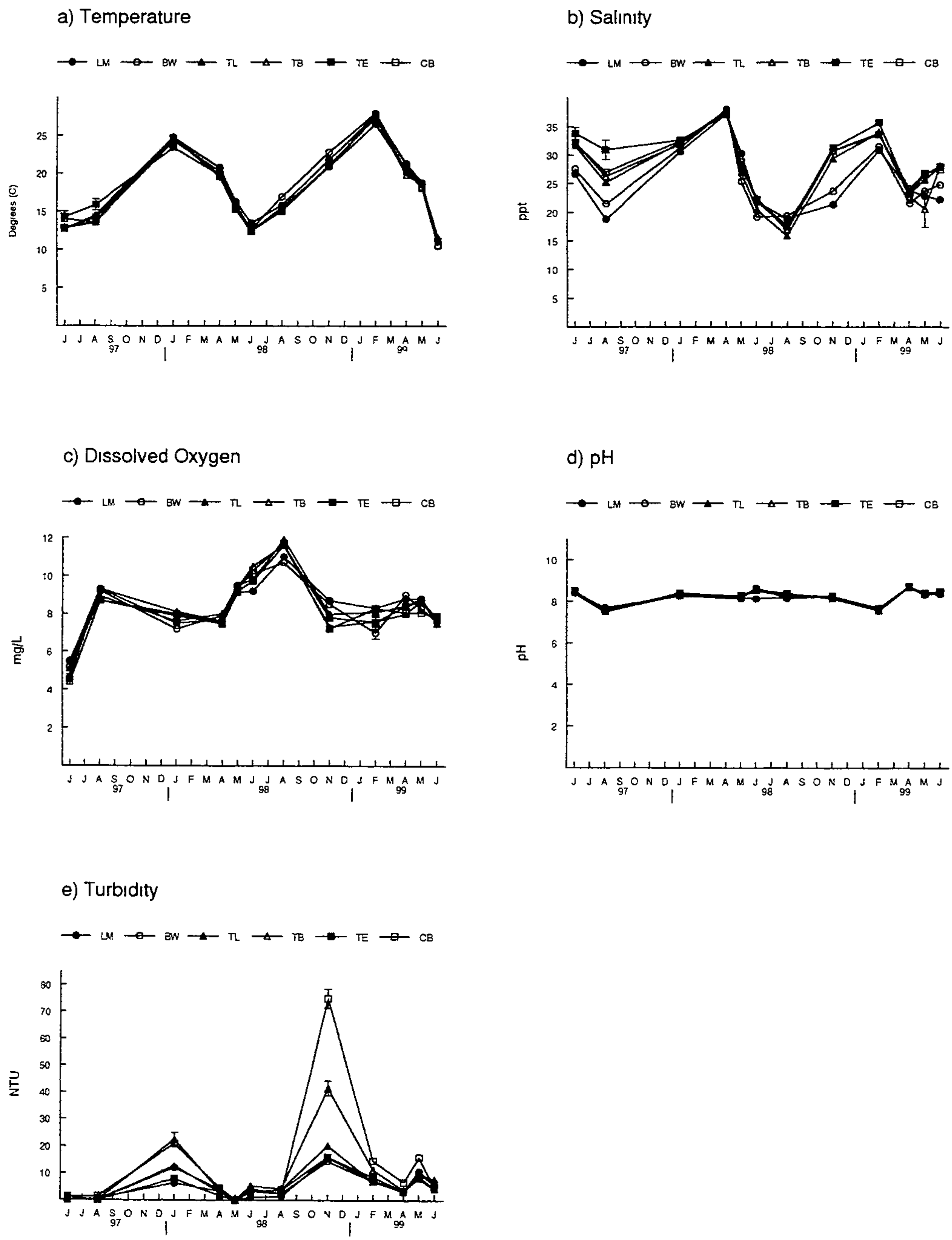

Figure 20. Mean concentration (± s.e) of physico-chemical water quality variables sampled within the estuary (n = 9, i.e. sites are pooled; LM - Lake Munmorah, BW - Budgewoi Lake, TL - Tuggerah Lake, TB - Tuggerah Bay, TE - The Entrance, CB - Chittaway Bay)

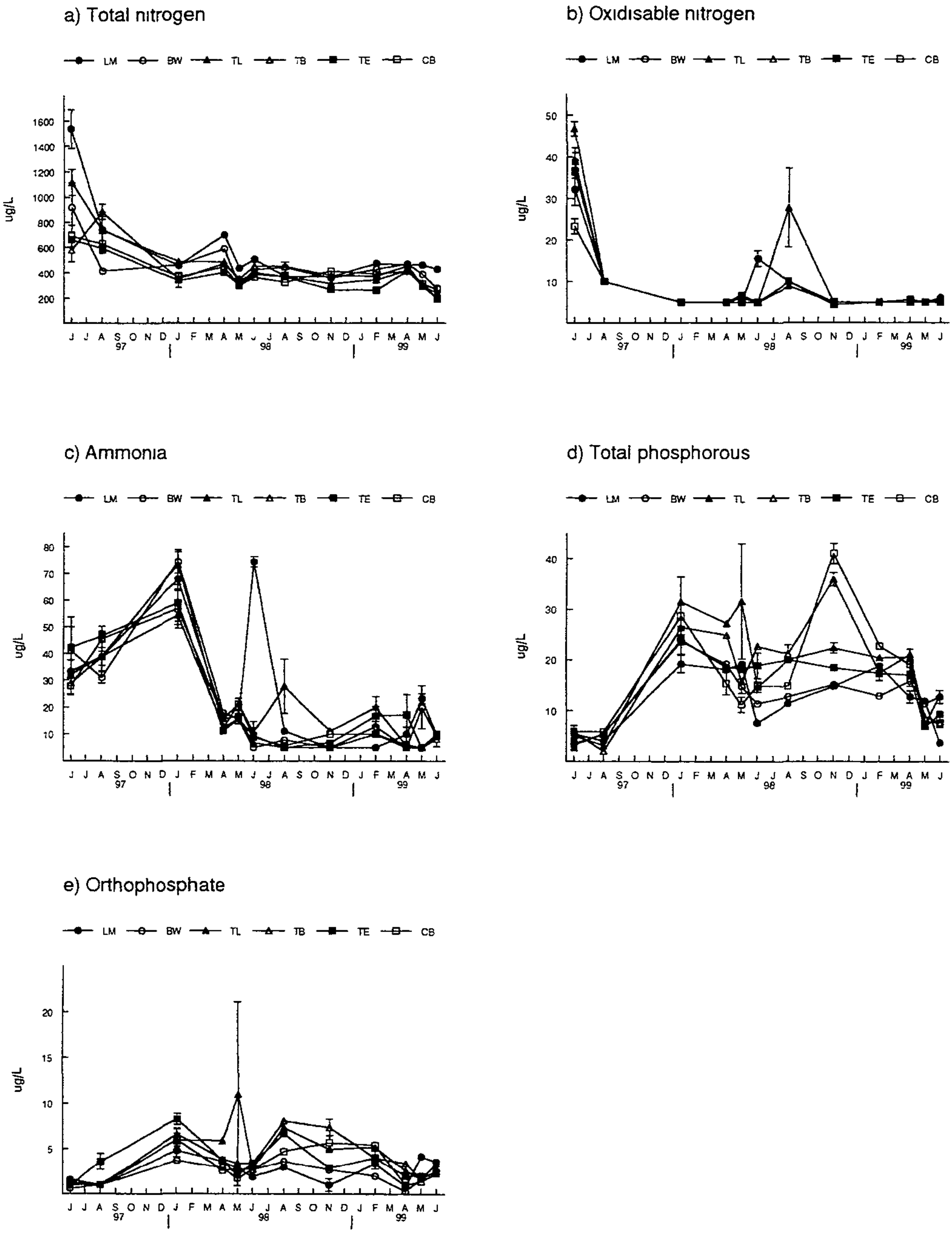

Figure 21. Mean concentration (± s.e) of nutrients sampled within the estuary (n = 9, i.e. sites are pooled; LM - Lake Munmorah. BW - Budgewoi Lake, TL - Tuggerah Lake, TB - Tuggerah Bay, TE - The Entrance, CB - Chittaway Bay)

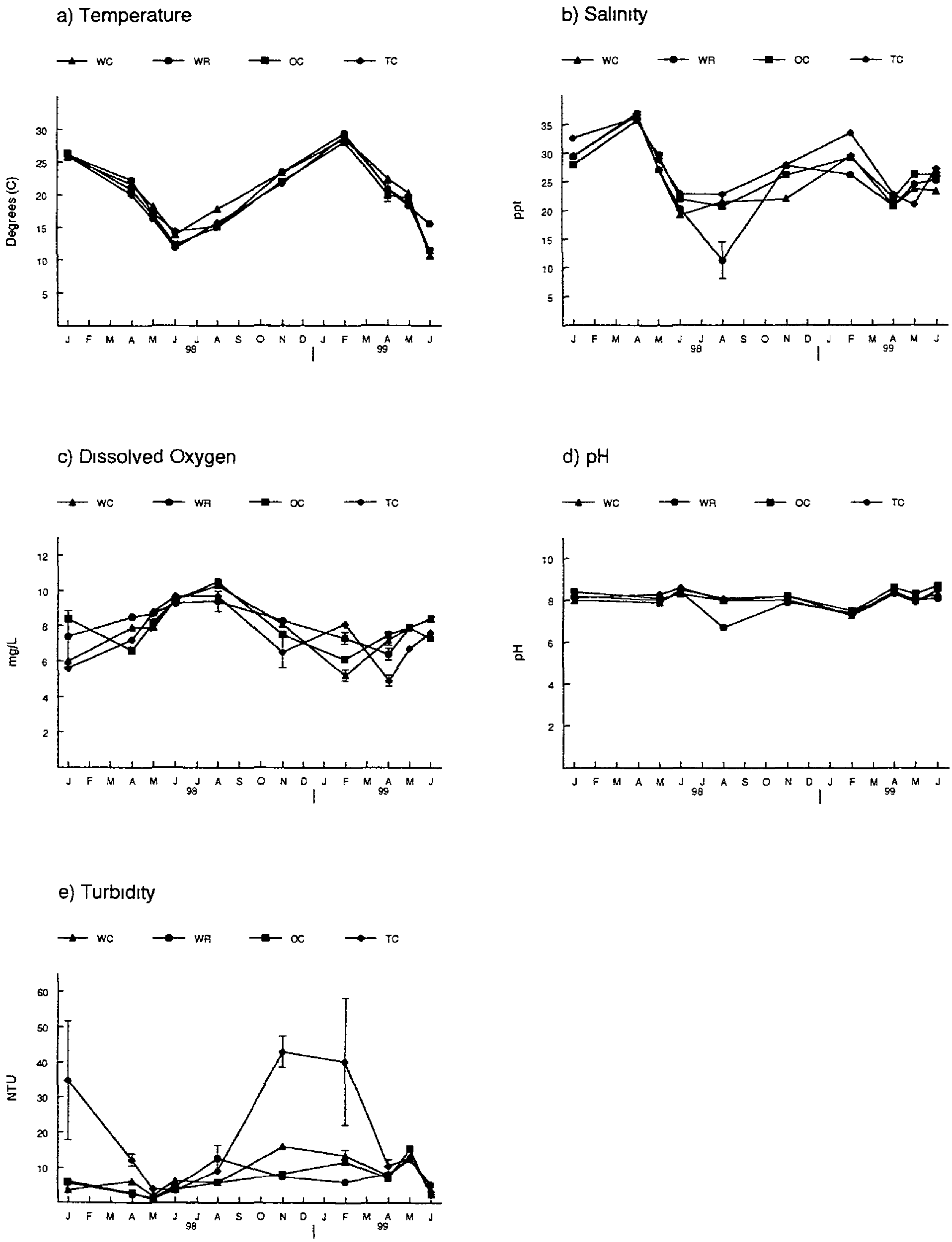

Figure 22. Mean concentration (± s.e) of physico-chemical water quality variables sampled within the main tributaries entering the Tuggerah Lakes estuary (n = 3; WC - Wallarah Creek, WR - Wyong River, OC - Ourimbah Creek, TC - Tumbi Creek)

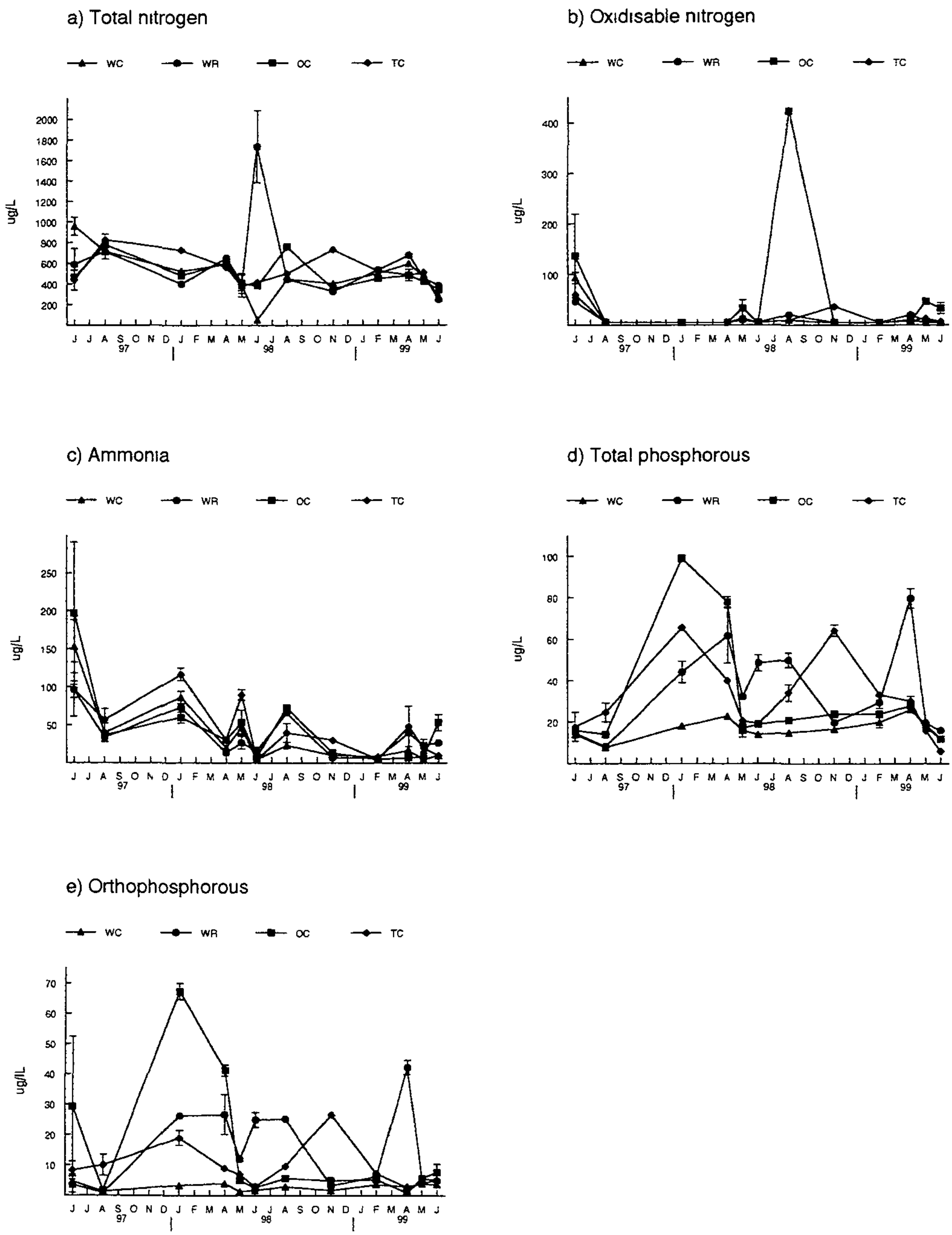

Figure 23. Mean concentration (± s.e.) of nutrient sampled within the main tributaries entering the Tuggerah Lakes estuary (n = 3; WC - Wallarah Creek, WR - Wyong River, OC - Ourimbah Creek, TC - Tumbi Creek)

3.1.4.3. Discussion

Ambient nutrient concentrations within the Tuggerah Lakes estuary were found to fluctuate significantly both spatially and temporally. Typically, biologically available and total nitrogen concentrations were higher than the new guideline values recommended for estuarine systems by the Australia and New Zealand Environment and Conservation Council (ANZECC), whilst phosphorous concentrations were below the threshold nutrient criteria (ANZECC, 1998). When comparing these results to those compiled by the Environment Protection Authority on other estuaries within New South Wales (Scanes *et al.*, 1997), the Tuggerah Lakes estuary would appear to have 'medium' total nitrogen concentrations, whilst total phosphorous concentrations were 'low'. These results give some indication of the nutrient status of the estuary however, there are some limitations as the guidelines are not system specific and estuaries vary significantly, in terms of their geomorphology and hydrological characteristics. For this reason it is also important to relate the concentrations of nutrients with observed responses by the plant communities (ANZECC, 1998).

Nitrogen, particularly in its biologically available forms (nitrite, nitrate and ammonium) is generally regarded as being the limiting nutrient for primary production in temperate marine waters (Dugdale, 1967; Ryther and Dunstan, 1971; Nixon, 1981; Boynton *et al.,* 1982; Paerl *et al.,* 1990; Harris, 1996). Care must be used though, when interpreting water column concentrations as available forms are often low and total nitrogen concentrations are highly variable (Coade, 1997). Plants, particularly algae, can rapidly expand their biomass to utilise inputs of available nitrogen and irrespective of large total nitrogen concentrations, it has been shown that for more than 95% of the time available forms can be virtually undetectable (Scanes *et al.,* 1997).

Despite recording 'high' nitrogen concentrations, DIN:DIP ratios indicated that the estuary was often nitrogen limited (Cuumins, *et al.*, 1999). This result would appear to conflict with the finding of high nitrogen concentrations, highlighting the importance of relating observed nutrient concentrations with the plant assemblages. In a number of estuaries where there is excess nitrogen, loss of species diversity and excessive primary production by phytoplankton and free-floating macroalgae are commonly observed (Gray, 1992; Paerl *et al.,* 1990; Mallin *et al.,* 1993; Kinney and Roman, 1998). Some shallow areas of the Tuggerah Lakes have experienced excessive growth of green macroalgae (Inter-Departmental Committee, 1979; Cheng, 1980; King and Hodgson, 1995; Cummins *et al.,* 2000), and phytoplankton blooms have been recorded on a number of occasions (Cheng, 1994; 1997; Cummins *et al.,* 2000), however, these blooms have mostly been at small scales. It is thought that the diversion of sewage discharge, from the estuary to the ocean outfalls at Norah Head and Bateau Bay, has been largely responsible for a reduction in the prevalence of the nuisance macroalgae blooms that occurred in the late 1980's and early 1990's.

Here and in previous studies, the major tributaries were shown to contribute significant nutrient loads to the estuary (Boake, 1991; King and Hodgson, 1995; Walkerden and Gilmour, 1996; Garofalow, 1998; Bourguès *et al.,* 1998). Nutrient inputs are quickly distributed within the system, probably as a result of wind-induced currents. Generally, spikes in nutrient concentrations reflected rainfall and freshwater inflows, however there were considerable variations at a number of scales. Harris (1996) states that the irregularity of flow events typified by Australian rivers and flow regulation activities exacerbate the problem of identifying any emergent patterns in system behavior. During this study, no flows were measured over the weirs for 25% and 60% of the time for Ourimbah Creek and Wyong River respectively. This has important implications for the transport of terrestrial materials to the estuary as it is likely that the pattern in catchment contributions of both nutrients has been altered dramatically due to the construction of the weirs and the drawing of water for urban, industrial and agricultural supply activities. Nutrient contributions from urban runoff are also likely to be important however, there has been some debate as to whether inputs are quickly dispersed or whether mixing is limited between the shallow vegetated areas and open waters (Walkerden and Gilmour, 1996; Bourguès *et al.,* 1998). Unpublished data collected by Wyong Shire Council and The University of Newcastle suggested that there was regular exchange between the two habitat types.

As well as particulate and soluble forms entering and leaving an estuary via terrestrial and atmospheric inputs and oceanic exchange, contributions may be made from other pools of nutrients and elements present in sediments, plant communities, fish, zooplankton and bacteria (Harris, 1996). In shallow estuaries, sediments are the most significant store and strongly interact with the over-lying surface waters, regulating or modifying most of the physical, chemical and biological processes that occur within the entire system (Jørgensen and Sørensen, 1985; Boynton *et al.,* 1997). This makes the input of nitrogen associated with rainfall and stormwater run-off critical, as they replenish sediment stores, enabling them to continue releasing nutrients to the estuary during periods of low rainfall. A spike in the concentration of ammonium was observed within all estuary and tributary locations in January 1998, and this occurrence was not coincident with rainfall or riverine inflows. It is likely that the excess ammonium was produced by mineralisation of organic nitrogen (i.e. ammonification) associated with suspended or bottom sediments. In studies done by Bourguès *et al.,* (1998a, 1998b) it was found that at both low (15ºC) and high (25ºC) temperatures, and after a major flood event, ammonium was released from the sediments into the overlying water column. Dissolved oxygen levels in January 1998 were close to

fro

saturation, confirming that ammonification was probably occurring in the sediments and not in the surface waters.

A spike in the level of total and ortho-phosphorous was also measured in January 1998, coincident with the high ammonium concentrations. It is likely that the redox potential of the sediments was lowered enough to allow phosphorous to migrate into the over-lying water column. Phosphorous exchanges between the sediments and the water column are mostly ruled by redox-dependant chemical reactions and resuspension events (Day *et al.*, 1989; Bourguès *et al.,* 1998b). Inorganic phosphorous is often not available for biological up-take because it strongly sorbs onto charged particles such as clay, or it readily forms insoluble precipitates in the presence of metal oxides and hydroxides (Day *et al.*, 1989). Increases in salinity (ionic strength) may increase the flocculation of the particulate fraction of phosphorous, resulting in its becoming incorporated into the sediments (Harris, 1996). Work by Suttle *et al.* (1990), showed that even at a range below laboratory detection limits, these phosphorous additions could be beneficial for primary production. Bourguès *et al.* (1998b) recorded elevated phosphorous levels and stimulation in phytoplankton (diatom) numbers after a flood event in May 1998, however they assumed that at the scale of the ecosystem, the stimulation in biomass was still a response to nitrogen limitation and calculated DIN:DIP ratios for the time of the survey would seem to support this view.

Turbidity levels within the estuary were highly variable, probably due to its shallow nature and resuspension of bottom sediments through wind action. Previous studies have indicated that the Tuggerah Lakes have high levels of turbidity, compared to a number of other estuaries within NSW, which include Lake Illawarra and Brisbane Waters (Doherty *et al.,* 1997). Turbidity is one means of assessing the amount of suspended particulate material within the water column and can be related to light available for plant growth. Plants require light for photosynthesis and light availability can determine the depth to which plants, particularly seagrass species can grow (Abal *et al.*, 1994). Several studies have shown that where light is a limiting factor, nuisance opportunistic algal species can become dominant (Gray, 1992; Abal *et al.*, 1994). Seagrasses, as well as providing important habitat and food for a number of biota, play an important role in the regulation of the total output of nutrients from the sediments. In Australia, over 45, 000 ha of seagrass meadows have been lost, as a direct result of decreased light availability associated with increased turbidity, eutrophication and epiphytic algal growth (Walker and McComb, 1992). There is evidence to suggest that the Tuggerah Lakes have lost extensive areas of seagrass meadows (see Seagrass Section).

This study represents an important step towards quantifying the spatial and temporal patterns of a number of water quality variables within the Tuggerah Lakes estuary and its major tributaries. However, to have confidence in interpreting concentrations and ratios of nutrients, we must further seek to understand the processes that link the sources and sinks at a variety of scales (Harris, 1996). Harris (1996) states that in estuarine systems, the key parameters can become residence times of the water and the major elements, not ratios of concentrations. During floods, system processes operate at large scales (approximating the scale of catchment) and the impact to receiving waters varies depending on the timing and magnitude of the event. Drought and flow regulation allow shallow, enclosed waters time to equilibrate with the sediments and system functioning becomes dominated by internal processes (Boynton, 1997; Harris, 1996). Whilst the retention capacity of the Tuggerah Lakes has been calculated as between 65-100 days (van Senden, 1997; Walkerden and Gilmour, 1996), Harris and Baxter (1995) state that actual water residence times of materials contributed to an estuary during flood events can fluctuate between a few days and many years. Rainfall and associated runoff pulses will need to be examined from short-term (days to months) and long-term (annual) perspectives. Biological responses, at small (site-specific) and large (catchment) scales, will need to be examined to help interpret processes. Ultimately, this information will assist in the development of predictive models to help make management decisions relating to sustainable loads of and the concentrations of nutrients to the Tuggerah Lakes estuary.

3.1.5. The Flow of Nutrients through the Estuary

The Tuggerah Lakes estuary has a constricted entrance to the ocean, which allows only limited water and nutrient exchange. Nutrients enter or exit the system through surface water, groundwater, ocean, sediment, atmosphere, flora, and fauna. Modeling was used to calculate the flow and nutrient loads entering the system from the surface catchment surrounding the estuary. An average annual flow of 311,500 ML and an average annual nutrient load of 60 and 219 tonnes of phosphorus and nitrogen were identified, respectively (Garofalow, 1998).

The immediate subcatchments (urban areas) contribute 37% of the total phosphorus and 43% of the total nitrogen load to the estuary wheras high flow periods contribute almost 90% of the total nutrient load. Groundwater may also contribute significant quantities of nutrients, particularly during periods of low rainfall however, there was insufficient data to estimate the nutrient load (Garofalow, 1998).

Flushing of the lakes is driven by three main processes, water pushed seaward by external flows, e.g. surface flow, groundwater flow, or direct rainfall, exchange of water due to differences in water height (Barotropic flow), e g. tides, wind driven currents, long period sea level fluctuations, and exchange of water due to differences in density (Baroclinic Flow), e g differences in salinity or temperature On average, the lakes would be flushed approximately 4 2 times per year, resulting in 545,000 ML of water leaving the entrance annually The average annual exchange with the ocean is 234,000 ML, indicating that around 43% of the flushing of the estuary is a result of water exchange through the entrance The average annual nutrient flux results in a loss to the ocean of 13 2 tonnes of total phosphorus and 258 tonnes of total nitrogen

Sediments act as a source or sink of dissolved inorganic nitrogen and phosphorus It was estimated that the lakes sediments could potentially provide 18 and 139 tonnes per year of phosphorus and nitrogen, respectively (Bourgeous *et al*, 1998) The loss of nutrients through burial and denitrification was not investigated however these processes could greatly reduce the net nutrient load from the sediments and result in the sediments acting as a sink Annual atmospheric contribution into the estuary was estimated at approximately 1 9 tonnes of total phosphorus and 40 5 tonnes of total nitrogen per year

During 1996/97, Wyong Shire Council mechanically harvested 18,474 m^3 of seagrass and macroalgae wrack from the foreshores surrounding the estuary resulting in approximately 4 4 tonnes of TN and 0 74 tonnes of TP being removed from the system Nitrogen and phosphorus were also removed through commercial fisheries, 11 5 tonnes of nitrogen and 0 47 tonnes of phosphorus

A total nutrient load of approximately 80 tonnes of phosphorus and 400 tonnes of nitrogen enters the estuary every year, with 125 tonnes of nitrogen (Figure 24) and 65 tonnes of phosphorus (Figure 25) available for primary production The main inputs are from the surface loads and sediment fluxes and the primary loss is through the exchange of water through the entrance Denitrification and burial are also likely to result in significant losses to the system As the budget stands, 65 tonnes of phosphorus and 125 tonnes of nitrogen are available annually, with the primary inputs being from the surface load and sediment fluxes The annual nutrient loading for the Tuggerah estuary is estimated at 0 12 tonnes/km^2 for total phosphorus and 0 6 tonnes/km^2 for total nitrogen

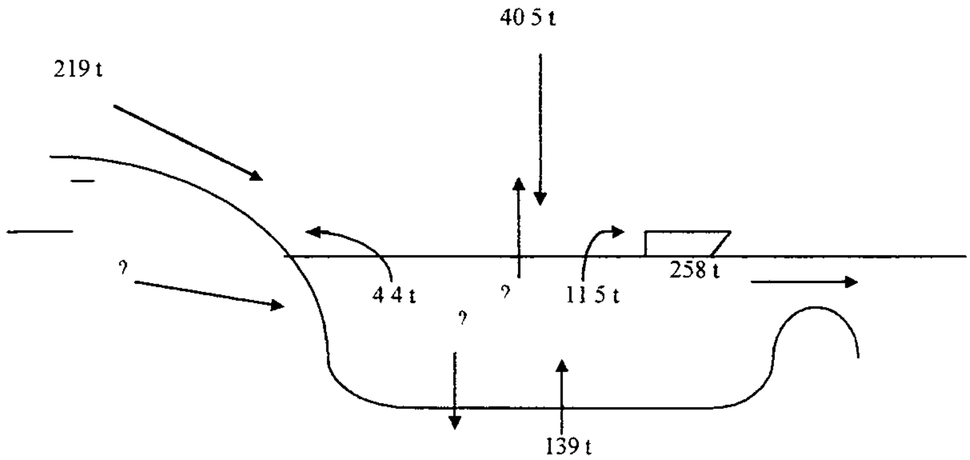

Figure 24. Annual nitrogen budget for the Tuggerah Lakes estuary

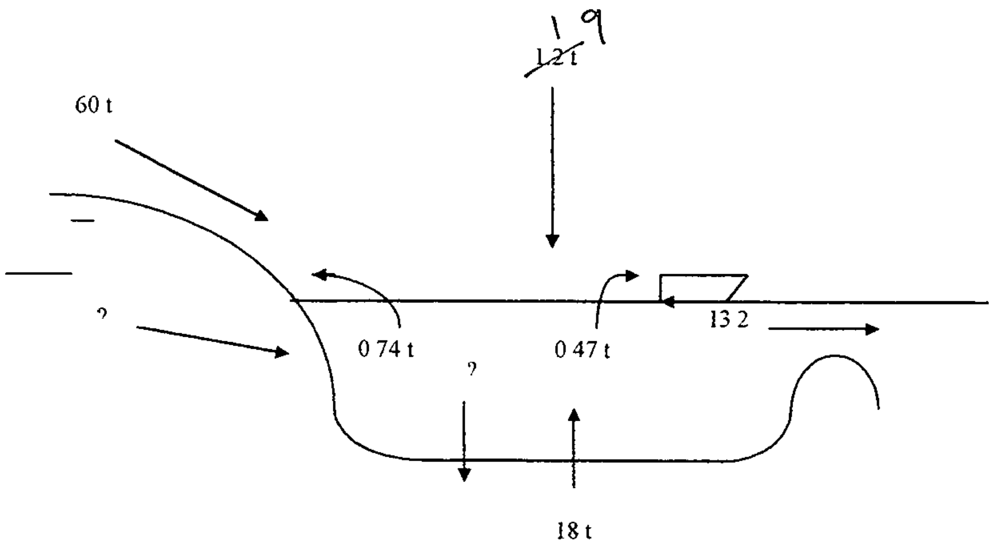

Figure 25. Annual phosphorus budget for the Tuggerah Lakes estuary

3.1.6. Groundwater Contributions to the Estuary

There is very little information on groundwater conditions in the Wyong catchment and no groundwater studies have been completed in the area immediately surrounding the estuary (Kerry, 1998) A study of existing ground water quality and its potential to contribute nutrients into the estuary was done (Kerry, 1998). The aim of the study was to determine the relative significance of groundwater nutrient fluxes into Lake Munmorah, Budgewoi Lake and Tuggerah Lake

Although little has been done in relation to groundwater studies in the Wyong catchment, geological studies have been completed for infrastructure e g roads, pipelines and treatment works This information along with the registered bore logs available for the area, were used to identify ten areas of similar geology Approximately sixty sampling bores were installed using an experimental design that allowed generalisations about the nutrient contributions from groundwater sources around the estuary

The experimental design for the groundwater study had the immediate catchments around the estuary broken into 10 distinct areas or locations (Figure 26) Within each location, two sites were randomly chosen and three random bores sunk to a depth of 2m The locations were chosen randomly from a number of potential subcatchments surrounding the estuary. From each borehole, a soil sample was taken to establish its pedological characteristics The sampling program involved taking water samples from each bore over a number of temporal scales and the ground water was analysed for total nitrogen, oxidisable nitrogen, total phosphorous and orthophosphate Physico-chemical water quality was also measured in each groundwater borehole

Nutrients within groundwater around the estuary were found to be highly variable between locations but were consistent over the two times that they were sampled (Kerry, 1998) Generally, the highest concentrations of groundwater nutrients were found in the San Remo and Charmhaven areas (Figure 26) Total groundwater nitrate loading to the estuary ranged from 22 to 21,700 kg/yr (Kerry, 1998) Orthophosphate loading ranged from 13 to 12,600 kg/yr whilst ammonia ranged from 200 to 196,100 kg/yr The aim of this program of sampling was to estimate the potential sources of nutrients that could enter the estuary from groundwater sources The ability of these nutrients to actually enter the estuary needs further consideration and will be followed up as part of the management studies

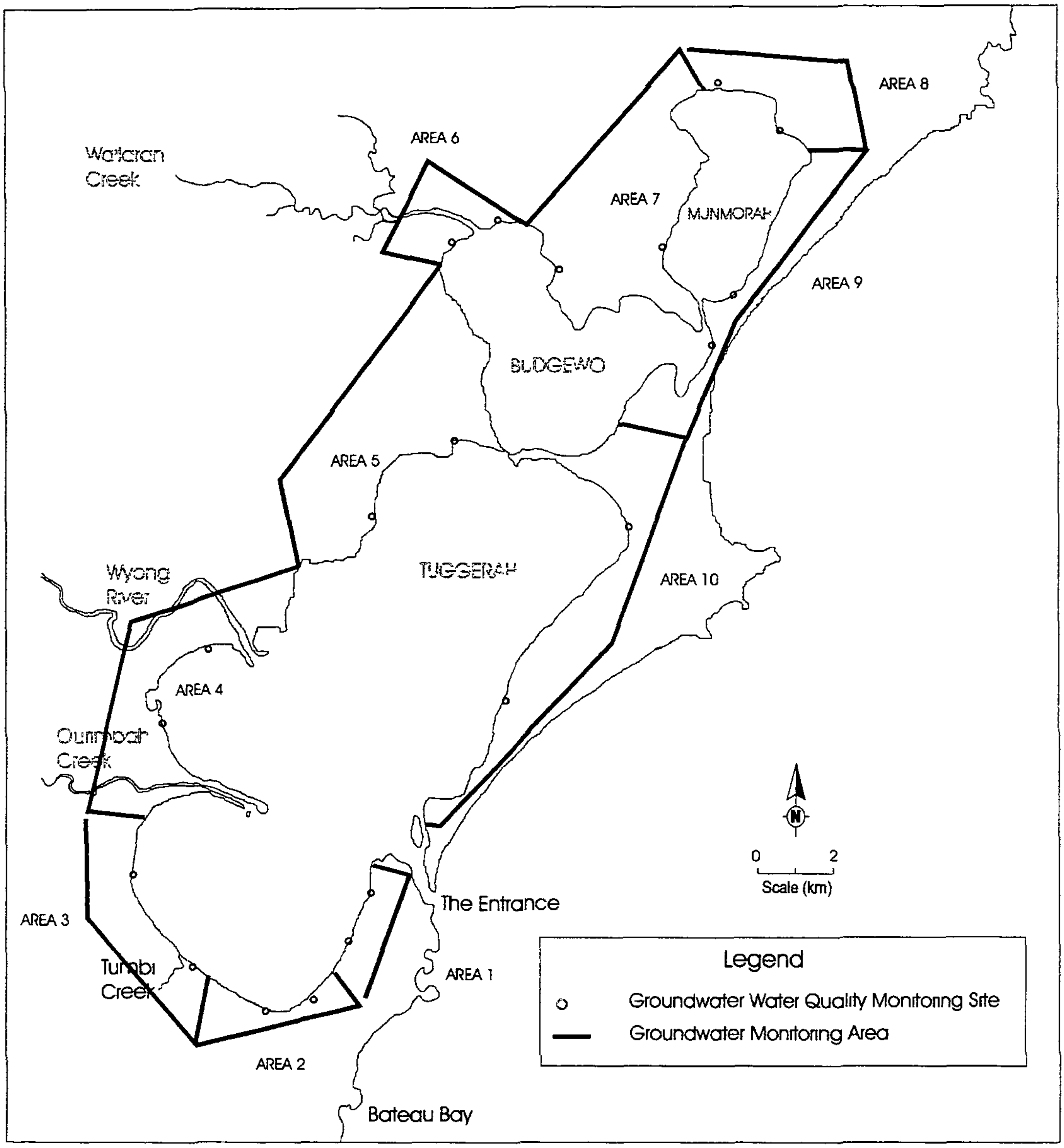

Figure 26. Location of groundwater monitoring sites

3.1.7. Recreational Water Quality Monitoring

3.1.7.1. Introduction

Wyong Council's Health Service Section monitors recreational water quality at both lakes and ocean bathing beaches throughout the Shire The aim of the monitoring is to evaluate recreational water quality at locations where the community choose to use the lakes and beaches for recreation This program was commenced in 1985 with a variety of sites located in recreational bathing areas. The presence of faecal coliforms is the criteria used to assess the water quality of lake and ocean bathing beaches.

3.1.7.2. Methods

Wyong Council uses the NH&MRC (1990) and the ANZECC (1992) Guidelines to assess the suitability of water for recreational use For primary contact (swimming), the median faecal coliform content should not exceed 150 organisms per 100ml (cfu/100ml) This median is calculated from a minimum of five samples taken at regular intervals not exceeding one month, with four out of five samples containing less than 600 cfu/100ml For secondary contact (boating), the median faecal coliform count should not exceed 1,000 organisms per 100 ml This median is calculated from a minimum of five samples taken at regular intervals not exceeding one month, with four out of five samples containing less than 4,000 cfu/100ml Eight locations are currently sampled and tested for faecal coliforms/100ml (Figure 27, Table 5)

Table 5. Location of recreational water quality sites and frequency of sampling

Location	Variable	Oct-April	May-Sept
Long Jetty Sail Club	Faecal coliforms	Weekly	Monthly
Tumbi Creek	"	Weekly	Monthly
Ourimbah Creek	"	Weekly	Monthly
Canton Beach	"	Weekly	Monthly
Toukley Aquatic Club	"	Weekly	Monthly
San Remo	"	Weekly	Monthly
Gwandalan Pool	"	Weekly	Monthly
Chain Valley Bay	"	Weekly	Monthly

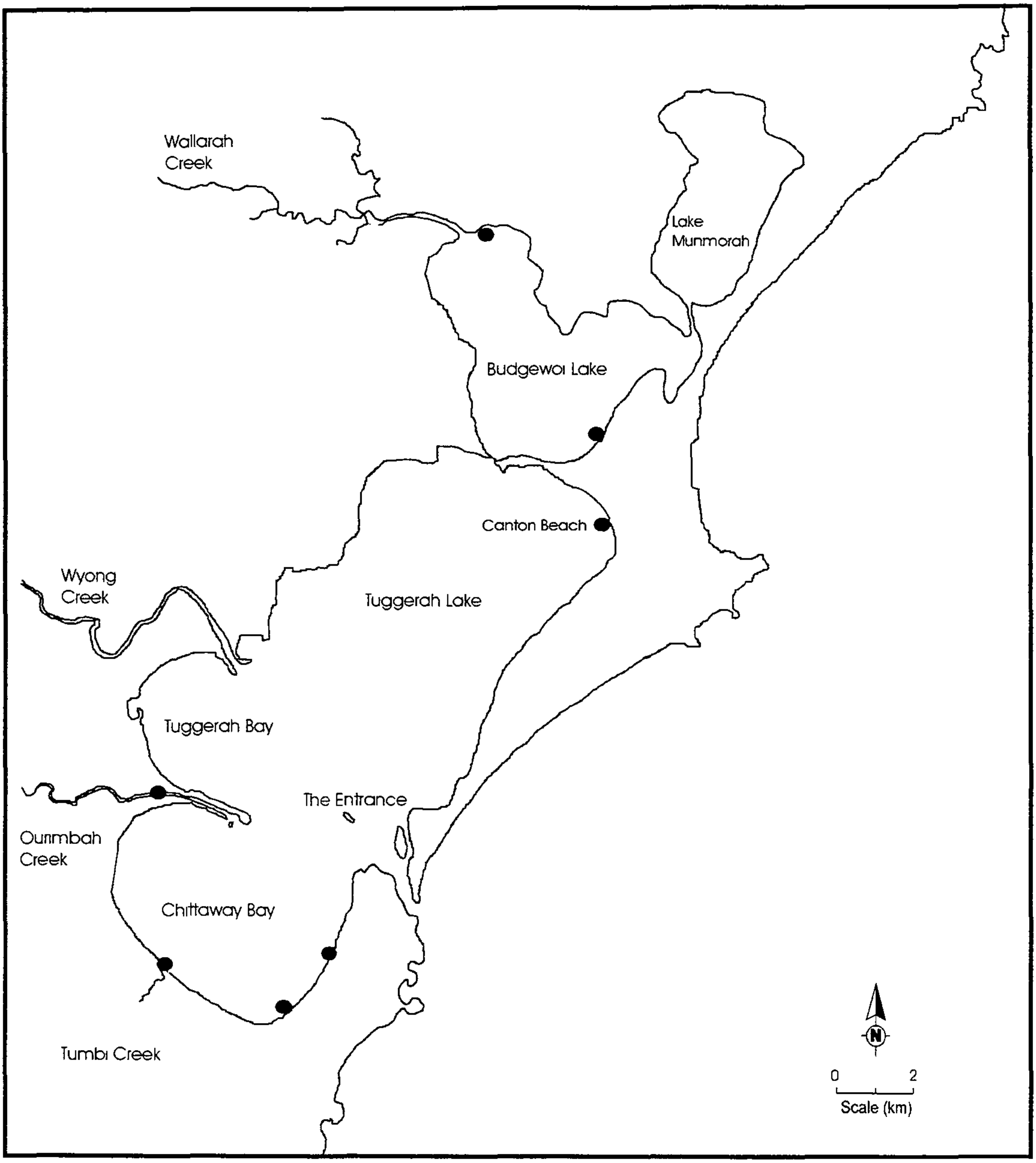

Figure 27. Location of recreational water quality sampling sites

3.1.7.3. *Results and Discussion*

The results of percentage compliance for lake beaches in 1996 and 1997 are typical of what has been recorded since sampliing began in 1985 (Table 6).

Table 6. Percentage compliance for recreational water quality in 1996-97

	1996		1997	
Location	**Primary Contact**	**Secondary Contact**	**Primary Contact**	**Secondary Contact**
Ourimbah Creek	36	91	58	83
Canton Beach	9	55	12	38
Tumbi Creek	18	91	36	73
San Remo	64	100	58	92
Toukley Aquatic	64	100	67	100
Gwandalan	73	100	92	100

The lakes beaches generally perform poorly in terms of the criteria for primary contact, whilst secondary contact performance is considered good for Toukley Aquatic and Gwandalin locations. The other locations all failed the secondary guidelines at certain times.

A major stormwater drain is the main source of faecal coliform contamination at Canton Beach, however the sample location is only one metre from the mouth of the outlet drain. The most likely time that contamination from the drain occurs is after rainfall, however, this is not the only time that it occurs. The gross pollution trap at the exit of the drain acts as a reservoir for faecal coliforms both within the water column and within the sediment. Tumbi Creek and Ourimbah Creek both have significant rural landuse with urban development in the lower part of the catchment, whilst the other sampling sites have largely urban catchments.

A study was commissioned into the use of faecal sterols to discriminate between the sources of faecal pollution within the Tuggerah estuary. The results of this study (CSIRO, 1998) indicated that human faecal matter is only a minor component of the total faecal pollution within the receiving waters during rain events. Faecal pollution at all sites is significant, but it appears to be derived principally from native birds and to a lesser extent domestic pets.

3.2. Chemical Interactions with Estuarine Sediments

Much of the particulate organic matter carried to the estuary by rivers, as well as that produced by biological organisms eventually deposits at the sediment surface This material provides the primary energy source for organisms living in the estuary The respiratory processes of these organisms are called redox reactions (oxidation-reduction) and are defined as the transfer of electrons from one material to another Much of the energy flow in estuarine sediments is regulated by the availability of suitable electron acceptors Oxygen is the most important electron acceptor but at the bottom of an estuary, far away from atmospheric sources, oxygen can become very low Therefore, as we move into the sediment, oxygen is depleted and other electron acceptors (e g sulfate) become important The major product of sulfate reduction is hydrogen sulfide, which occurs naturally in soils with low oxygen concentrations and causes an unpleasant odor There is a natural predictable sequence of chemical processes, which change down the sediment profile The interactions that occur between nutrients, biota and the sediments are complex and we begin this section by describing the current status of nutirents within the bottom sediments of the Tuggerah estuary

3.2.1. Nutrients in Sediments

Nutrient cycling within the Tuggerah Lakes estuary is not well understood and there is uncertainty as to the actual mechanisms and the associated interactions that occur between the biota, sediments and the water column. The estuary acts as a sink for nutrients and sediments that enter via creeks and stormwater An understanding of the way that nutrients cycle within the estuary is essential so that appropriate strategies can be put in place that minimise the risks of environmental degradation (Walkerden and Gilmour, 1996) Quantifying the concentrations of nutrients within the sediments at a number of spatial scales was the first step in gaining an understanding of the process Previous studies have attempted to quantify the concentration of nutrients within the bottom sediments (see King and Hodgson, 1995), however they were generally associated with power station operations and were therefore limited in their spatial assessment The ecological interactions between the seagrass and deeper water habitats have often been the focus of speculation and generalisation with respect to describing the ecology of the estuary It has been stated that there is a significant degree of separation between the nearshore seagrass habitats and the open waters within the estury (Cheng, 1995) A study of the distribution of nutrients within the sediments was therefore done with the aim of quantifying nutrient concentrations at various spatial scales

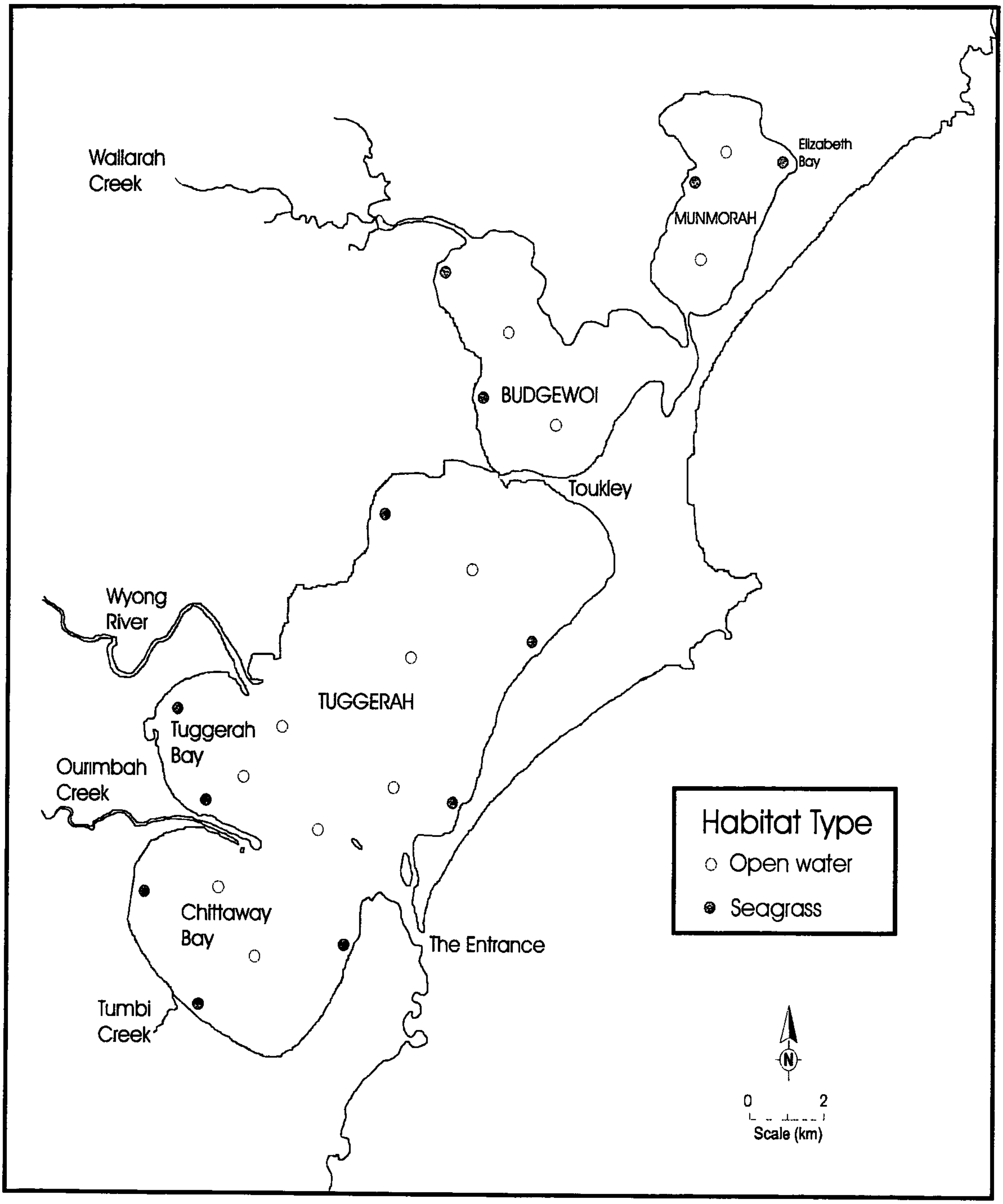

Figure 28. Location of the sites used to estimate the concentration of nutrients in sediments

3.2.1.1. Methods

Sediments were collected using a diver held core from within the lakes at a number of spatial scales The sediments were analysed for total nitrogen, oxides of nitrogen and total phosphorus. There was no temporal component to this study The experimental design had the estuary divided into six locations (Figure 28) Both Lake Munmorah (Location 1) and Budgewoi Lake (Location 2) were considered to be two independent locations whilst Tuggerah Lake was divided into four locations, based on its flushing characteristics This study attempted to quantify the differences in nutrient concentrations within the sediments between the six locations and among the two habitat types Within each location, sampling was done in open water and seagrass habitat Within each habitat, two random sites were sampled by collecting three replicate core sediment samples

3.2.1.2. Results

The concentrations of total nitrogen, oxidisable nitrogen and total phosphourus were generally higher in the open water sediments compared with the shallow seagrass sediments (Figure 29) Lake Munmorah and Budgewoi Lake recorded the highest levels whilst Tuggerah Bay and The Entrance were the lowest There were no significant differences between seagrass locations although site 1 in Tuggerah Bay recorded the lowest concentration (Figure 29) Total oxidisable nitrogen or the nitrogen available for biological activity was generally low (Roberts *et al*, 2000)

A temporal comparison of the nutrient concentrations found within the sediments in both shallow seagrass and deeper open water habitats was done by contrasting data reported by King and Hodgson (1995) with those found in this study (Table 7). The data suggested that there were reductions in the concentration of total nitrogen and increases in total phosphorus in the open water since 1988 In the shallow seagrass habitats however, there appeared to be a significant decrease in nutrient concentrations within the sediments Caution must be applied because the data presented by King and Hodgson (1995) were expressed without any estimates of variation It is difficult to establish whether there was a significant change in the total organic carbon in the sediments through time although generally it appeared to have decreased

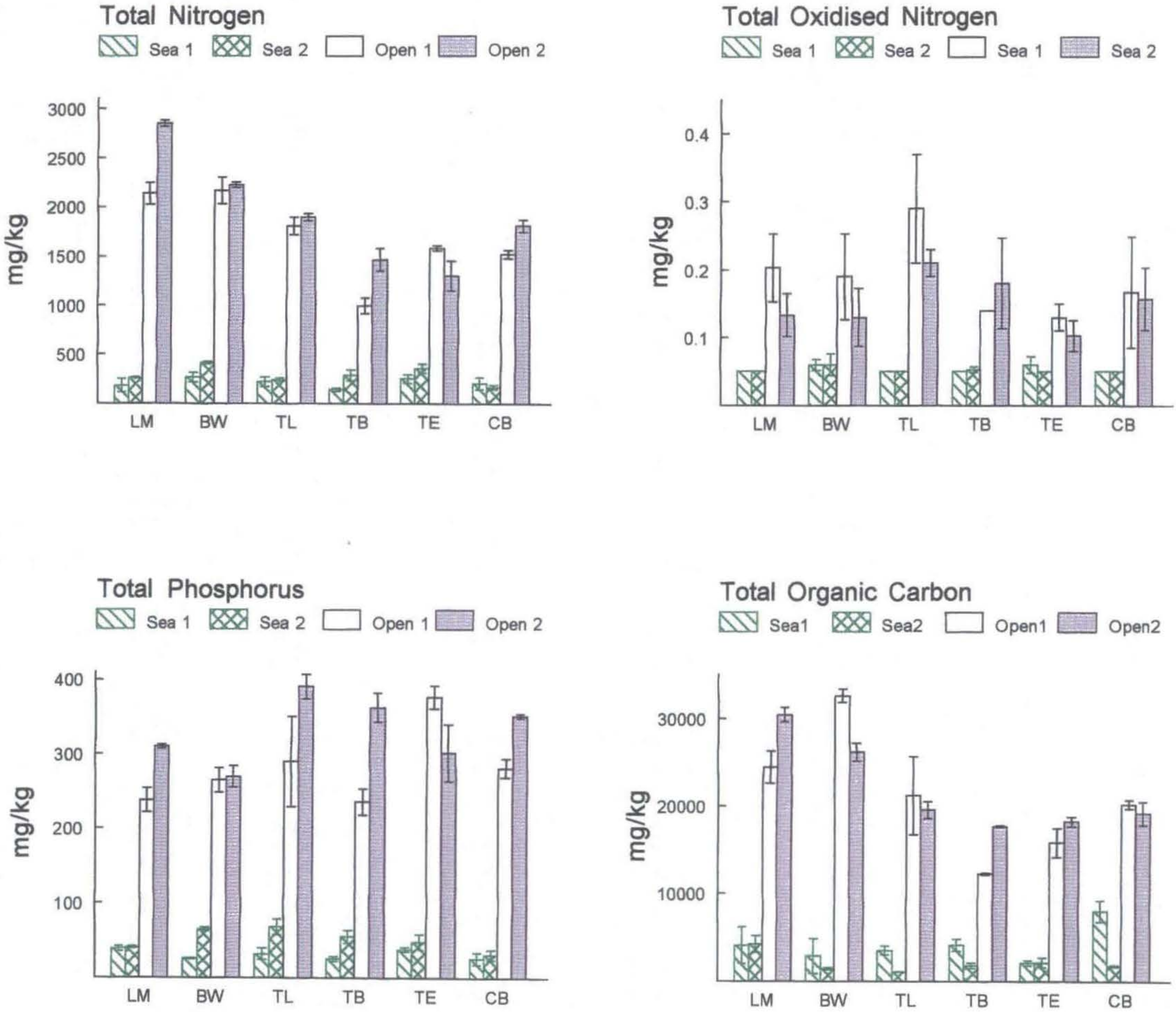

Figure 29. Nutrient concentrations within the sediments of the Tuggerah estuary

Table 7. Comparison of nutrients in the sediments 1988-1997

Open	Munmorah		Budgewoi		Tuggerah	
Nutrient	**1988**	**1997**	**1988**	**1997**	**1988**	**1997**
Total N mg/kg	3400	2500	2500	2200	2400	1850
Total P mg/kg	220	270	250	260	240	340
Total OC (%)	5	2 8	2 7	2 9	3 7	2

Seagrass	Munmorah		Budgewoi		Tuggerah	
Nutrient	**1988**	**1997**	**1988**	**1997**	**1988**	**1997**
Total N mg/kg	2111	220	2100	340	1555	230
Total P mg/kg	112	40	170	45	262	50
Total OC (%)	0 2 - 3 8	0 4	1 6 - 3 2	0 2	1 – 5	0 2

3.2.1.3. Discussion

Generally, the concentrations of nutrients within the sediments were always higher in the deep open water habitats compared to the shallow seagrass habitats The fine muddy sediments found in the deeper habitats are capable of retaining greater concentrations of nutrients (Trimmer *et al*, 1998) Sediments with high organic content have more “places” for nutrients to attach The organic content of sediments generally increases, as the sediment texture becomes finer

For the Tuggerah estuary, the mean total nitrogen concentrations in the sediments across all open water locations was 2,040 5 (± 87 7) mg/kg, whilst total phosphorus was 344 47 (± 10 6) mg/kg To place these results in some regional context, Mann *et al* (1996) reported similar fine-grained sediments from the Hawkesbury River estuary with concentrations of total nitrogen and phosphorus at 3,900 (± 310) mg/kg and 1,035 (±40) respectively Furthermore, the bottom sediments of Sydney Harbour were reported as having total nitrogen and phosphorous concentrations of 2,200 mg/kg and 1,000 mg/kg respectively (Mann *et al.*, 1996) The concentrations of nutrients in the Tuggerah estuary were found to be less than or similar to those reported by King and Hodgson (1995) and from those in other local estuaries (Mann *et al.*, 1996). The ecological significance of these results continues to be the focus of ongoing studies associated with the flux of nutrients from the sediments (Bourgues *et al*, 1998)

3.2.2. Sediment-water Fluxes of Oxygen and Nutrients

Many chemical interactions occur between the sediments at the bottom of an estuary and the water column Organic material is continually deposited onto the bottom and therefore the surface of the sediment becomes an important place where organic matter is broken down and recycled When dissolved oxygen levels at the sediment/water interface become low or drop to zero the potential for nutrients "locked up" in the sediments to re-enter the water column is greatly increased It is necessary therefore to quantify the contribution of sediment-water exchanges to oxygen and nutrient cycling within the estuary (Bourgues *et al*, 1998) The flux of dissolved oxygen and the nutrients ammonium, nitrate, nitrite and phosphate were quantified within the sediments of the Tuggerah estuary using the core incubation technique under dark conditions (Bourgues *et al*, 1998) The full details of the methods used are described in Bourgues *et al* (1998)

Oxygen was never highly depleted from the water column, whilst its uptake ranged from 9-75 mmol $m^2.d^{-1}$ and was enhanced by increased water temperatures (Bourgues *et al*, 1998) Ammonium fluxes varied from 0 02-0 24 mmol m^2 d^{-1} Oxidisable nitrogen fluxes were low and directed into and out of the sediment at low temperature Phosphate fluxes were low regardless of the temperature The potential for sediments within the Tuggerah estuary to act as a sink of nitrogen and phosphorus has probably buffered the system against increasing nutrient loads leading to eutrophication The presence of benthic flora and fauna also help to remove nutrients from the sediments and assist in oxygenating the sediment water interface It was estimated that the sediments could potentially provide up to 100 tonnes of nitrogen and 13 tonnes of phosphorus to the system per year

3.2.3. Heavy Metals and Organochlorines in Sediments

Heavy metals and organochlorine pesticides can accumulate within sediments and have the potential to cycle through the food chain These compounds can be toxic to aquatic organisms and can bioaccumulate in fish, shellfish and humans These compounds enter estuaries from urban stormwater, atmospheric fallout and industrial discharges An assessment of the current concentrations of heavy metals and pesticides in the estuarine sediments was done to ascertain any potential for bioaccumulation (Roberts *et al*, 2000) The main objective was to quantify the concentrations of heavy metals and organochlorine pesticides in the sediments at various spatial scales The hypothesis that there would be no significant differences of the various contaminants within sediments between nearshore (vegetated) and deeper (open) zones at a number of spatial scales was tested.

3.2.3.1. Methods

Sediment samples were collected *in-situ* using appropriately prepared hand held corers and sealed containers A total of 72 samples were collected for analysis of the following trace metals, Arsenic (As), Silver (Ag), Cadmium (Cd), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni), Selenium (Se), Zinc (Zn), Chromium (Cr), Iron (Fe), Silicone (Si) and a suite of organochlorine pesticides The experimental design required that the estuary be divided into six locations where both Lake Munmorah (Location 1) and Budgewoi Lake (Location 2) were considered to be two independent locations whilst Tuggerah Lake was divided into four locations based on its flushing characteristics (see Figure 28) Within each location, sampling was done in fixed open water and seagrass habitats Within each habitat, two random sites were sampled by collecting three (3) replicate core sediment samples

3.2.3.2. Results and Discussion

The concentrations of pesticides within the sediments were below the detection limits at all the spatial scales examined There were however, measurable concentrations of all trace metals examined In general, there were greater concentrations of metals in the deep sediments compared to sediments within seagrass habitats (Figure 30) Smaller sediment particles and high total organic carbon within the deep habitats partly explain the higher concentrations of metals because they have greater surface area available for attachment. Sandy sediments generally have less site attachment potential Generally, the concentration of trace metals within the Tuggerah Lakes estuary were below levels recommended by Long *et al* (1995) for adverse environmental effects within estuarine sediments A full description of the contaminants within sediment results can be found in Roberts *et al* (1999) Tuggerah Bay generally had the lowest concentration of metals within the open water habitats, whilst cadmium, copper, mercury and zinc were generally highest in Lake Munmorah and Budgewoi Lake These relatively higher concentrations may be attributed to the operation of the Munmorah Power Station A review by Batley *et al.* (1990) on heavy metal contamination within the sediments of the Tuggerah estuary focused on the potential effects associated with power station operations Although the data used in the review were spatially limited, it is worthwhile comparing these data with those collected in the current study (Table 8). The concentration of copper, zinc and lead within the sediments were generally lower in 1997 compared with those reported by Batley *et al* (1990) Batley *et al*, (1990) provided data on heavy metals within the estuarine water column and suggested that the concentrations of zinc and copper from the cooling water discharge was a primary source of these metals to the estuary

Table 8. Temporal comparison of trace metals within sediments

	Munmorah		Budgewoi		Tuggerah	
Metal mg/kg	**1990***	**1997**	**1990***	**1997**	**1990***	**1997**
Copper	60 - 70	42 ± 7	30 - 60	46 ± 9	20	15 ± 1
Zinc	140 - 150	91 ± 13	100 - 140	90 ± 11	110	72 ± 7
Lead	35 - 40	27 ± 3	25 - 40	30 ± 1	40	24 ± 2

*After Batley *et al* (1990)

Sediment contamination within the Tuggerah estuary was considered to be reasonably low and whilst there are some potential elevated levels due to anthropogenic sources we can be reasonably sure that adverse ecological implications for the estuary is minimal To place the Tuggerah estuary into perspective it is useful to compare trace metal concentrations of sediments from other NSW estuaries (Table 9) Scanes *et al* (1998) reported "background" concentrations of pesticides and trace metals in natural oysters growing at the mouth of the Tuggerah Lakes estuary Interestingly they did not detect trace metals within the oysters but did detect some pesticides

Table 9. Comparison of trace metals in sediments with other estuaries

Trace Metal mg/kg	Tuggerah Lakes	(a) Berowra Creek	(a) Sydney Harbour (*)	(b) Lake Illawarra	(c) Lake Macquarie
Ag	0 1 ± 0 01	0 4 ± 0 04	2 0 ± 0 8 (2)	-	-
As	14 5 ± 0 9	16 ± 0 9	24 ± 22 (25)	-	-
Cd	0 09 ± 0 01	0 31 ± 0 04	2 ± 0 6 (3)	3	2 4 ± 0 4
Cr	38 4 ± 1 6	57 ± 4	51 ± 25 (118)	-	-
Cu	23 1 ± 3 3	30 ± 4	10 ± 10 (124)	28 - 40	16 ± 1 5
Hg	0 05 ± 0 003	< 0 5	-	-	-
Ni	17 6 ± 0 6	24 ± 2	26 ± 14 (38)	-	-
Pb	26 4 ± 1 5	60 ± 13	33 ± 25 (268)	17 – 33	79 2 ± 9 9
Se	2 79 ± 0 2	1 9 ± 0 1	-	-	-
Zn	72 2 ± 4 2	116 ± 7	47 (548)	46 - 550	72 7 ± 9 9

* Data are from polluted locations in Sydney Harbour

Data source - (a) Mann *et al* (1996), (b) Chenhall *et al* (1994), (c) Batley (1987)

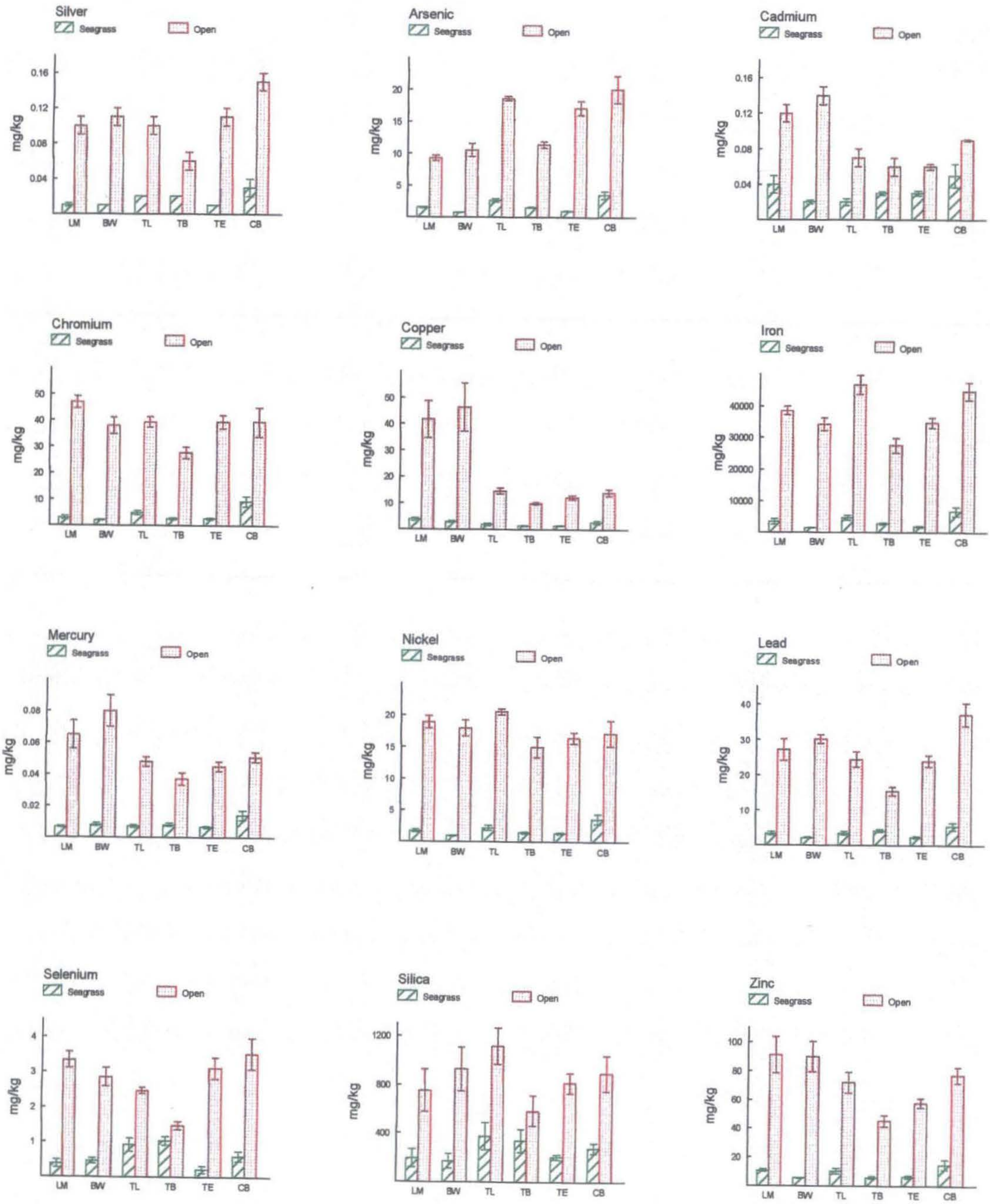

Figure 30. Trace metals within the sediments of the Tuggerah estuary

3.2.4. Potential Acid Sulfate Soils

When exposed to air, acid sulfate soils oxidise and can form sulphuric acid. After rain this acid can wash into waterways and effect aquatic organisms. Acid in the soil can also reduce the ability of the soil to support plants. Potential acid sulfate soils within the catchment and around the estuary have been identified and mapped (Figure 31). Generally, potential acid sulphate soils dominated the estuary and any distubance to these soils may have an impact on the receiving waters quality. Under current legislation any disturbance of soil must be approved by the appropriate agencies with a plan of management for acid sulphate soils (see WSC, 1999).

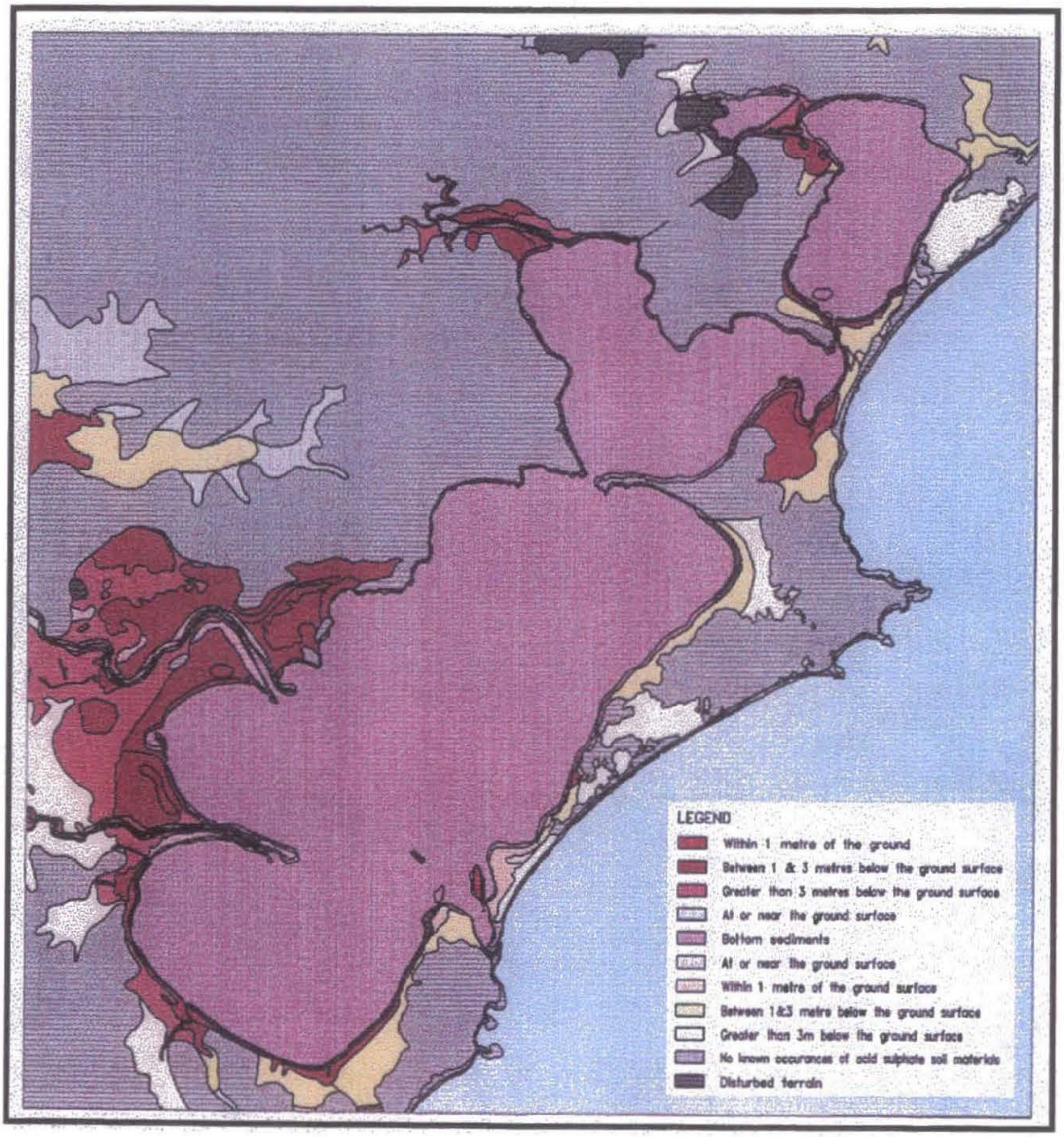

Figure 31. Potential acid sulphate soils around the estuary

4. PATTERNS IN THE BIOLOGICAL ASSEMBLAGES

4.1. Introduction

The Tuggerah Lakes estuary supports a range of aquatic, semi-aquatic and terrestrial biological communities. The major habitats within the estuary are the water column, the sediments and the fringing shoreline that surrounds all three lakes (Figure 32). The individuals, populations and assemblages of organisms that occupy these habitats have adpated to a way of life that may be considered harsh from a biological point of view. Estuaries are difficult places for organisms to live because of the highly variable physical and chemical processes that occur, over small spatial and temporal scales. However, estuaries are considered to be one of the most productive of ecosystem types. In reporting spatial and temporal patterns in the assemblages of plants and animals that live in the estuary we should begin with the smallest organisms which are essential to the cycling processes i.e. bacteria. For our purposes however they will be discussed later, in terms of their role in ecological processes. The reason we do this is it is more relevent to examine why they are important to the estuary rather than just describing their distribution and or abundance. The assemblages described below have been divided into the flora (plants) and animals (fauna) and are discussed separately. Biological assemblages can never truely be studied in isolation because of the complex ecological interactions that occur at various scales of organisation. It should be remembered that descriptions of biological patterns should never be used to infer processes in ecology (Underwood, 1997).

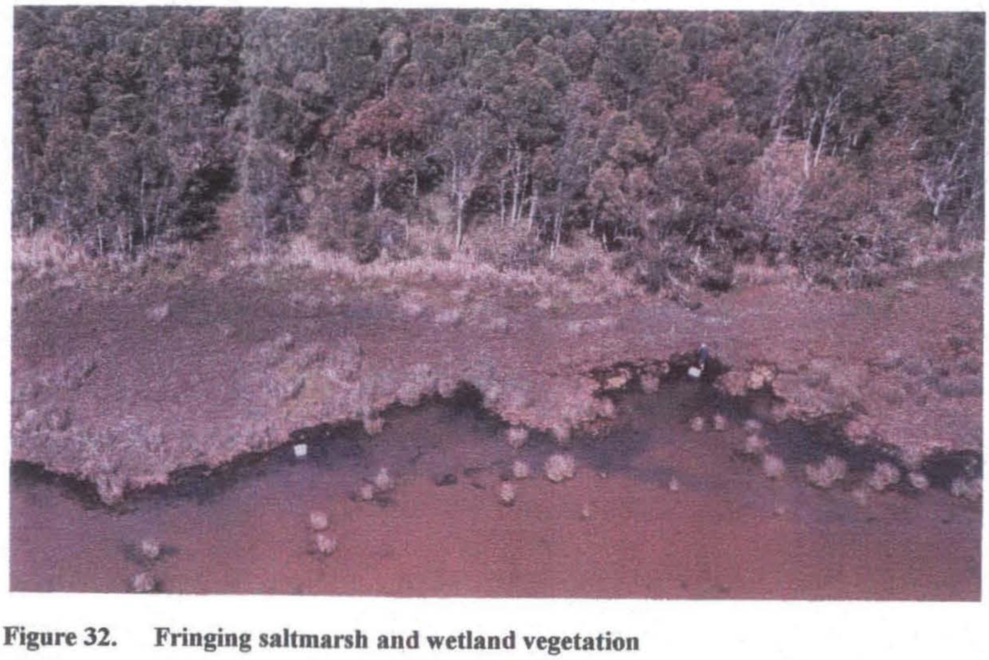

Figure 32. Fringing saltmarsh and wetland vegetation

4.2. Flora of the Tuggerah Estuary

4.2.1. Fringing Wetlands

4.2.1.1. Introduction

Saltmarshes and fringing wetlands are important to estuaries because they are believed to be one of the most productive of plant communities, and prior to human disturbances, often occupied the largest area of the shoreline vegetation They provide a source of food to estuarine consumers and serve as a habitat for large numbers of juvenile and adult estuarine organisms (Sainty, 1998) These habitats are also considered to be very important in the nutrient cycling process within estuaries and this role is currently being investigated

There are a number of remnant wetlands surrounding the estuary and whilst there was qualitative information on these communities (WSC, 1994, NPWS, 1995, TBC, 1997) no quantitative data existed A study was done to gain baseline information at a number of spatial scales on the existing fringing wetland flora of the estuary The objective was to gain quantitative background data on the fringing vegetation so that assessment of long-term changes associated with estuary management practices could be made (Sainty, 1998) The data were to be further used to assess the management effectiveness of foreshores and sub-catchments Further work on fragmented and disturbed saltmarsh and foreshores is now being done and will be reported in the management studies

4.2.1.2. Methods

Quantitative estimates of the distribution and abundance of fringing wetland flora were made by sampling nine (9) locations around the estuary (Figure 33) At each location, three (3) random plots (10m x 10m) were randomly sampled, and estimates of the species composition and percentage cover of flora determined Within each plot, five (5) replicate, 2m x 2m quadrats were sampled The locations were (1) Tuggerah Bay, (2) Chittaway Point, (3) Tacoma, (4) Eel Haul Bay, (5) Terilbah Island, (6) Ooroaloo Point, (7) East Budgewoi (behind sandmass), (8) Colangra Swamp and (9) Elizabeth Bay

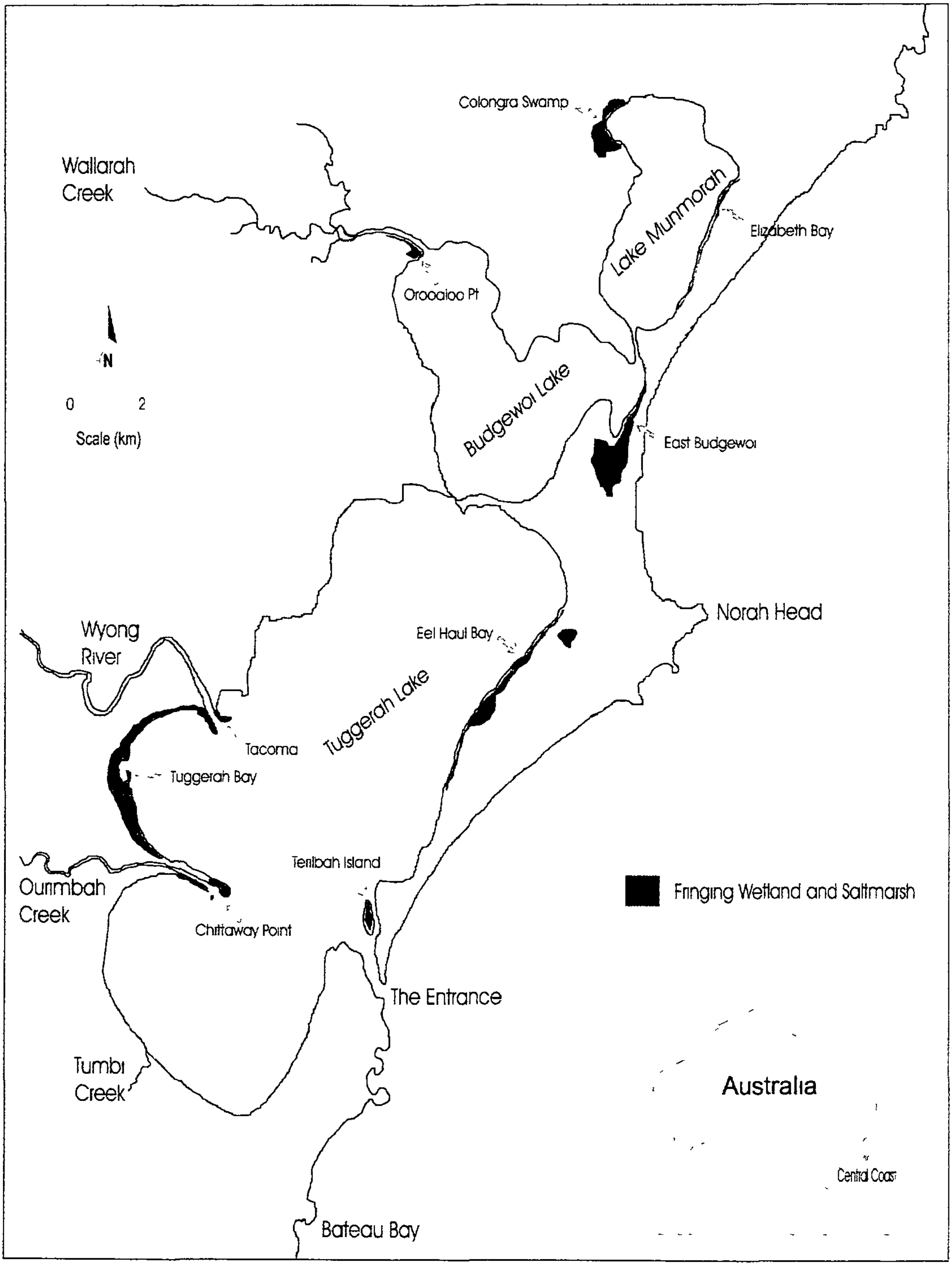

Figure 33. Study locations for fringing wetland vegetation assessment

4.2.1.3. Results and Discussion

The Tuggerah Lakes estuary was found to have diverse saltmarsh and wetland assemblages (Sainty, 1998) At the spatial scales examined, seventy-eight species were identified, however of these approximately thirty percent were weeds (Table 10) The assemblages of saltmarsh plants were typical of others described along the eastern coast of New South Wales (Adam *et al*, 1988) *Sporobolus virginicus, Sarcocornia quinqueflora* and *Juncus kraussii* were commonly the dominant species found within each habitat (Figure 34)

Long-term changes to the quantity and frequency of the inundation by water have probably changed the vegetation patterns at some sites These processes appeared to be changing the distribution of the flora at Colongra Swamp and Orooaloo Point Evidence is provided by the transitional state of the vegetation from dominance of saltmarsh species to that of species only partially tolerant of saline conditions (e g *Bolboschoenus caldwellii* and *Baumea juncea*) The occurrence of these particular species within the saltmarsh indicated that the area has not been inundated with saline water for some period This may be attributed to a natural stage of succession, common to low lying areas, where sedimentation gradually raises the level of the shore and effectively decreases the level of inundation by sea water (Morrisey, 1995)

A large proportion of the remaining fringing saltmarsh and wetland habitats exist in areas that historically have had little economic value, in terms of urban or industrial development Human encroachment around the estuary has reduced their total area by over eighty percent The Wyrrabalong National Park offers some measure of protection, however the issues regarding weed invasions into these areas is of some concern Furthermore, the National Park does not encompass any of the remaining significant saltmarsh habitats Of the nine sites studied, only two appeared to be unaffected by direct or indirect anthropogenic disturbance (Orooaloo Point and Colongra Swamp) The remaining seven sites varied from severely (Elizabeth Bay and Eel Haul Bay) to moderately degraded, with respect to the extent of weed invasions

Three sites were situated within the Wyrrabalong National Park and unfortunately at least two of these appear to be under the greatest threat from weed invasions Sites with difficult or no access were relatively free from weeds and appeared to be the most healthy (e g Orooaloo Point and Colongra Swamp) The Tuggerah Bay site is in urgent need of management attention because of its unique value to the estuary (from both an ecological and conservation viewpoint)

Table 10. List of species within the fringing saltmarsh and wetland habitats of the Tuggerah Lakes estuary (* denotes weed species).

Acacia longifolia	Lagunaria patersonia*
Acetosa sagittata*	Lantana camara*
Agrostis avenacea	Lepidium sp *
Apium prostratum	Leptinella longipes
Aster subulatus*	Leptospermum laevigatum
Atriplex australasica	Livistona australis
Atriplex prostrata*	Lobelia alata
Avicennia marina	Lomandra longifolia
Baumea juncea	Melaleuca ericifolia
Bolboschoenus caldwellii	Melaleuca quinquenervia
Bolboschoenus fluviatilis	Mimulus repens
Cakile maritima*	Paspalum distichum
Carex appressa	Paspalum vaginatum
Carpobrotus glaucescens	Paspalum urvillei*
Casuarina glauca	Pennisetum clandestinum*
Centaurium sp *	Phragmites australis
Chrysanthemoides monilifera*	Protasparagus aethiopicus*
Cladium procerum	Pteridium esculentum
Commelina cyanea	Samolus repens
Conyza canadensis*	Sarcocornia quinqueflora
Cotula coronopifolia	Schoenoplectus mucronatus
Crinum pedunculatum	Schoenoplectus validus
Cynodon dactylon	Selliera radicans
Cyperus laevigatus	Senecio anacampserotis
Dianella tasmanica	Senecio biserratus
Einadia trigonos	Senecio minimus
Eleusine indica*	Sesuvium portulacastrum
Erechtites valerianifolia*	Setaria gracilis*
Ehrharta sp *	Solanum americanum*
Entolasia marginata	Sonchus asper*
Gladiolus undulatus*	Spergularia marina*
Hemarthria uncinata	Sporobolus virginicus
Hydrocotyle bonariensis*	Stenotaphrum secundatum*
Hypolepis muelleri	Stephania japonica
Imperata cylindrica	Suaeda australis
Ipomoea cairica*	Tetragonia tetragonoides
Ischaemum australe	Triglochin striatum
Isolepis nodosa	Typha domingensis
Juncus kraussii	Zoysia macrantha

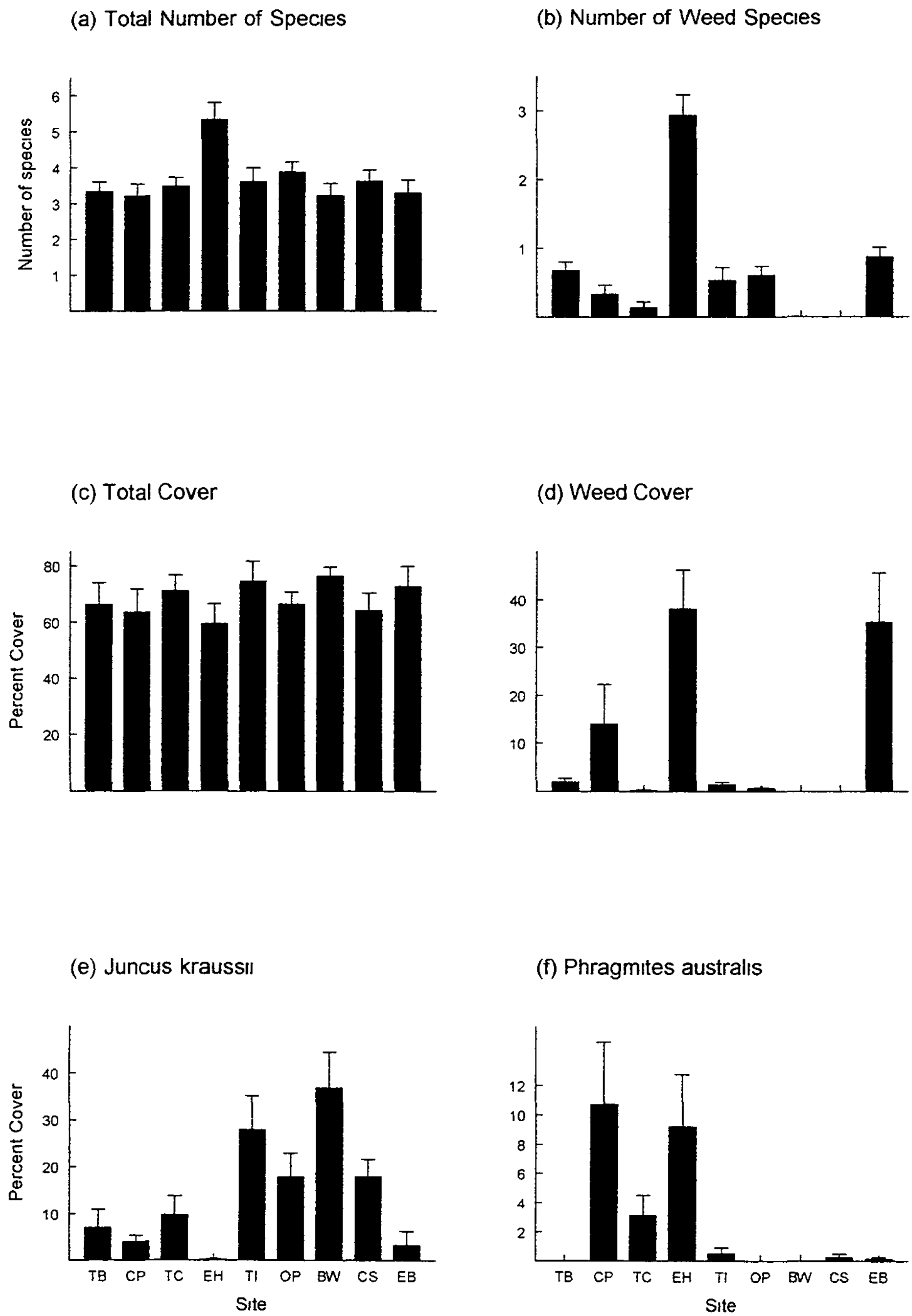

Figure 34. Mean (± se) richness and abundance of saltmarsh and wetland flora

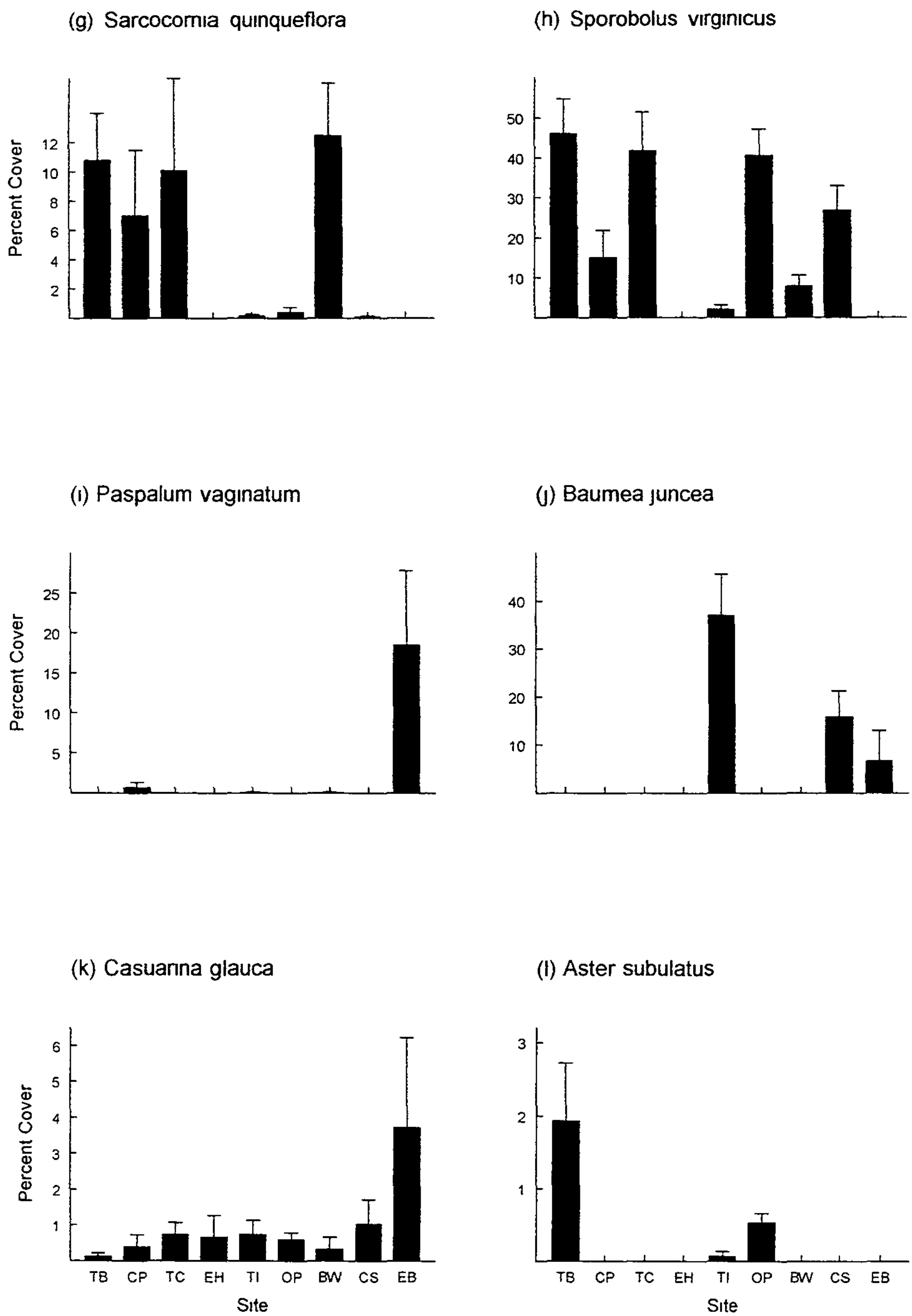

Figure 34. continued

4.2.2. Seagrasses

4.2.2.1. Introduction

Seagrasses are aquatic angiosperms (flowering plants) that are important biological components of coastal estuaries They provide nursery grounds and food for commercially important prawns, fish and wading birds (Gallegos and Kenworthy, 1996) and generally act as a structural habitat for a variety of estuarine animals and plants Seagrasses provide a role in stabalising bottoms and shorelines and act as a natural water filter for suspended solids Large-scale declines (up to 85%) in seagrass meadows have been recorded within NSW estuaries (West *et al*, 1985, Walker and McComb, 1992, Smith *et al*, 1997) and in some instances (e g Botany Bay) these changes appeared to have resulted in permanent loss (West *et al*, 1990) Increased turbidity, siltation, nutrients and epiphytic and benthic algae have the potential to cause a reduction in the distribution and abundance of seagrasses (West *et al*, 1985) Light is the primary environmental factor influencing photosynthesis, growth and depth distribution of submerged plants (Dennison, 1987) therefore water clarity, is the primary water quality variable that can affect seagrasses, although salinity will limit their distribution Provided with a suitable substratum for their establishment, seagrasses will colonise to a depth where reductions in light reaching the plant preclude effective photosynthesis Any significant reduction in light transmission through the water column will bring about a reduction in the depth at which seagrasses will survive In clear waters, seagrass should be able to survive at much greater depths than in turbid waters (if substratum characteristics are favourable and no limitation is imposed through other interactions).

Seagrass meadows are an important component of the Tuggerah Lakes estuary and an assessment of the spatial and temporal abundance of seagrass meadows was considered important The spatial extent of the seagrass meadows within the estuary was mapped in the early 1960's (Higginson, 1965) and since that time, seagrass distribution has been mapped many times (West *et al*, 1985, King and Holland, 1986, King and Hodgson, 1995) King (1996) recently mapped the seagrass meadows within the estuary, whilst comparative seagrass mapping within the Tuggerah Lake was completed as part of collaborative studies between ERM (for COAL Australia) and Wyong Shire Council (Pearson, 1998) The effects of pollution (Higginson, 1971) and power station operations (Batley *et al*, 1990, King and Hodgson, 1995) on seagrasses have also been doen Daley (1997) examined the physical effects of disturbance on seagrass meadows in Chittaway Bay and Tuggerah Bay whilst Otway *et al* (1998) included Tuggerah Lake as part of a larger experiment examining the effects of haul netting on seagrass meadows in NSW estuaries

Three species of seagrass occur within the Tuggerah estuary, *Halophila ovalis* (R Brown) Hooker f , *Ruppia megacarpa* (Mason) and *Zostera capricorni* (Ascherson) and their spatial extent and relative abundance in all three lakes were last assessed by King (1996) A series of seasgrass maps were produced from 1963 through to 1975, from data collected by the Electricity Commission of NSW (Inter-Departmental Committee, 1979) Early reports by District Fisheries Inspectors suggested that the growth of *Ruppia* (Stackweed) in the 1920's was so vigorous that it hampered fishing and boating, whereas in the 1940-1950's seagrass distribution had declined (Inter-Departmental Committee, 1979) Anecdotal evidence suggesting significant fluctuations in the extent of seagrass meadows in the estuary were re-afirmed by Scott (1999) using oral history techniques in an attempt to describe the long-term changes to the ecology of the estuary The first published maps of seagrass distribution were produced in 1962 using air photograph interpretation and groundtruthing (Inter-departmental Committee, 1979) The distribution of seagrass in the estuary changed significantly over the period from 1963 to 1996 (see Figures 35-43) Generally, the extent of seagrass cover in the estuary has declined and a comparison of the changes in the spatial extent of seagrass meadows (km^2) was made using data published in King and Hodgson (1995) with the most recent seagrass maps produced by King (1996) In the 1960's, it was estimated that there were over 40 km^2 of seagrass meadows within the estuary (King and Hodgson, 1995) and by 1996 this had been reduced to approximately 20 km^2, representing a decline of around 50% (Figure 44) This situation has been documented in estuaries worldwide, and there are many mechanisms that cause seagrass decline including dredging, reclamation and the effects of eutrophication (Walker and McComb, 1992) Increased turbidity caused by localised disturbance and increased runoff from the catchment may also have resulted in an overall loss of seagrass meadows through time (Doherty, 1998) The historical water quality data, suggested increased turbidity in the estuary since 1993, whilst the decline in seagrass extent corresponds with decreased secchi depth from 1980 to the early 1990's An alternative model that could explain changes to seagrass distribution is the fluctuating salinity caused by entrance channel closures and flooding Caution must be applied when interpreting patterns in bological assemblages and natural fluctuations in seagrass distribution and abundance may just represent long-term natural changes irrespective of anthropogenic disturbance

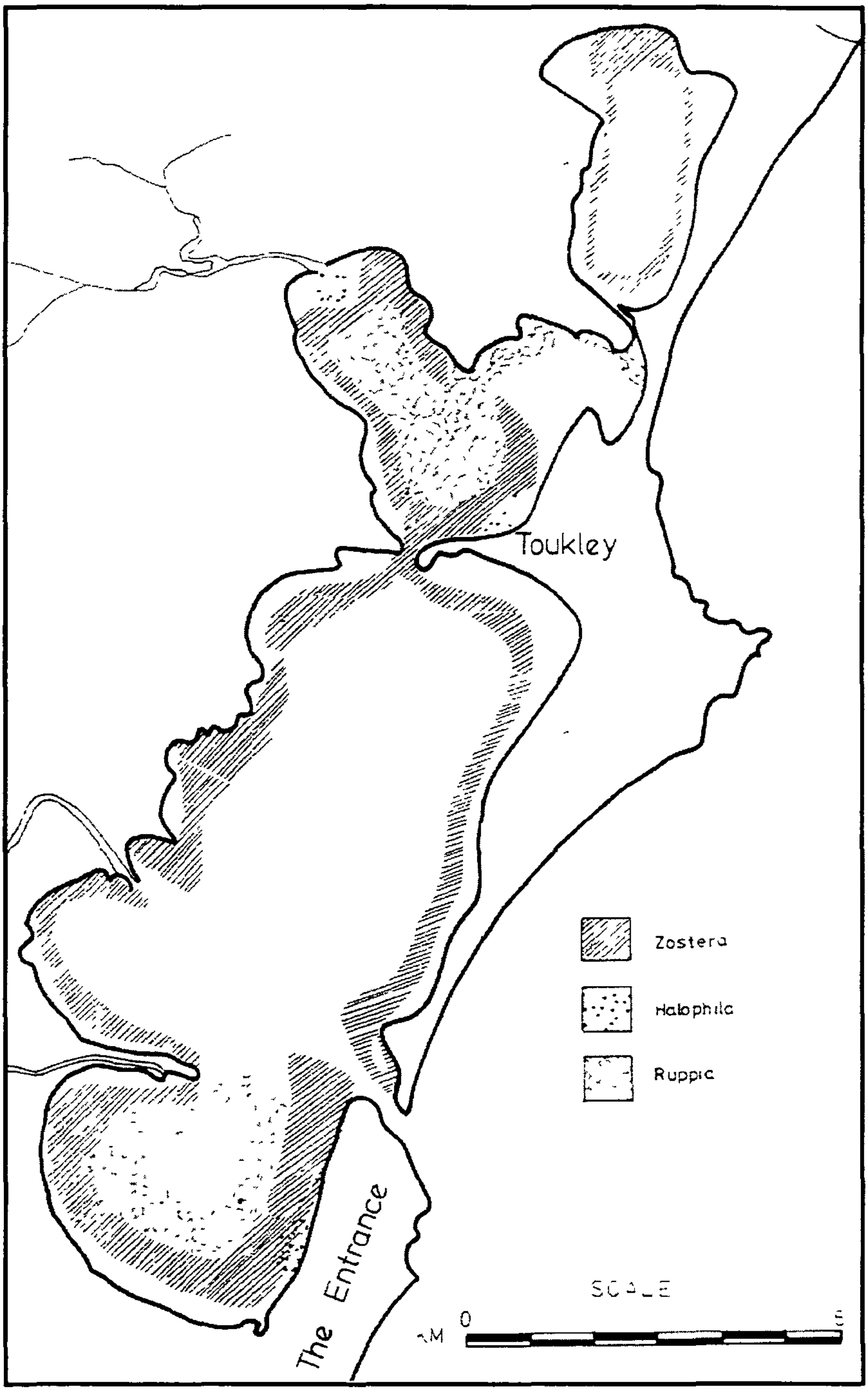

Figure 35. Distribution of seagrasses in 1963 (after Inter-Departmental Committee, 1979)

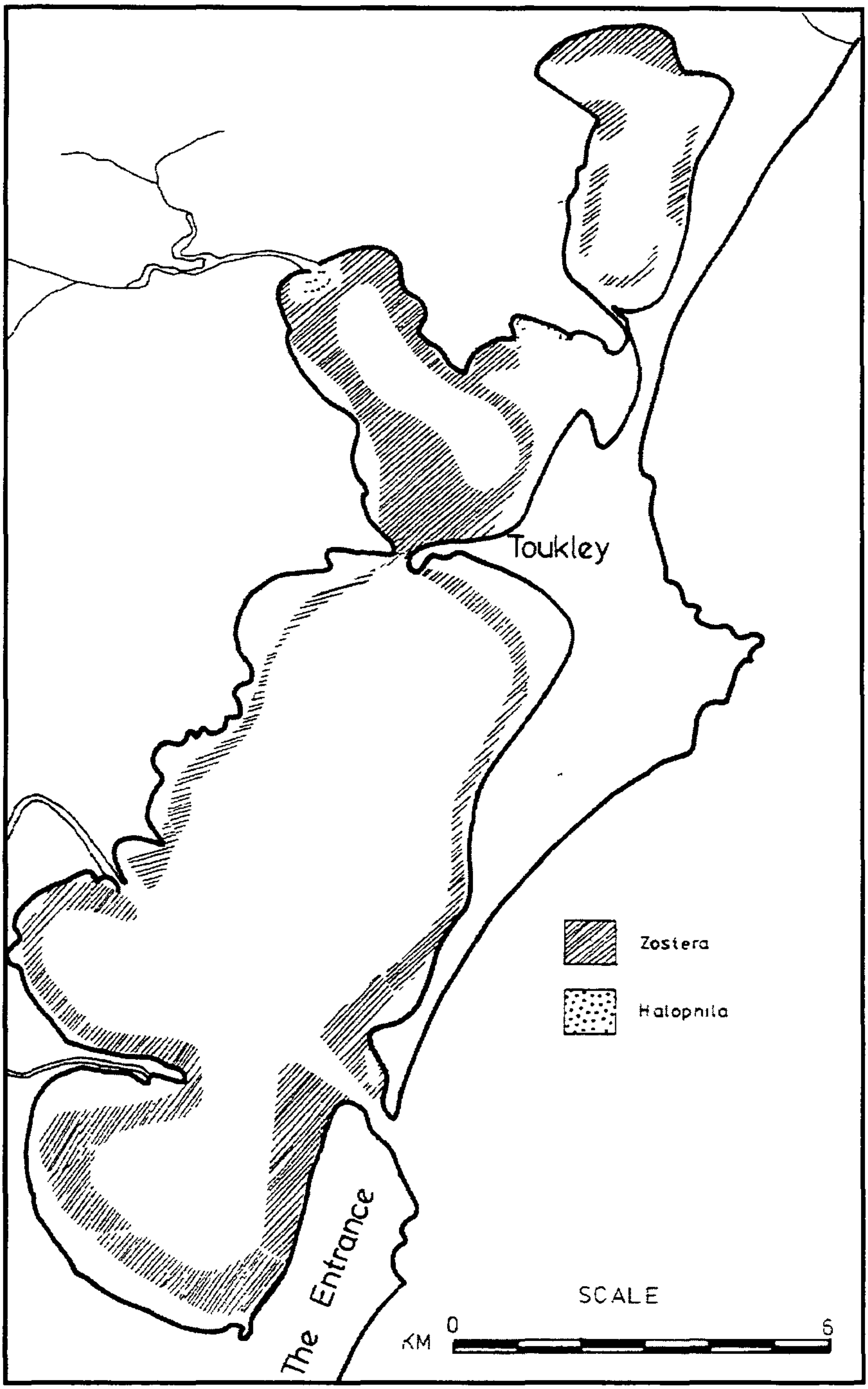

Figure 36. **Distribution of seagrasses in 1966 (after Inter-Departmental Committee, 1979)**

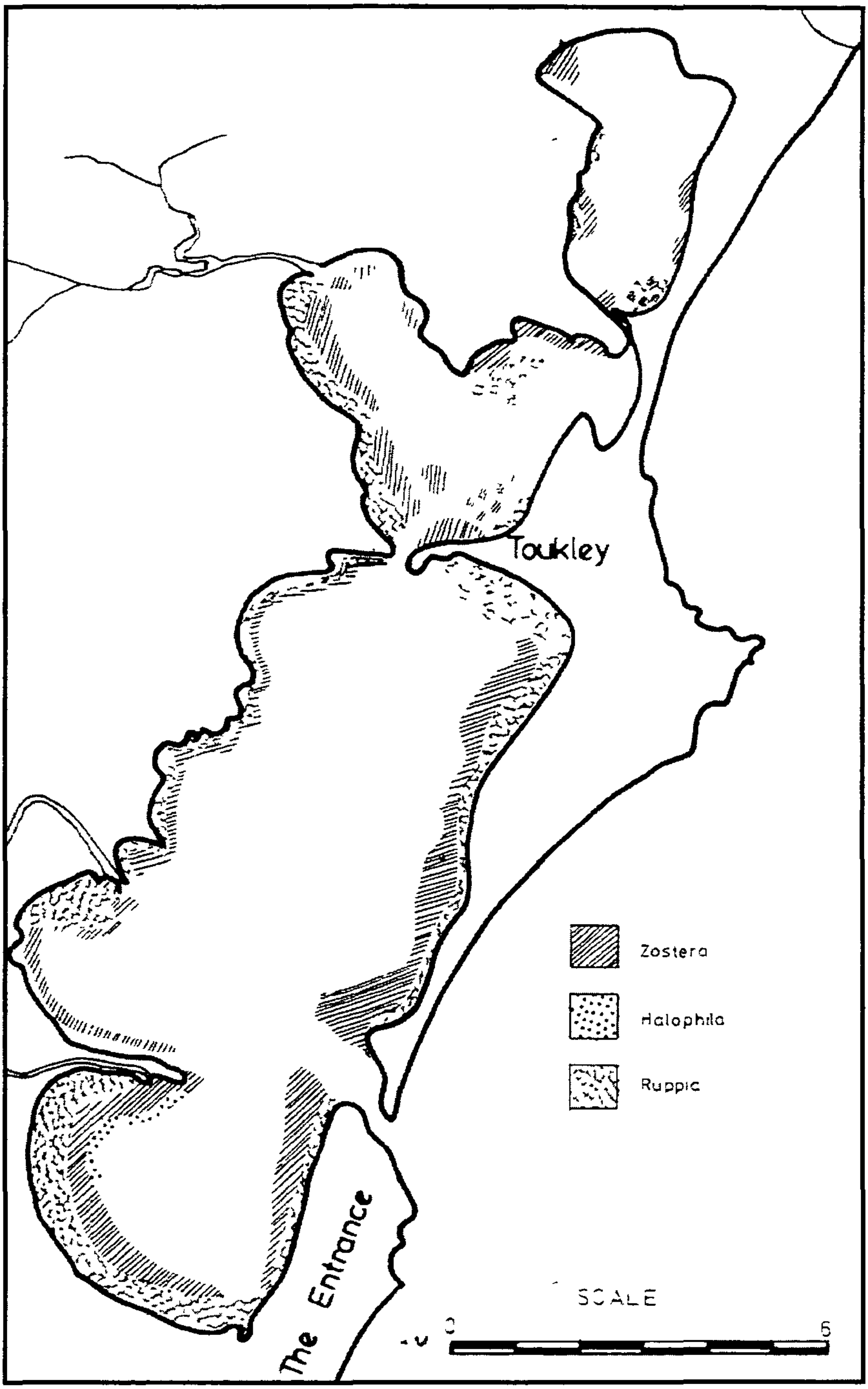

Figure 37. Distribution of seagrasses in 1974 (after Inter-Departmental Committee, 1979)

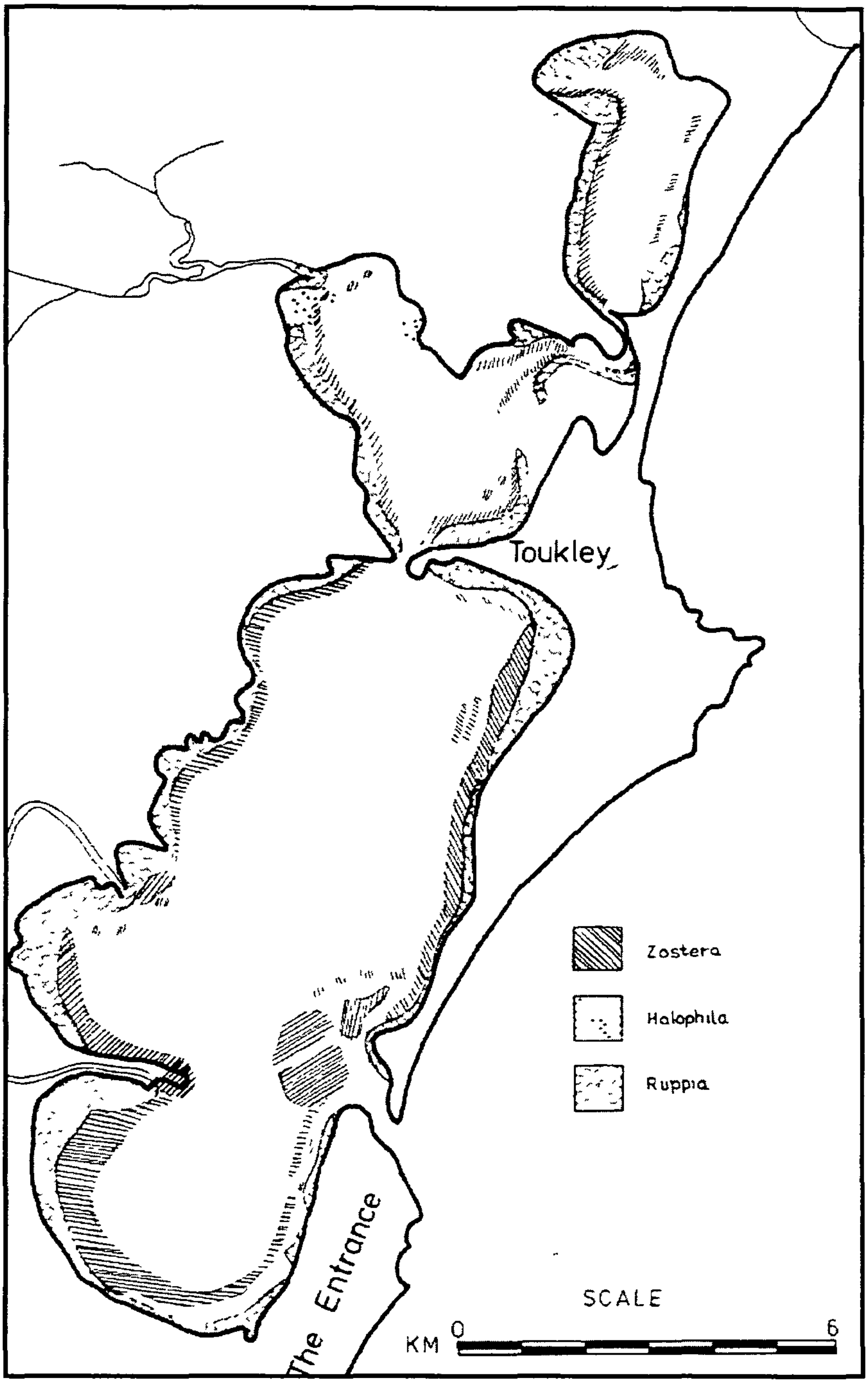

Figure 38. **Distribution of seagrasses in 1976 (after Inter-Departmental Committee, 1979)**

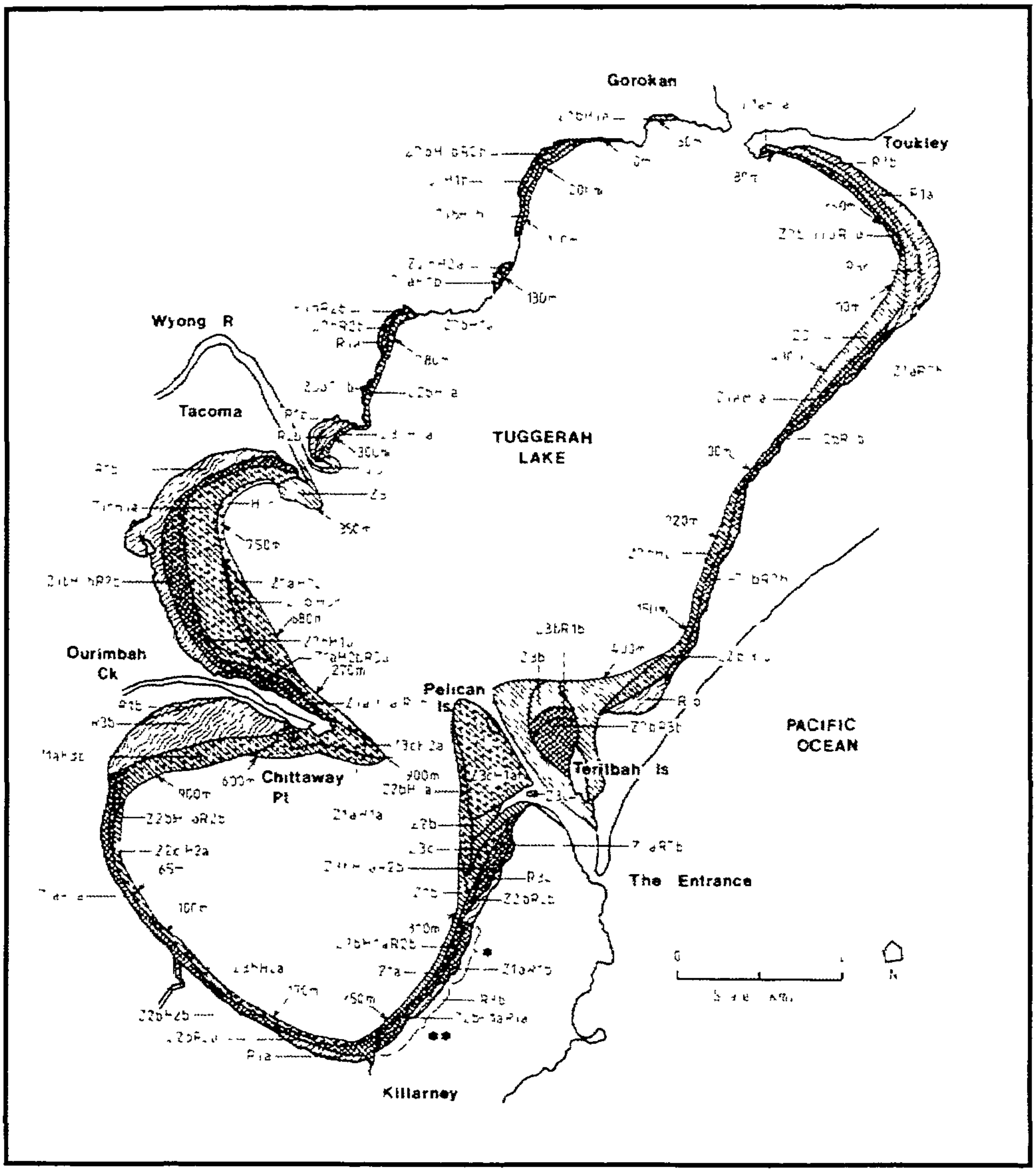

Figure 39. Distribution of seagrasses in Tuggerah Lake in 1985 (after King and Holland, 1986)

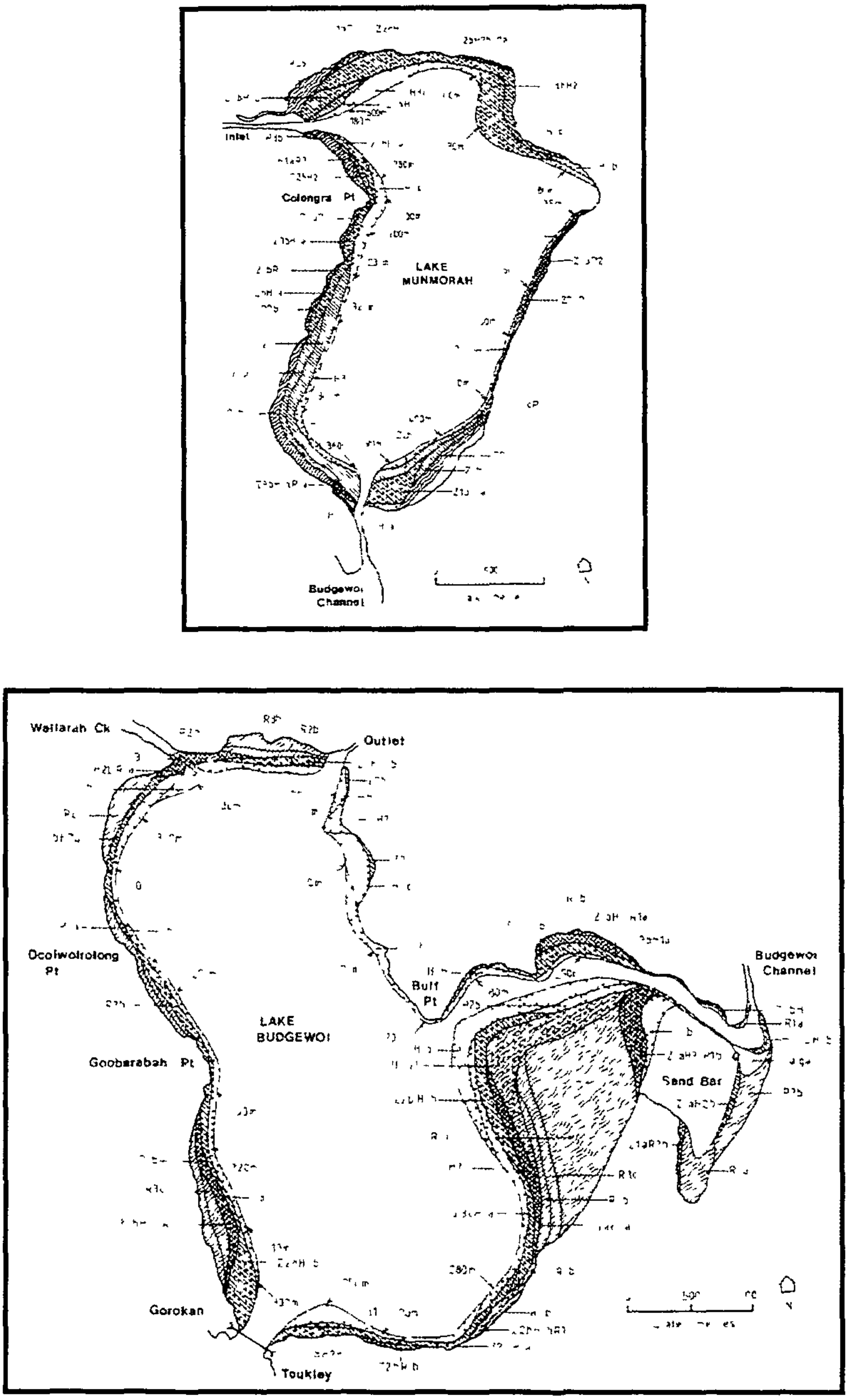

Figure 40. Distribution of seagrasses in Budgewoi Lake and Lake Munmorah in 1985 (after King and Holland, 1986)

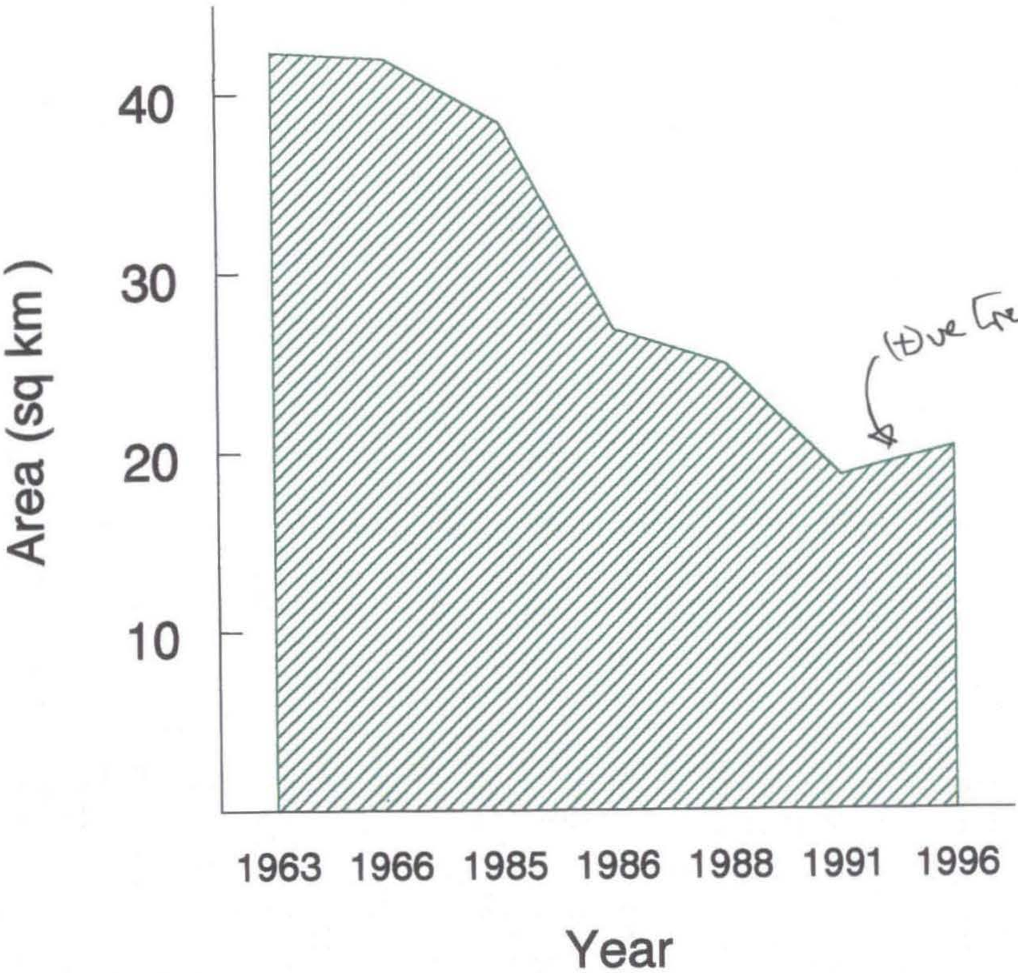

Figure 44. **Area of seagrass decline since 1963**

Whilst there have been many studies done on seagrasses within the Tuggerah Lakes estuary, there are limited data which quantify spatial and temporal patterns of seagrass distribution and abundance at appropriate scales (however see Otway *et al.*, 1998). Assessment of seagrass abundance is currently being done at various spatial and temporal scales as part of monitoring associated with "weed" harvesting (Casey, 1999). This research will quantify changes in leaf length, shoot density and biomass of the seagrass *Zostera capricornii*, and assess the effects of the mechanical weed harvester on seagrass assemblages.

4.2.3. Macroalgae

4.2.3.1. Introduction

Benthic macroalgae carry out a number of important functions in aquatic habitats (Smith, 1999) as they contribute to primary production and provide a habitat and food source for many organisms including macroinvertebrates and fishes Unlike seagrasses, macroalgae are confined to obtaining their nutrients from the water column (Nielson and Jernakoff, 1996) Ephemeral species of macroalgae can rapidly expand their biomass in response to nutrient enrichment of the water column (Duarte, 1995) and shading by these assemblages can reduce the abundance and diversity of slow-growing macrophyte species such as seagrasses (Ork and Moore, 1983, Cambridge and McComb, 1984, Burkholder *et al*, 1992) Large clumps of macroalgae or vegetative breakdown after a bloom event can create anoxic conditions and promote the flux of inorganic nitrogen from the sediments or the production of hydrogen sulphide gas (Jorgensen, 1980, Hansen and Kristensen, 1997) Furthermore, severe anoxia can result in the death of the underlying benthic community (Jorgensen, 1980, Sfriso *et al*, 1992, Valiela *et al.,* 1992)

Blooms of ephemeral macroalgae occurred regularly in shallow areas around the Tuggerah Lakes estuary during the late 1980's and early 1990's, and caused lack of amenity for the local community (Cheng, 1990) Excessive growth of certain macroalgae species was thought to be in response to nutrients from urban runoff A number of studies have examined macroalgal populations within the estuary, however these studies have been largely qualitative (see Cheng, 1980, 1984, 1985, 1986a, 1986b, 1987, 1990) Management of these plant assemblages was identified as a high priority and it was thought that macroalgae could be developed as a biological indicator of the success of proposed catchment management strategies (Walkerden and Gilmour, 1996) The main objective of this program was to gain quantitative data that could be used to evaluate changes to macroalgal assemblages over small and large temporal and spatial scales and to determine whether there were differences among developed foreshores and relatively undisturbed shoreline This information was to be used to determine patterns of macroalgae abundance and to assess the response of the assemblage to potential changes in catchment management practices (Cummins *et al*, 1999)

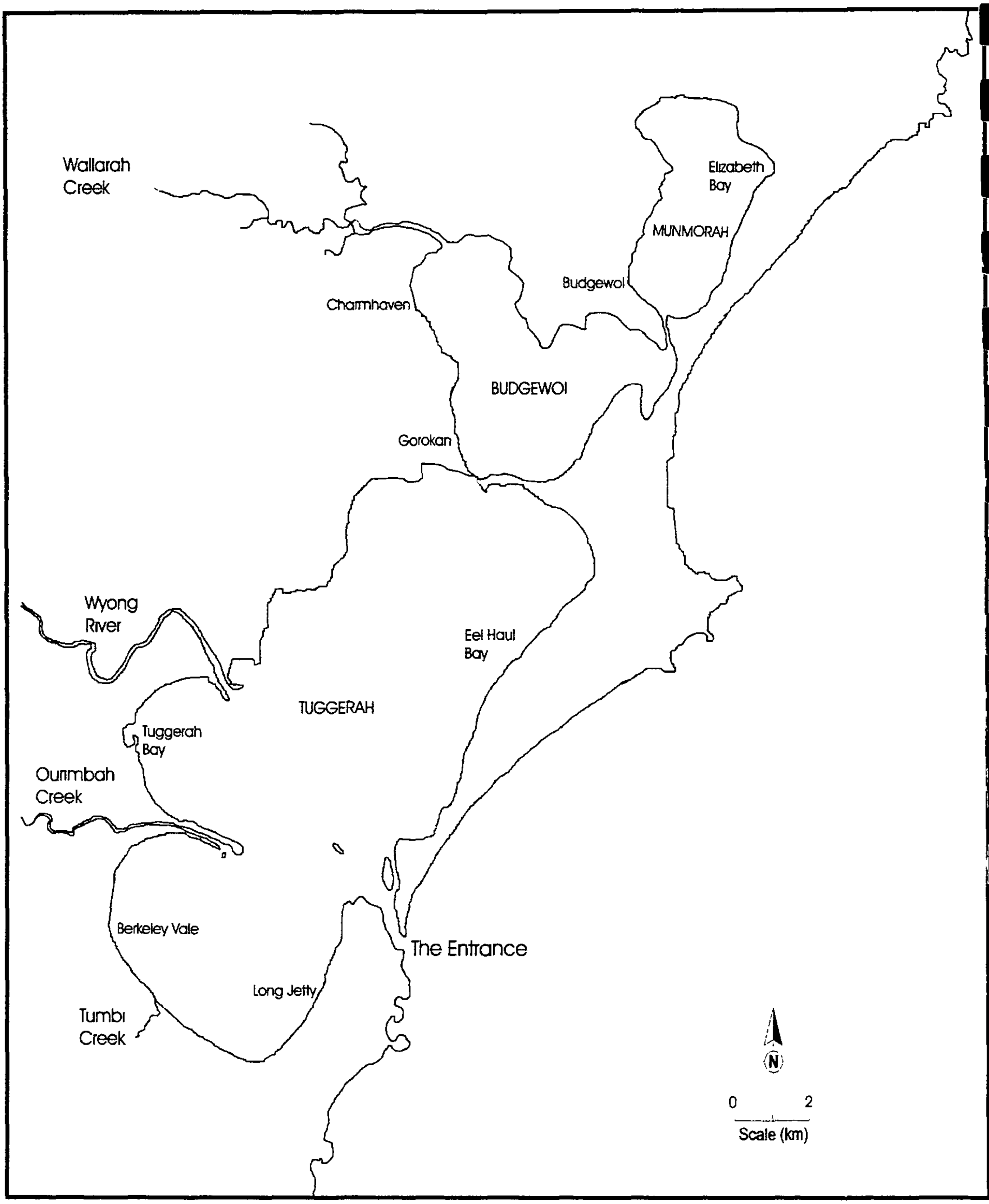

Figure 45. Macroalgae study locations within the Tuggerah Lakes estuary

4.2.3.2. Methods

To examine patterns in macroalgae community structure, twelve sample periods were done randomly between November 1997 and May 1999 Three locations were chosen in areas adjacent to undisturbed foreshores, Elizabeth Bay (EB), Eel Haul Bay (EB) and Tuggerah Bay (TB), whilst five locations were chosen in areas adjacent to developed foreshores, Budgewoi (BW), Charmhaven (CH), Gorokan (GK), Berkeley Vale (BV) and Long Jetty (LJ) (Figure 45) At each location, two sites were randomly selected and macroalgae (excluding epiphyte species) were harvested from fifteen randomly placed quadrats ($0.25m^2$) Samples were placed into labeled plastic bags and returned to the laboratory where they were washed and sorted to species level The samples were oven dried to a constant weight at 105°C for 48 hours prior to weighing to the nearest 0 01g In addition to the collection of biomass samples, water quality data were also collected at the same sites using the methods described in the water quality section (Cummins *et al*, 1999)

Multivariate statistical techniques were used to look for patterns of similarity or dissimilarity in species abundance and composition at various scales, using the PRIMER software package (Plymouth Marine Laboratories, UK) The abundance data were transformed using the double-square-root transformation to reduce the weighting given to abundant taxa and increase the weighting given to rare taxa (Clark and Warwick, 1994) Non-metric multi-dimensional scaling (nMDS) was used to generate two-dimensional ordinations, using the average of all the replicates in each site, to graphically illustrate the similarity (or dissimilarity) of samples at the different spatial scales Analysis of similarity (ANOSIM) tests were used to examine differences among locations and between disturbed and undisturbed foreshores (Clarke and Warwick, 1994) The SIMPER procedure was used to identify the contribution of individual species abundance to the Bray-Curtis similarity measure (Clark, 1993)

Regression analysis was used to investigate the degree of linear association between selected water quality variables and total biomass sampled within each location Analysis of variance (ANOVA) was used to test whether there were significant differences in a number of selected variables, at the temporal and spatial scales sampled For the macroalgae samples, ANOVA was done on total biomass, total number of taxa and on four species that represented different relative abundance's (small, medium and large) Specifically, ANOVA models were used to test the following hypotheses i) significant differences exist among locations around the estuary and ii) significant differences exist among areas adjacent to developed foreshores compared to undeveloped foreshores To examine differences among locations, time was treated as a random factor, locations as random and sites were nested within locations and time For the second model, time was treated as random, the factor disturbed versus undisturbed (DvU) was treated as fixed and orthogonal, locations were random and orthogonal (with respect to time) and sites were nested within time, DvU and locations To ensure a balanced model for the developed versus undeveloped foreshore model, samples collected from EB, EH and TB (undeveloped foreshores) and BW, BV and LJ (developed foreshores) were used in the analyses Prior to these analyses, the assumption of homogeneity of variance was examined with the aid of Cochran's test (Winer, 1971), and where variances were unstable, the appropriate transformations were used (Underwood, 1981) Were variances could not be stabilised analyses were performed on the untransformed data with consideration given to the increased probability of Type I errors (Underwood, 1981) Where significant differences were found in the analysis of variance, Student-Newman-Keuls (SNK) multiple comparisons were done to determine differences among means (Winer, 1971)

4.2.3.3. Results

A total of 18 species were recorded, from the divisions Chlorophyta (green algae), Rhodophyta (red algae) and Phaeophyta (brown algae) Generally, assemblages were dominated by free-floating, ephemeral species such as *Chaetomorpha linum*, *Enteromorpha intestinalis* (Figure 46) and *Microdictyon umbilicatum* (Division Chlorophyta) The red algae, *Callithamnion* sp dominated assemblages within Lake Munmorah between November 1997 and April 1998, however it was not found in either Budgewoi Lake or Tuggerah Lake Significant lower order interactions were detected for all of the variables examined, indicating that variation in the assemblages was as great between sites as within sites (Cummins *et al.*, 1999) Generally, macroalgae biomass and species richness displayed considerable temporal variation (figure 47) however, developed foreshore's consistently recorded higher species richness and biomass than undeveloped foreshores (Figure 48) Eel Haul Bay (Tuggerah Lake) recorded the lowest mean biomass (3.12 gDW\m^2 $\pm$ SE 0 68) during the sampling period Locations sampled in Budgewoi Lake, at Charmhaven and Gorokan, recorded the highest biomass (145 6 gDW/m^2 $\pm$ SE 44 4 and 124 4 gDW/m^2 $\pm$ SE 44.3 respectively), in September 1998 The high biomass was mostly comprised of the filamentous species, *Chaetomorpha linum,* which occurred in dense patches within the seagrass beds (Cummins *et al*, 1999) The average biomass recorded in the estuary was 16 65 gDW/m^2 $\pm$ SE 5 9 and if this is contrasted with other estuaries around Australia or world-wide, the current status of macroalgal biomass and cover within the Tuggerah Lakes is not considered to be excessive

Non-metric multidimensional scaling ordination's (nMDS) were done on the combined macroalgae assemblages identified at each site during the 12 sampling times with considerable variation in the patterns of similarity (and dissimilarity) found among samples (Cummins *et al.*, 1999). Generally, there was no consistent separation of samples into groups that readily distinguished among the eight locations or between developed and undeveloped foreshores (Cummins *et al.*, 1999). One-way ANOSIM tests were done to further test the hypotheses concerning differences in assemblages among locations and foreshores, and sites within each location were pooled to increase the power of the tests. Examination of the pairwise comparisons confirmed that all locations differed from each other (Cummins *et al.*, 1999). Thus, the structure of macroalgae assemblages within the estuary is highly variable at a number of temporal and spatial scales. The SIMPER analysis identified species, ranked in order of importance that contributed to the similarities within a location (Cummins *et al.*, 1999). During each time, the dominant contributing species at most locations was *Chaetomorpha linum*. Other species providing a major contribution over time included *Chondria succulenta*, *Laurencia obtusa* and *Dictyota acutiloba*. The abundance and distribution of species such as *Microdictyon umbilicatum* and *Enteromorpha intestinalis* was highly variable.

Figure 46. Bloom of *Enteromorpha intestinalis* around disturbed foreshore at Chittaway Bay

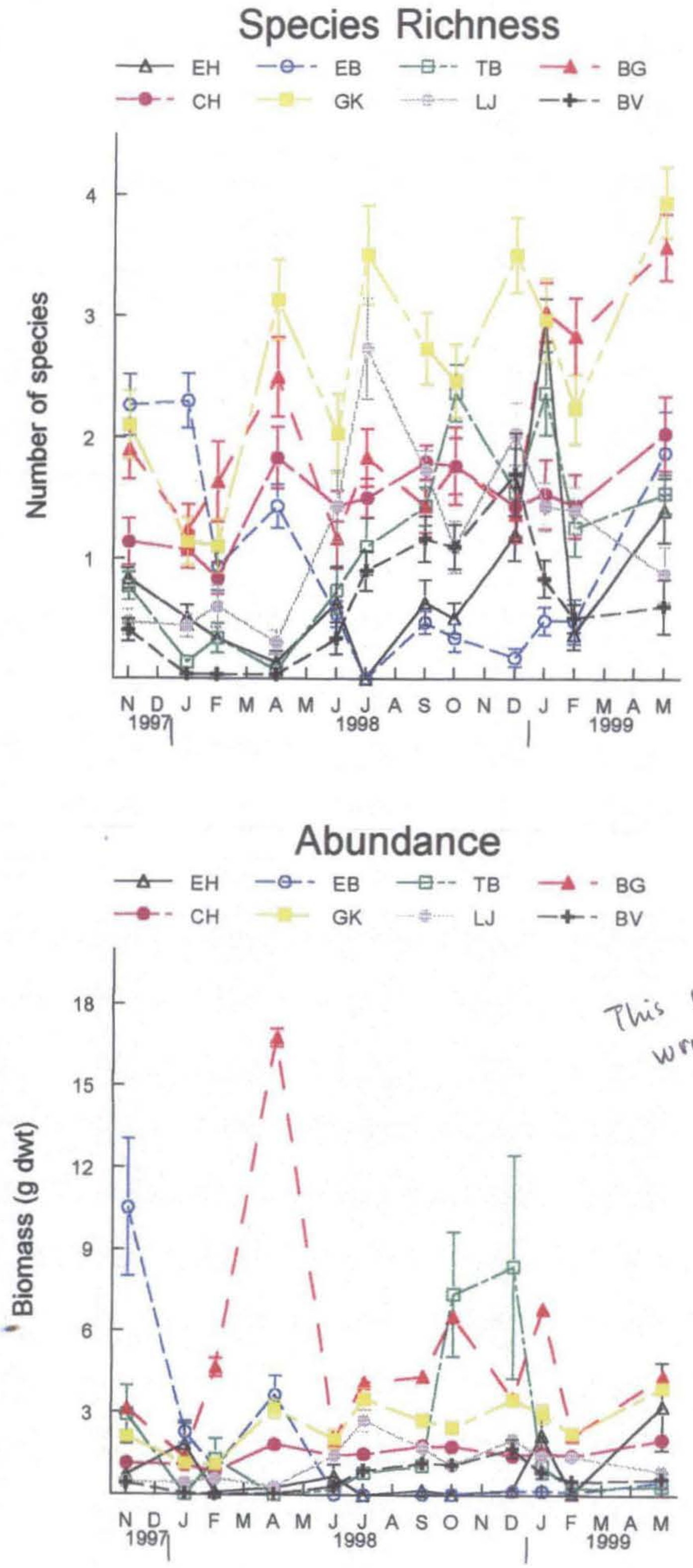

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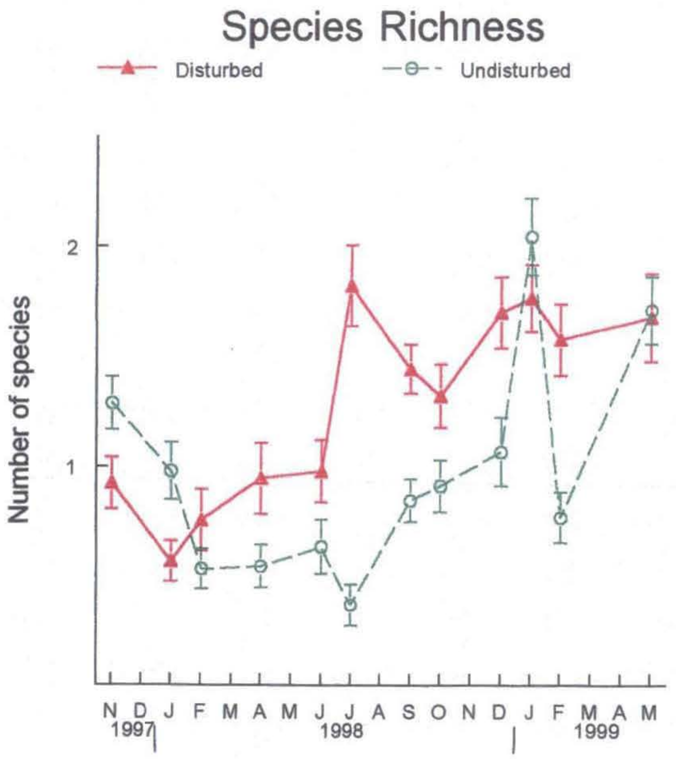
Figure 47. Mean species richness and abundance ($\pm$ SE; n = 30) of macroalgae harvested from locations around the estuary (Eel Haul Bay (EH), Elizabeth Bay (EB), Tuggerah Bay (TB), Budgewoi (BG), Charmhaven (CH), Gorokan (GK), Long Jetty (LJ), Berkeley Vale (BV)



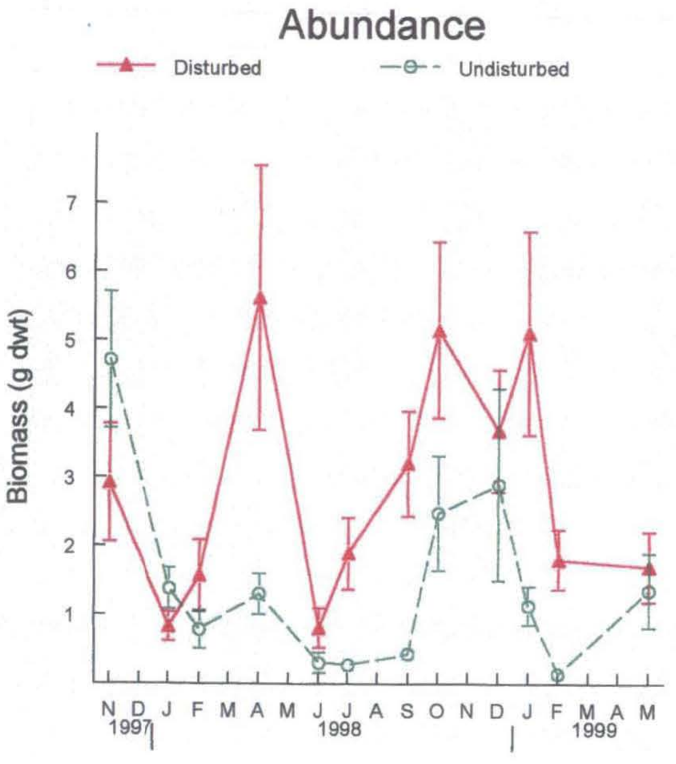


Figure 48. Mean species richness and abundance (± SE; n = 90) estimates for disturbed (Budgewoi, Long Jetty and Berkeley Vale) and undisturbed (Elizabeth Bay, Eel Haul Bay and Tuggerah Bay) locations

4.2.3.4. Discussion

There were significant differences among all of the scales examined for macroalgal biomass, indicating that variation within assemblages was as great between sites as within sites. Macroalgal assemblages were dominated by un-attached (drift algae), ephemeral species, which existed as highly aggregated clumps. The distribution of drift species is highly subject to wind and water currents and it is likely that these physical processes made significant contributions to the high variance among samples. Furthermore, within-site differences may largely reflect variation in seagrass morphologies and their ability to capture and retain drift macroalgae. When examining macroalgal accumulations to address questions of scale, Bell *et al.* (1995) suggested that dynamic characteristics of an area would strongly contribute to among-site differences.

Generally, macroalgae biomass and species richness displayed considerable spatial and temporal variation however, developed foreshore's consistently recorded higher macroalgae biomass than undeveloped foreshores. We were unable however, to show a clear link between higher biomass and ambient nutrient concentrations (Cummins *et al.*, 1999). Ephemeral macroalgae, such as *Chaetomorpha* and *Enteromorpha* species, can rapidly respond to nutrient enrichment of the water column (Duarte, 1995) and massive blooms are a commonly reported symptom of eutrophication. However, whilst nutrient supply will set the 'productivity potential' of algae in marine systems (Fong *et al.,* 1994), few studies have demonstrated a clear, direct link between bloom events and ambient nutrient concentrations (Hanisak, 1983; Bayne *et al.,* 1999). It is thought that this is probably due to the ability of ephemeral species to act as sources of nutrients or luxury consume and store nutrients until conditions (such as light availability and temperature) become favorable for growth. Macroalgal nutrient up-take and release has been shown to influence water column nitrogen concentrations on a bay-wide scale (Sfriso *et al.,* 1992; Piriou and Ménesguen, 1992; Peckol *et al.,* 1994). Furthermore, macroalgae are able to rapidly take-up ambient nutrients, causing low concentrations of biologically available forms to be measured irrespective of potentially large concentrations being cycled through the system. Further work within the Tuggerah Lakes estuary is to focus on the relationships between key nutrient sources and sinks and macroalgae growth. In terms of assessing the success of catchment management strategies, it has been recommended that additional locations be sampled within external reference systems.

why sample more sites to determine differences

4.2.4. Phytoplankton

4.2.4.1. Introduction

Phytoplankton are the photosynthetic component of an aquatic systems planktonic community, and represent a major source of energy for higher trophic levels such as zooplankton, fish and many benthic animals (Moss, 1988) Estuarine phytoplankton assemblages are characterised by a diverse range of taxa, which are generally dominated by diatom and dinoflagellate species (Day *et al.*, 1989) Phytoplankton are extremely dynamic in response to a number of interacting environmental factors, such as temperature, salinity, light availability and nutrient concentrations (Day *et al.*, 1989) River discharge, tidal inflows and wind-induced currents create environmental gradients, which cause available resources for phytoplankton production to be quite patchy in their distribution (Dustan and Pinckney, 1989, Franks, 1992, Malone *et al.*, 1996, Pinckney *et al.*, 1998) Biological interactions also occur and include grazing by zooplankton or other water-column filter feeders (Cloern, 1992, Boynton *et al*, 1997) It has been shown that in some eutrophic estuaries, phytoplankton biomass can remain low despite optimum conditions, probably because of predation pressure (Cloern, 1992, Malone *et al*, 1996)

Estuaries are the receiving waters for significant amounts of organic and inorganic materials and the available forms of key plant nutrients, particularly nitrogen and phosphorous, are quickly taken up by primary producers (Boynton *et al*, 1997) If there is a surplus of nutrients entering the estuary it may become eutrophic (nutrient enriched) and develop plant biomass that can severely alter ecosystem structure and function (Boynton *et al*, 1995b) Responses to nutrient enrichment are varied, with some systems developing phytoplankton blooms whilst others exhibit a macroalgae-dominated response (Kinney and Roman, 1998) As well as increased plant biomass, changes in species composition can occur, with assemblages often becoming dominated by one or a few ephemeral, opportunistic species (Gallegos, 1992) Although eutrophication effects have been well documented, the exact conditions and mechanisms responsible for promoting algal proliferation (bloom events) and persistence are poorly understood

Hallegraeff (1993) has stated that phytoplankton blooms are increasing in their frequency and extent in marine and estuarine waters worldwide In some cases, blooms can have negative effects either directly, some species produce toxic organic compounds, or indirectly by increasing light attenuation or generating anoxic conditions (Hallegraeff, 1993) The development of long-term strategies to prevent or alleviate the impact of phytoplankton blooms requires an understanding of the key processes responsible for their occurrence Furthermore, we need to understand how anthropogenic change alters these processes

The variation in the phytoplankton assemblages of the Tuggerah Lakes estuary were examined at various spatial and temporal scales using a nested sampling design The main objectives of the sampling program were to quantify variation in the patterns of diversity and abundance within the estuary and to contrast the assemblages within seagrass meadows and open water habitats (Cummins *et al*, 2000) Phytoplankton were examined in terms of their suitability as a tool for assessing the effectiveness of catchment management strategies.

4.2.4.2. Methods

Twenty surveys were done randomly between May 1997 and September 1999 The estuary was divided into four locations (Figure 49) based on its hydrological characteristics Lake Munmorah (LM) and Budgewoi Lake (BW) were considered to be two independent water bodies, whilst Tuggerah Lake was divided into two locations termed Tuggerah Lake (TL), and The Entrance (TE) At each location, two sites were randomly selected within two fixed habitats termed open water and seagrass Three replicate samples were collected within each site, using a rigid polycarbonate pole (50mm in diameter and 2m in length), which was considered ideal for the collection of longitudinally representative samples (Sournia, 1978) A 125mL grab sample was taken from each pole sample and preserved by adding 2mL of neutralised gluteraldehyde solution At each site, ambient physical and chemical data were also collected (sub-surface), using a Yeokal-611 water quality instrument, calibrated to the manufacturer's specifications prior to each field survey Measurements of pH, temperature (°C), dissolved oxygen (mg/L), salinity (ppt), turbidity (NTU) and secchi depth (m) were also recorded Zooplankton samples were also collected at the same temporal and spatial scales as the phytoplankton (Redden and Blacklock, 1999)

Prior to counting, phytoplankton samples were concentrated using a sedimentation technique One hundred millilitres of sample were allowed to stand for 48 hours before the supernatant was siphoned off, leaving a final volume of 10mL Sample identification and enumeration were performed using a Standard Compound Microscope (Light Microscopy) and the Lund Cell Technique (Lund *et al*, 1958) Phytoplankton were identified to species level, where possible, using the appropriate taxonomic keys It should be noted that very small cells belonging to the picoplankton fraction (diameter = <2 µm) were sometimes impossible to identify using light microscopy or were sometimes masked by larger cells or debris Where possible, these cells were counted and included under the taxonomic categories 'unidentified flagellate' or 'unidentified non-flagellate' species Algal blooms were defined as cell concentrations greater than their respective 90% quantile values calculated from the data collected between May 1997 and September 1999

Longer-term patterns of relative abundance was assessed using data collected by Cheng (1994, 1997) from single grab samples, collected from eleven sites around the estuary between May 1992 and January 1997 (Cummins *et al*, 2000) Samples were collected at approximately fortnightly intervals however surveys became less frequent towards the end of the program The samples were preserved with Lugol's iodide solution and the dominant taxa were later identified and enumerated using the inverted microscope method (Lund *et al.*, 1958) The data for Lake Munmorah, Budgewoi Lake and Tuggerah Lake were pooled to calculate the mean abundance for total individuals and for diatom species referred to as *Nitzchia seriata*

The total number of individuals, total number of taxa, total number of diatom individuals and total number of dinoflagellate individuals, were each analysed using a 4-factor nested analysis of variance (ANOVA) In all analyses, time was treated as a random factor, habitats and locations were fixed and sites were nested within the factors time, habitats and locations (Cummins *et al*, 2000) Prior to analysis, the data were examined for homogeneity of variances using Cochran's test (Winer, 1971) Generally, the distribution of relative abundance data was positively skewed so logarithmic transformations were applied where necessary (Underwood, 1981) Where the transformation was not successful in 'correcting' the inequality of the variances, analyses were performed using the raw data (Underwood, 1981) Where significant differences were found, the Student-Newman-Keuls (SNK) multiple comparison procedure was used to differentiate means (Winer, 1981)

Multivariate statistical techniques were used to look for patterns of similarity or dissimilarity in species abundance and composition at various scales, using the PRIMER software package (Plymouth Marine Laboratories, UK) The abundance data were transformed using the double-square-root transformation to reduce the weighting given to abundant taxa and increase the weighting given to rare taxa (Clark, 1993) Non-metric multi-dimensional scaling (nMDS) was used to generate two-dimensional ordinations, using the average of all the replicates in each site, whilst one-way analysis of similarity (ANOSIM) tests were used to examine differences among locations and among habitats (Clark, 1993) The SIMPER procedure was used to identify the contribution of individual species abundance to the Bray-Curtis similarity measure (Clark, 1993)

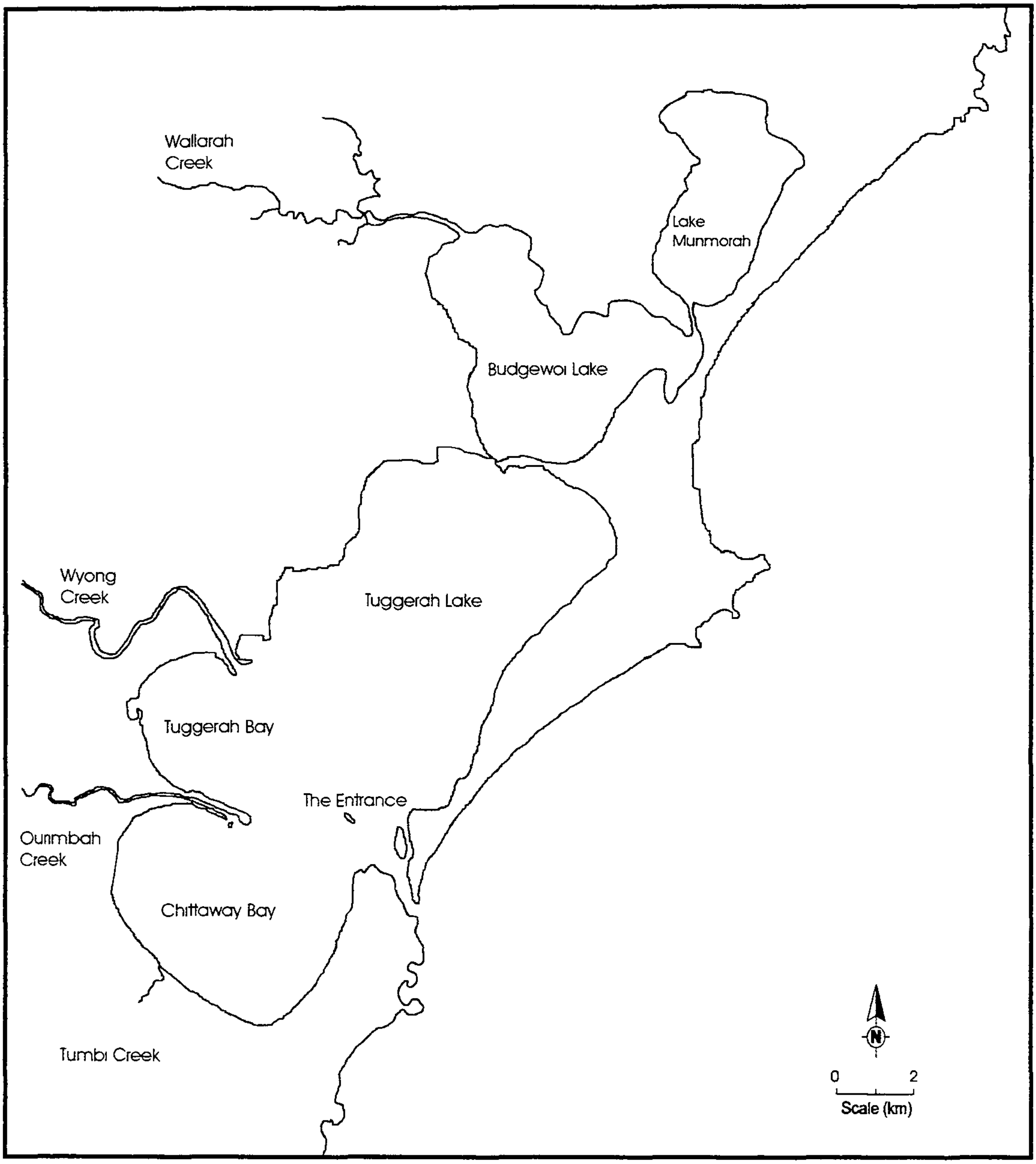


Figure 49. Phytoplankton sampling locations in the estuary

4.2.4.3. Results

A total of 71 taxa were identified from within the Tuggerah Lakes estuary Generally, the family Diatomophyceae (diatoms), represented by 36 species, numerically dominated the phytoplankton at all locations, followed by the family Dinophyceae (Dinoflagellates), which consisted of 23 species Other species belonged to a number of taxonomic groups including Chrysophyceae, Chryptophyceae, Euglenophyceae, Prasinophyceae, Cyanophyceae, Silicoflagellates and Raphidophytes. Some picoplankters (size fraction <2 0μm) could not be identified during sample analysis and therefore could not be included in any quantitative estimates of community structure (Cummins *et al.*, 2000)

There were significant lower order interactions detected for all of the selected variables examined, indicating that variation in assemblage structure was as great between sites as within sites Generally, phytoplankton abundance and species richness did not vary significantly between locations or habitats however, there were considerable variations through time (Figure 50) Phytoplankton reached maximum abundance during the winter period (April - September) whilst species richness was highest in samples collected during the summer (October - March) (Figure 50) The mean phytoplankton concentration for the entire sampling period was 3,325 cells/mL $\pm$ 520 The highest mean cell concentration (22,016 cells/mL $\pm$ 1,069, n = 6) was recorded at The Entrance in the open water habitat in July 1999 (Figure 50) The 90% quantile value calculated for the estuary was 7,810 cells/mL The Tuggerah Lake (TL) and Entrance (TE) locations were the most diverse, in terms of species richness, possibly as a result of their proximity to the entrance to the ocean and the presence of some marine species (Figure 50)

Diatoms numerically dominated the samples and were the most species rich component of assemblages throughout the estuary High cell concentrations of the pennate species, *Pseudonitzchia pseudo-delicatissima*, were the major component of all bloom events (i e cell number's greater than 7,810 cells\mL) *Pseudonitzchia* species also frequently dominated samples collected between 1992 and 1997, however bloom events occurred during the summer (Cummins *et al* , 2000)

Generally, the most abundant taxa listed within this study did not vary considerably from those listed by Cheng (1994, 1997) *Pseudonitzschia* sp (previously referred to as *Nitzschia seriata*) consistently made significant contributions to assemblage structure, particularly in November and December 1992, when bloom events were recorded in the estuary Notable is the apparent increase in the frequency of bloom events between 1997-1999 and lower mean cell concentrations (~878 cells/mL $\pm$ 160) between 1992-1997 (Figure 51)

Non-metric multidimensional scaling ordination's (nMDS) were done on the combined phytoplankton assemblages identified at each site during the 20 sampling times (Cummins *et al* , 2000) There was considerable variation in the patterns of similarity (and dissimilarity) among samples however there was no consistent separation of samples into groups that readily distinguished between the four locations or distinguished the open water from the seagrass habitat (Cummins *et al* , 2000) One-way ANOSIM tests were done to further test the hypotheses concerning differences in assemblages among locations and habitat types, and sites within each location were pooled to increase the power of the tests Examination of the pairwise comparisons confirmed that locations and habitats within locations differed from each other (Cummins *et al.*, 2000) The structure of phytoplankton assemblages within the Tuggerah Lakes estuary is highly variable at a number of temporal and spatial scales

The SIMPER analyses revealed that diatoms generally dominated community structure within all groups of samples Of the 36 diatoms identified, 19 were ranked within the top 5 species and of those, *Pseudonitzcschia pseudo-delicatissima* was the most common Six dinoflagellate species and 5 species belonging to other taxonomic groups were also ranked as important The taxonomic groups termed unidentified flagellate and non-flagellate species, which represent the picoplankton fraction of the phytoplankton, were included in the analysis and these groups were also commonly identified as making considerable contributions to community structure Generally, there appeared to be little variation in the species that typified assemblage structure among locations and between open water and seagrass habitats, or between times (Cummins *et al* , 2000) A species list of phytoplankton identified from the estuary was compiled (Table 11)

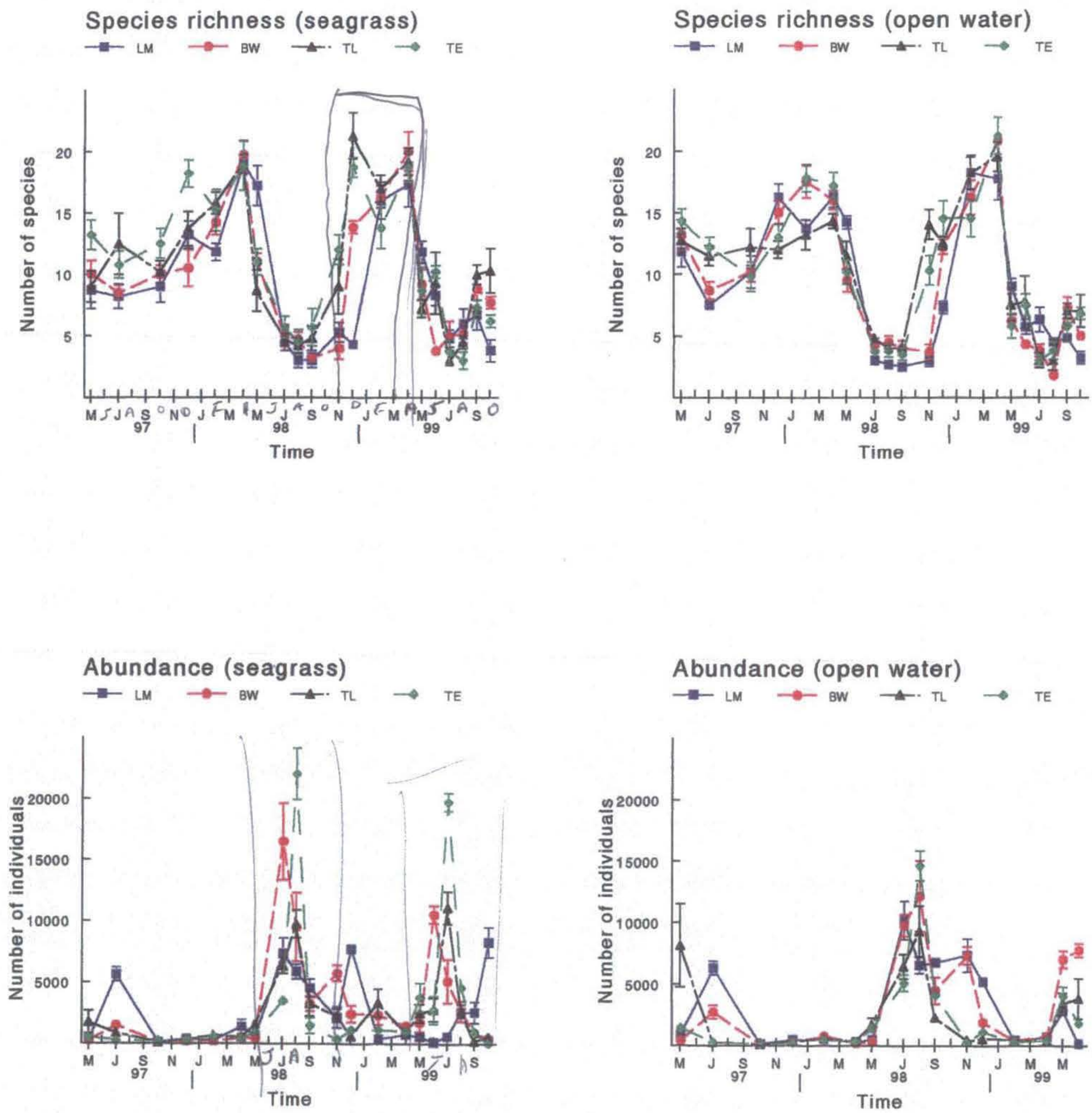


Figure 50. Mean abundance and richness (± SE; n = 6) for phytoplankton in seagrass and open water habitats (Lake Munmorah – LM, Budgewoi Lake - BW, Tuggerah Lake - TL, The Entrance –TE)

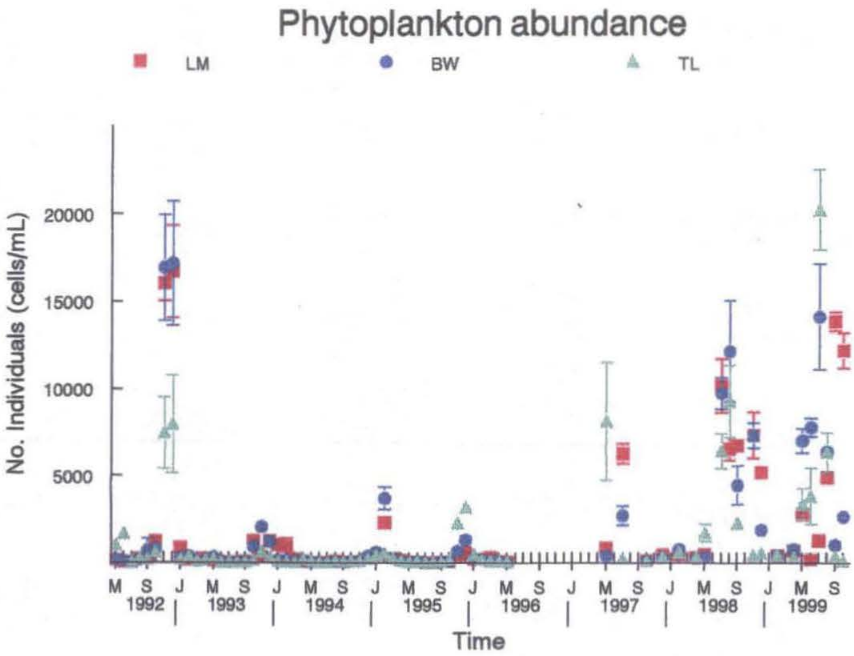


Figure 51. Comparison of phytoplankton abundance from 1992 – 1999 (Lake Munmorah – LM, Budgewoi Lake - BW, Tuggerah Lake - TL)

4.2.4.4. Discussion

Phytoplankton assemblages exhibited significant small-scale variability among and within sites. A number of studies examining the distribution and abundance of phytoplankton communities have shown that community structure can be determined by different resource limitations (silicate and phosphate) imposed on a different population within the community (Turpin and Harrison, 1979; Day *et al.,* 1989). Furthermore, resource availability is often patchy in its distribution within estuarine systems due to a number of interacting environmental processes such as tidally induced fronts (Dustan and Pinckney, 1989).

Generally, phytoplankton abundance and species richness did not vary considerably among locations or between habitats, however they did vary through time. Phytoplankton productivity typically varied through time, often displaying annual cycles of winter minima and summer maxima coincident with temperature and irradiance patterns (Mallin *et al.,* 1991; Day *et al.,* 1989). Typical annual productivity cycles were observed by Cheng (1994; 1997), however in this study total phytoplankton biomass was consistently highest during the winter months Despite wide fluctuations in abundance of many of the constituent species, assemblages varied little in their qualitative composition We were unable to relate productivity to temporal variations in rainfall or freshwater inputs to the estuary however, it is likely that these processes were operating at smaller temporal scales than could be quantified by program (Cummins *et al*, 2000) The importance of freshwater nutrient sources has been well documented (see Mallin *et al*, 1991, Rudek *et al*, 1991) and Bourguès *et al* (1998b) demonstrated significantly increased phytoplankton biomass by sampling weekly immediately after a major flood event in the Tuggerah Lake

Patterns in phytoplankton productivity could also be related to observed pulses in zooplankton assemblages Zooplankton displayed similar patterns of distribution and abundance however they were most abundant during the summer (Redden and Blacklock, 1999) Redden and Blacklock (1999) suggested that increased grazing which probably accompanied the zooplankton pulses could have produced the observed declines in phytoplankton biomass It has previously been shown that even in some eutrophic estuaries, phytoplankton biomass can remain low despite optimum conditions, due to predation pressure (Cloern, 1992, Malone *et al*, 1996)

Seagrasses did not appear to provide a predation refuge for zooplankton or facilitate increased species richness of either zooplankton (Redden and Blacklock, 1999) or phytoplankton assemblages Furthermore, there was little variation in the relative composition of phytoplankton assemblages between both habitat types The Tuggerah Lakes estuary is shallow (average depth of 1 7m) and well-mixed even between the open water and seagrass habitats (Cummins *et al*, 1999)

All phytoplankton blooms (i e cell numbers greater than 7,810 cells/mL) recorded within the Tuggerah Lakes estuary, were comprised of high abundance's of the pennate diatom *Pseudonitszchia pseudo-delicatissima* *P. pseudodelicatissima* is one of the dominant bloom-forming species in Australian coastal waters (Hallegraeff, 1994) This species has been found to be weakly toxic and has been implicated as the causative organism of amnesic shellfish poisoning (Hallegraeff 1994) however, toxicity analyses on samples collected from Australian waters have been consistently non-toxic (Hallegraeff, 1994) A number of other species or taxonomic groups identified within the estuary have been associated with harmful occurrences, however these have been extremely rare in estuaries throughout New South Wales (Hallegraeff, 1993).

Table 11. Phytoplankton taxa identified in the Tuggerah Lakes Estuary

Diatomophyceae

Achnanthes sp
Amphora sp
Bacillaria sp
Biddulphia sp
Campylodiscus sp
Cerataulina cf pelagica
Chaetoceros cf affinis
Chaetoceros danicus
Chaetoceros cf didymus
Chaetoceros cf distans
Chaetoceros cf compressus
Chaetoceros cf peruvianus
Cocconeis sp
Coscinodiscus sp
Cyclotella sp
Cymbella sp
Diploneis sp
Eucampia sp
Fragilariopsis sp
Guinardia sp
Leptocylindrus spp
Licmophora sp
Melosira nummuloides
Navicula spp
Nitzschia closterium
cf Paralia sulcata
Pleurosigma sp
_Pseudonitzschia pseudodelicatissima_*
Rhizoselenia sp
Skeletonema costatum
Striatella sp
Entomoneis sp
Synedra sp
Thalassionema sp
Thalassiothrix sp
Thalassiosira sp *
Unknown Pennate spp
Unknown Centric spp

Chrysophyceae\Chryptophyceae
Euglenophyceae\Prasinophyceae

Apedinella sp
Chilamonas sp OR Cryptomonas
Dinobrynon sp
Eutreptiella sp
Mallomonas sp
Meringosphaera sp
Micromonas/Mantoniella
Pyramimonas sp

Dinophyceae

cf _Alexandrium sp_ *
Amphidinium sp
Ceratium cf tenue
Ceratium furca
Ceratium fusus
Dinophysis caudate
Dinophysis sp *
Gonyaulax sp *
_Gymnodinium breve_*
Gymnodinium sp *
Gyrodinium sp
cf Heterocapsa sp *
_Noctiluca scintillans_*
Oxyphysis sp
Oxytoxum sp
Podolampus sp
Polykrikos sp
_Prorocentrum lima_*
_Prorocentrum minimum_*
Prorocentrum triestinum
Protoperidinium pellucidum
Protoperidinium sp
_Scrippsiella cf trochoidea_*

Cyanophyceae

_Trichodesmium erythraeum_*

Silicoflagellate

_Dictyocha octanaria_*
Ebria tripartita
Hermesinum adriaticum

Un-identified Raphidophyte

* indicates species, or groups that contain species that have been associated with the occurrence of toxic organic compounds (Hallegraeff, 1993)

4.3. Fauna of the Estuary

4.3.1. Terrestrial Macrofauna

The fringing terrestrial macrofauna of an estuary is composed of higher vertebrates such as mammals, birds, reptiles and amphibians These animals have different geographic ranges and some live their entire life around the estuary The associated fringing vegetation habitats will strongly influence the types of macrofauna found around an estuary A large proportion of the Tuggerah Lakes estuary has been urbanised and much of this fringing structural habitat has been lost Research on fringing macrofauna around the Tuggerah Lakes estuary is being done by the University of Newcastle (Wallbridge, 1999) Preliminary reports describing the associated macrofauna in Colongra Swamp (Wallbridge, 1998) and various other locations are being prepared (Wallbridge, 1999)

4.3.1.1. Methods

Faunal surveys were done within remanent bushland at various locations around the Tuggerah Lakes estuary The locations reported here included Colongra Swamp, Munmorah State Recreational Area, Wyrrabalong National Park and Tacoma South (Wallbridge, 1999) The locations varied in size from 50 to 1000 hectares, as did the degree of fragmentation from other areas of bushland Most of the areas were relatively flat or slightly undulating, with very little relief between the various survey points The study was designed to identify as many fauna species using the sites as possible and to quantify habitat for native species A subjective assessment of the general habitat value of each area was made and included the habitat type, degree of disturbance and degradation, area occupied by the habitat, continuity with similar adjacent habitat by way of corridors, and the structure of vegetation

Survey methods were based on the Comprehensive Regional Assessment (CRA) fauna surveys used by the National Parks and Wildlife Service Live trapping was done using Elliott Type A traps (8 x 10 x 33cm), and six large cage traps (20 x 20 x 50cm), which were positioned using a gradsect system (Ridge, Mid-slope and Gully). The terrestrial mammal trapping was done over three nights with all gradsects (which included a total of 36 traps) done simultaneously The traps were placed approximately 20 m apart, hidden in thick grass, under shrubs or were camouflaged with vegetation where the ground cover was sparse or where human interference may occur The baits used were a mixture of rolled oats and honey, “Good-O’s” and peanut butter, which were replaced when necessary The traps were left out for 3 nights, giving a total of 108 trap-nights per survey and were checked in the early morning Nine Elliot Type A traps and nine Elliot B traps (15 5 x15 x 45cm) were placed in trees to determine the presence of arboreal mammals The traps were placed two to three meters aboveground, on platforms on or near trees Targeted trees contained hollows, were flowering and or had scratches present on the boles Three of each type of trap was placed within each survey point Baits consisted of rolled oats and honey, peanut butter, Good O's and aniseed rings The traps were sprayed with vanilla essence and honey mixed in water before being placed in the trees, to mask the smell of humans The tree trunks were also sprayed with this mixture each day Eighteen traps were left out for 3 nights giving a total of 54 trap nights per site, per survey In all cases, the traps were checked early the next day and where necessary reset and re-baited The mammal trapping data was supplemented by "spotlighting" using a 55 watt hand-held spotlight. Secondary indications (scats, scratches, diggings, tracks etc) of resident fauna were noted and included searches for whitewash and regurgitation pellets from owls and chewed *Casuarina* cones from Cockatoos Bat echo-location calls were tapped at each position using an Anabat detector and were recorded for at least 30 minutes at each survey point The transformed calls were analysed using an Anabat Zero Crossing Analysis, interfaced with a computer Calls were identified by comparison with sample calls supplied by the manufacturer of the equipment Diurnal surveys of frogs were done within drainage lines and dams using spotlights and augmented by recording any frog calls. Recorded calls were identified by auditory comparison with commercially available frog call recordings Identifications made this way were confirmed by computer analysis using an Anabat ZCA analyser and software The presence of herpetofauna and avifauna were recorded from opportunistic sightings as well as a diurnal survey

4.3.1.2. Preliminary Results

The bushland vegetation surrounding the Tuggerah Lakes estuary varied from closed sublittoral rain forest to open woodland with grass understorey In the Colongra Swamp, small mammals included the brown antechinus (*Antechinus stuartii*), the Bush Rat (*Rattus fuscipes*) and the Yellow-footed Antechinus (*Antechinus flavipes*) No large mammals were noted, however scats consistant with those of a wallaby were found and swamp wallabies (*Wallabia bicolor*) were observed on road verges The Brown Hare (*Lepus capensis*) was also found at this location Three species of arboreal mammal were recorded, the common brush tailed possum (*Trichosurus vulpecula*), the common ringtail possum (*Pseudocheirus peregrinus*) and the squirrel glider (*Petaurus norfolcensis*). Bats included the greater broad-nosed bat (*Scoteanax rueppellii*), Gould's wattled bat (*Chalinolobus gouldi*) and the lesser long-eared bat (*Nyctophilus geoffroyi*) Specimens of the Grass Skink (*Lampropholis delicata*) and a Lace Monitor (*Varanus varius*) were also found The Common Eastern

Froglet (*Crinia signifera*), the Striped Marsh Frog (*Limnodynastes peronii*) and the Brown Toadlet (*Pseudophryne bibronii*) were also detected

Within the Munmorah State Recreational Area, small mammals included the Brown Antechinus (*Antechinus stuartii*), the Dusky Antechinus (*Antechinus swainsonii*), the New Holland Mouse (*Pseudomys novaehollandiae*), the Bush Rat (*Rattus fuscipes*), the Swamp Rat (*Rattus lutreolus*) and the Black Rat (*Rattus rattus*) Large Mammals included the Swamp Wallaby (*Wallabia bicolor*), the Echidna (*Tachyglossus aculeatus*), the Brown Hare (*Lepus capensis*) and the Rabbit (*Oryctolagus cuniculus*) Arboreal species included the Common Brush Tailed Possum (*Trichosurus vulpecula*), the Common Ringtail Possum (*Pseudocheirus peregrinus*) and the Sugar Glider (*Petaurus breviceps*) Also reported from this area is the Feather tail Glider (*Acrobates pygmaeus*) and the Squirrel Glider (*Petaurus norfolcensis*) Five species of bat were recorded at this site, the Grey-headed Flying Fox (*Pteropus poliocephalus*), the Common Bent-wing Bat (*Miniopterus schreibersii*), the Little Bent-wing Bat (*Miniopterus australis*), the Little Forest Eptesicus (*Vespadelus vulturnus*) and Gould's Long-eared Bat (*Nyctophilus gouldii*) During the spotlighting surveys, seven species of bat were recorded at this site, the Grey-headed Flying Fox (*Pteropus poliocephalus*), the Common Bent-wing Bat (*Miniopterus schreibersii*), the Little Bent-wing Bat (*Miniopterus australis*), the Greater Broad-nosed Bat (*Scoteanax rueppellii*), the Little Forest Eptesicus (*Vespadelus vulturnus*), Gould's Wattled Bat (*Chalinolobus gouldii*) and the Gould's Long-eared Bat (*Nyctophilus gouldii*) Six species of reptile were recorded and included the Eastern Water Skink (*Eulamprus quoyii*), the Eastern Water Dragon (*Physignathus leseurii*), the Grass Skink (*Lamporphoris delicata*), the Blue Tounge Lizard (*Tiliqua scincoides*), the Jacky Lizard (*Amphibolurus muricatus*), and the Red Bellied Black Snake (*Pseudechis porphyriacus*) The Common Eastern Froglet (*Crinia signifera*), the Brown Toadlet (*Pseudophryne bibronii*), the Striped Marsh Frog (*Limnodynastes peronii*), the Eastern Dwarf Tree Frog (*Litora fallax*), and Lesueur's Frog (*Litora Lesueuri*) were also common

Within the Wyrrabalong National Park small mammals included the Brown Antechinus (*Antechinus stuartii*), the Northern Brown Bandicoot (*Isoodon macrourus*) and the Bush Rat (*Rattus fuscipes*) The Brown Hare (*Lepus capensis*) was noted on the fringe of the park as well as the Fox (*Vulpes vulpes*) Three species of arboreal mammal were noted within this area, the Common Brush Tailed Possum (*Trichosurus vulpecula*), the Common Ringtail Possum (*Pseudocheirus peregrinus*) and the Squirrel Glider (*Petaurus norfolcensis*) Six species of reptile are known from this site, the Eastern Water Skink (*Eulamprus quoyii*), the Eastern Water Dragon (*Physignathus leseurii*), the Grass Skink (*Lamporphoris delicata*), the Blue Tounge Lizard (*Tiliqua scincoides*), the Jacky Lizard (*Amphibolurus muricatus*), and the

Green Tree Snake (*Dendrelaphis punctulata*). The Common Eastern Froglet (*Crinia signifera*), the Striped Marsh Frog (*Limnodynastes peronii*), Green Tree Frog (*Litora caerulea*), and the Eastern Banjo Frog (*Limnodynastes dumerilii*) were also found

Within the Tacoma South area, small mammals included the Brown Antechinus (*Antechinus stuartii*), the Bush Rat (*Rattus fuscipes*), the Swamp Rat (*Rattus lutreolus*) and the Black Rat (*Rattus rattus*) Larger Mammals included Swamp Wallabies (*Wallabia bicolor*), and Eastern Grey Kangaroos (*Macropus giganteus*) The Brown Hare (*Lepus capensis*) was also noted on this site Three species of arboreal mammal were found including the Common Brush Tailed Possum (*Trichosurus vulpecula*), the Common Ringtail Possum (*Pseudocheirus peregrinus*) and the Squirrel Glider (*Petaurus norfolcensis*) Also reported from this area is the Koala (*Phascolarctos cinerus*) Seven species of bat were recorded and include the Common Bent-wing Bat (*Miniopterus schreibersii*), the Greater Broad-nosed Bat (*Scoteanax rueppellii*), the Large-footed Mouse Eared Bat (*Myotis adversus*), Gould's Wattled Bat (*Chalinolobus gouldii*) and the Gould's Long-eared Bat (*Nyctophilus gouldii*) Five species of reptile are known from this site, the Eastern Water Skink (*Eulamprus quoyii*), the Eastern Water Dragon (*Physignathus leseurii*), the Grass Skink (*Lamporphoris delicata*), the Blue Tounge Lizard (*Tiliqua scincoides*) and the Red Bellied Black Snake (*Pseudechis porphyriacus*) The Common Eastern Froglet (*Crinia signifera*), the Striped Marsh Frog (*Limnodynastes peronii*), Green Tree Frog (*Litora caerulea*), the Green and Golden Bell Frog (*Litora aurea*-NPWS), Perons Tree Frog (*Litora peronii*), the Eastern Dwarf Tree Frog (*Litora fallax*), and Lesueur's Frog (*Litora Lesueuri*) were also detected

The avi-fauna at all locations were typical of the forest, woodland and grassland habitats throughout the Central Coast region Larger birds including the Torresian Crow (*Corbus orru*), Laughing Kookaburra (*Dacelo novaeguineae*), Eastern Rosella (*Platycercus examius*) and Australian Magpie (*Gymnorhina tibicen*) were common Smaller birds preferring the small shrubs and longer grass for foraging included the Willy Wagtail (*Rhipidura leucophrys*), Yellow Rumped Thornbill (*Acanthiza chrysorrhoa*), and the Superb Blue Fairywren (*Malurus cyaneus*) The full results of the faunal surveys will be reported in Wallbridge (1999)

4.3.2. Wetland Birds

4.3.2.1. Introduction

Fringing vegetation around the Tuggerah Lakes estuary ranges from saltmarsh to woodland swamp forests which provides excellent foraging and nesting opportunities for a number of aquatic and terrestrial species of bird (Morris, 1996, Sainty, 1998, Mackey, 1999) The estuary also has a range of open muddy habitats that support many species of invertebrates, which are important as a food source for birds (Powis, 1973, Wettin, 1981). Birds are high up the food chain and have important ecological functions within estuaries Their activities contribute to pollination in plants and they assist in controlling populations of many species of insect (Recher *et al*, 1986, Adam and Stricker, 1993)

With the increased pressure placed on wetlands and estuarine systems by development, especially in the Sydney region, and the loss of a large part of Botany Bay with the construction of the Third Runway, the Tuggerah Lakes estuary takes on renewed importance for migratory species using the South-East Asian Flyway Not only does it provide a feeding point for a number of migratory birds, it also provides an important feeding ground for those birds that winter around the estuary (Wettin, 1981, Morris, 1996)

The Tuggerah Lakes catchment is under pressure from a range of development activities and many shifts in biological community composition include the rapid invasion of species such as Lantana (*Lantana camara)* and Bitou Bush (*Chrysanthemoides monilifera)*, and dogs, foxes and cats (WSC, 1997, Wallbridge, 1998, Sainty, 1998). To assess the relative importance of the fringing vegetation communities to birds utilising the estuary, a sampling program which examined richness and abundance at a number of spatial scales was done Mackey, 1999)

4.3.2.2. Methods

Nine fringing vegetation sites were chosen around the estuary and sampled for bird species diversity and abundance (Figure 52) The sites were Tuggerah Bay (site 1), Chittaway Point (site 2), Tacoma (site 3), Eel Haul Bay (site 4), Terilbah Island (site 5), Orooaloo Point (site 6), East Budgewoi (behind the Budgewoi sandmass) (site 7), Colongra Swamp (site 8) and Elizabeth Bay (site 9) At each site, three (3) replicate, 50m transects were randomly run and assessed using the area search method (Davies, 1984), which involved two people walking along each transect and recording the birds observed up to a distance of 30m on either side In the majority of cases this allowed for coverage of $1500m^2$ Species noted outside the area, or flying over it, were also recorded

Multivariate statistical techniques were used to examine patterns of similarity or dissimilarity in species abundance and composition at each site, using the PRIMER software package (Plymouth Marine Laboratories, UK) The abundance data were transformed using the double-square-root transformation to reduce the weighting given to abundant taxa and increase the weighting given to rare taxa (Clark, 1993) Non-metric multi-dimensional scaling (nMDS) was used to generate a two-dimensional ordination and ANOSIM tests examined differences between sites (Clark, 1993) The SIMPER procedure was used to identify the contribution of individual species abundance to the Bray-Curtis similarity measure (Clark, 1993)

Analysis of variance (ANOVA) was used to test for differences associated with the bird populations around the estuary. Prior to analysis, the data were examined for homogeneity of variances using Cochran's test (Winer, 1971) and where necessary were transformed to log $(x \pm 0\ 5)$ (Underwood, 1981). Where the transformation was not successful in 'correcting' the inequality of the variances, analyses were performed using the raw data (Underwood, 1981) Where significant differences were found, the Student-Newman-Keuls (SNK) multiple comparison procedure was used to identify where the differences were located among the population means (Winer, 1981)

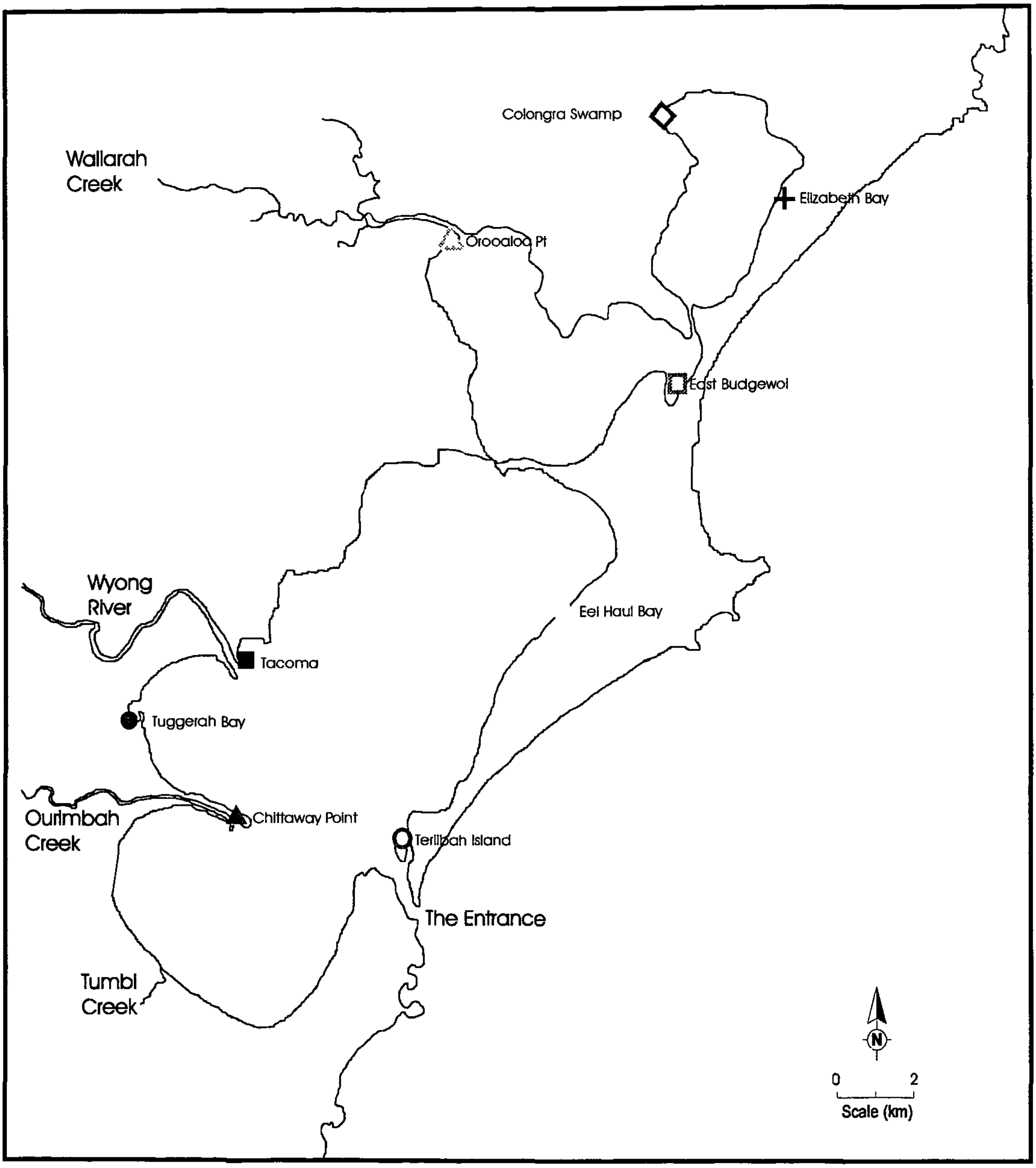


Figure 52 Location of bird sampling sites around the estuary

4.3.2.3. Results

Forty-seven bird species from twenty-nine families were identified from the fringing vegetation sites around the Tuggerah Lakes In addition, forty-three species and seven families, which were not found along transects, were observed in the general area (Mackey, 1999) Of the families recorded, the Melphagidae was the most diverse, represented by nine species Three exotic species were also present, *Streptopelia chinensis* (Spotted Turtledove), *Pycnonotus jocosus* (Red Whiskered Bulbul) and *Acridotheres tristis* (Common Myna), comprising around 5% of the total population sampled Only one threatened species, *Haematopus longirostris* (Pied Oystercatcher), was observed during the survey period (TSA, 1995) This species has been listed as Vulnerable under schedule 2 of the Threatened Species Conservation Act 1995

The non-metric multi-dimensional scaling ordination (nMDS) indicated that there was variation between sites, with Eel Haul Bay (site 4) and Elizabeth Bay (site 9) appearing to be the most similar (stress = 0 12) (Figure 53) Clusters formed at similarity levels of 25% and 30-40% were superimposed upon the nMDS ordination and it was found that there was good agreement between the 2 techniques This agreement indicates that the 2-dimensional plot is an accurate representation of the sample relationships (Clarke and Warwick, 1994) ANOSIM tests confirmed that significant differences existed between sites (P < 0 01, R = 0 268), however, due to the low number of possible permutations in the analysis, the pairwise comparisons were unable to identify where these differences were

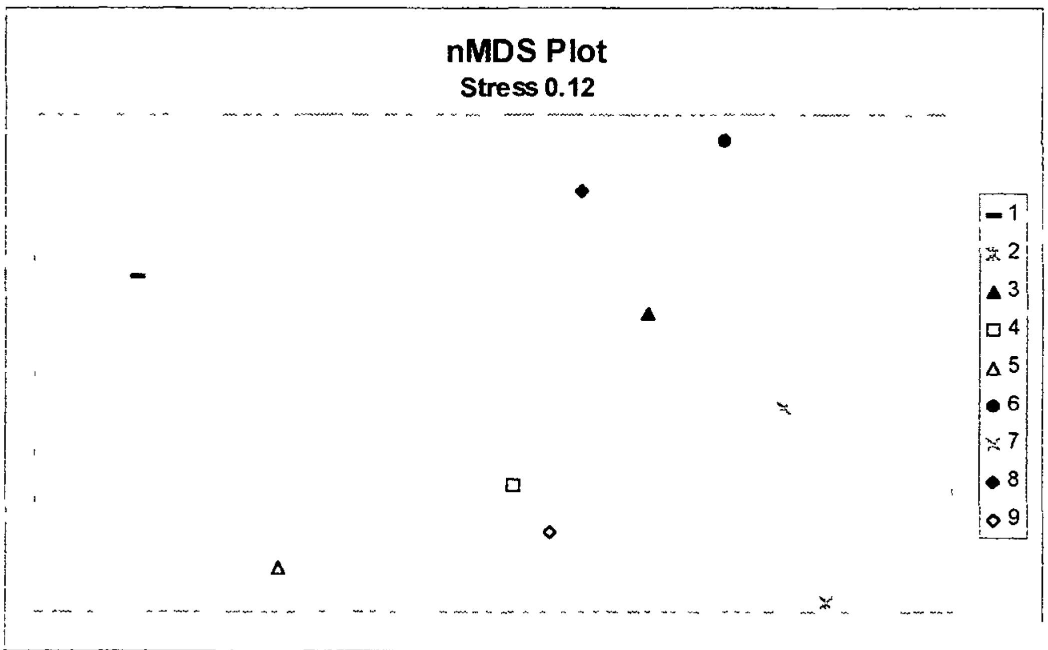


Figure 53. nMDS plot of bird species abundance at sites around the estuary.

The SIMPER procedure identified bird species, ranked in order of importance that contributed to the similarity within each site (Table 12) No one species was found to be consistently important across the 9 sites however, *Malurus cyaneus* (Superb Fairy Wren) was ranked within the top 4 species contributing to the average similarity of a site, at five of the nine sites (Table 12)

Table 12. Species ranked in order of importance (1-4 presented), which contributed to the similarities within a site, as determined by using the SIMPER procedure

Site	Birds	Comments
Tuggerah Bay (Site 1)	**Haliastur sphenurus* **Glossopsitta pusilla*	Fringing vegetation included several large dead trees that provided excellent roosting places for raptors The presence of these raptor species could discourage utilisation of this habitat by other smaller bird species This site should support a wide diversity of species, especially from the family Melphagidae, when the Eucalypt and Melaleuca trees begin to flower
Chittaway Point (Site 2)	*Malurus cyaneus* **Phylidonyris novaehollandiae*	Large Casuarina trees and a dense ground cover provided by Typha and sedges Members of the Melphagidae were observed feeding on the flowering Norfolk Hibiscus trees A westerly wind would expose a large area of mudflats, ideal for foraging by migratory wading birds
Tacoma (Site 3)	*Hirundapus caudacutus* *Vanellus miles* *Malurus cyaneus* *Eurystomus orientalis*	Dominated by large Casuarinas interspersed by shrub (including wattle trees) understorey A number of flowering Norfolk Hibiscus trees and a large area of mudflats that would be exposed during a westerly wind Notable was the low number of species representing the Melphagidae
Eel Haul Bay (Site 4)	*Rhipidura fuliginosa* *Meliphaga lewinii* *Malurus cyaneus* *Pachycephala rufiventris*	Dominated by large Eucalypts that would be expected to attract a number of species when flowering Diverse shrub layer which included palm species Overrun by Lantana and Bitou Bush
Terilbah Island (Site 5)	*Malurus lamberti* *Anthochaera chrysoptera* *Acanthiza pusilla* *Sericornis frontalis*	Dominated by Casuarina Melphagidae species observed feeding on the flowering Norfolk Hibiscus Lantana invading the understorey Only record of a nesting species, *Oriolus sagittatus* (Olive-backed Oriole)
Orooaloo Point (Site 6)	*Malurus cyaneus* *Gracticus torquatus*	Dominant trees were Casuarina, Swamp Mahogany and Red Gum A thick undergrowth ideal for the smaller passerine species Several tall, dead trees provided habitat for *Artamus leucorynchus* (White Breasted Woodswallow)
East Budgewoi (Site 7)	**Stipiturus malachurus* * *Malurus cyaneus* **Hirundo ariel*	Vegetation comprised of sedges fringed by small Casuarinas To the east of the Budgewoi sand-mass, this site offers little protection from prevailing weather conditions
Colongra Swamp (Site 8)	*Hirundo neoxena* *Phalacrocorrax melanoleucos*	Well established Casuarina, Melaleuca and Swamp Mahogany with a sedge understorey A tranquil site with roosting *Butorides striatus* (Striated Heron)
Elizabeth Bay (Site 9)	*Anthochaera chrysoptera* *Sericornis frontalis* *Malurus cyaneus*	Dominated by flowering *Banksia serrata,* with *Acanthorhynchus tenuirostris* (Eastern spinebill) and *Anthochaera chrysoptera* (Little Wattle Bird) species observed to be feeding on it Large Melaleuca trees and dense Bitou Bush also present

*At sites where SIMPER did not identify significant species of importance, the most abundant species were listed

No sıgnıficant dıfferences were found between sıtes for total specıes rıchness (Fıgure 54) however, sıgnıficant dıfferences were found for total abundance (Fıgure 55) Comparıson of the sıte means ındıcated that the total number of bırds at Tacoma (sıte 3) were sıgnıficantly hıgher than all other sıtes

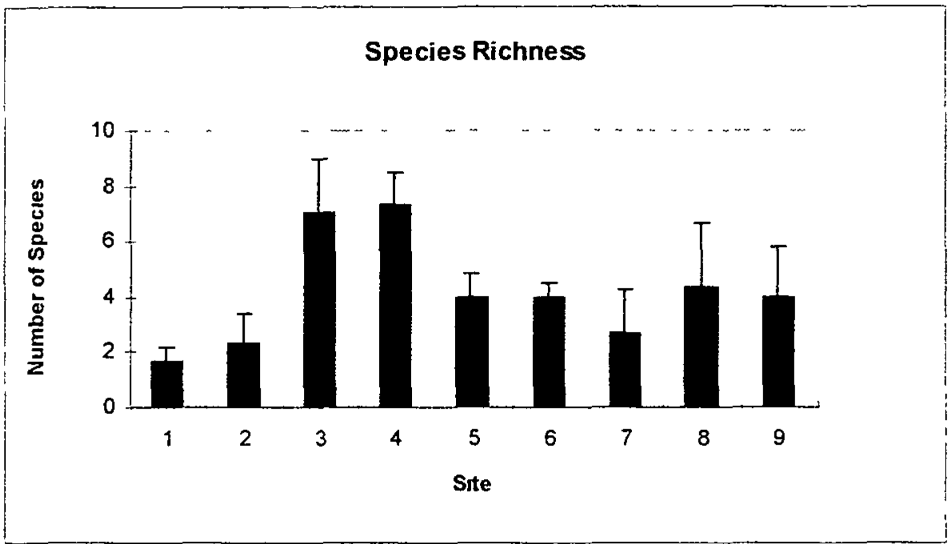


Figure 54. Mean number of species (± SE) identified at each site

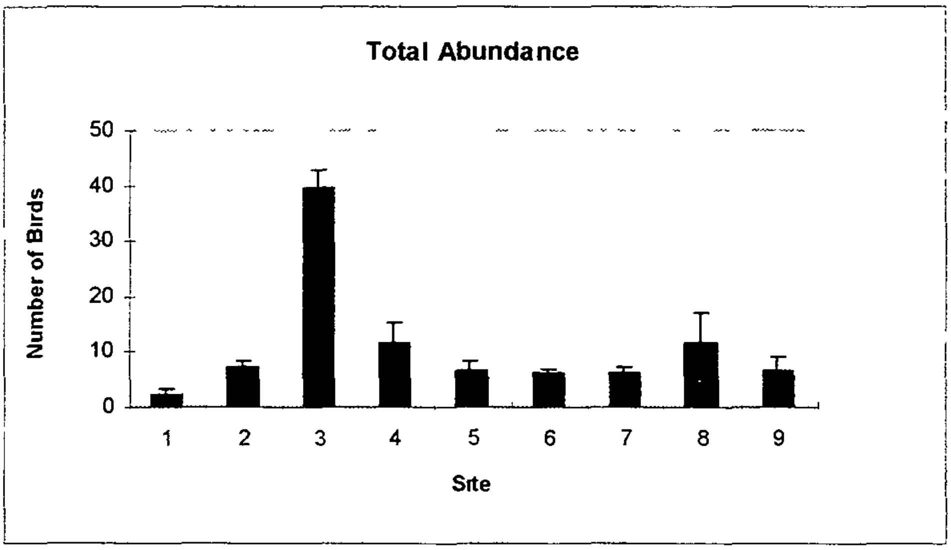


Figure 55. Mean number of birds (± SE) counted at each site

4.3.2.4. Discussion

There is some debate as to whether vegetation structure, in terms of complexity of the canopy or floristic diversity and abundance, is the major determinant of bird community structure (French and Zubovic, 1997) There was little variation in both the structure and composition of vegetation communities fringing the Tuggerah Lakes estuary (Sainty, 1998), and this appeared to be reflected by the structure of the bird assemblages Statistical tests found no significant differences between the sites sampled, for species diversity, however, the site at Tacoma did record significantly greater numbers of individuals Multivariate analyses showed this was due to the presence of the insectiverous bird *Hirundapus caudcutus* (White Throated Needletail) *Hirundapus caudcutus* is a summer migratory species, which is often observed around the estuary, where it may flock whilst feeding on aerial insects made abundant by thermal up-draughts (Morris, 1996) While in Australia, the birds are thought to spend most of their time in the air so their distribution is most likely driven by the availability of an adequate food supply (HANZAB, 1996)

The non-metric multidimensional scaling ordination revealed that Eel Haul Bay and Elizabeth Bay had the most similar bird assemblages Both sites had significant infestations of the introduced weed species *Chrysanthemoides monilifera* (Bitou Bush), whilst Eel Haul Bay also had extensive stands of *Lantana camara* (Lantana) A number of studies have shown that weed infestations can be a major determinate of bird composition, due to the resultant changes in food supply and habitat structure (French & Zubovic, 1997) *C monilifera* has displaced native plant species to form monotypic stands in a number of coastal areas within New South Wales, which in the long-term can reduce the establishment of tall understorey and canopy species (French and Zubovic, 1997)

Only one species listed under the Threatened Species Conservation Act 1995, was observed during the survey period (TSA, 1995) *Haematopus longirostris* (Pied Oystercatcher) has been recorded breeding on islets near The Entrance (Morris, 1992) Smith (1991) stated that the Pied Oystercatcher's habitat is entirely coastal in NSW and it favors ocean beaches and estuarine mud flats Generally, the birds build their nests in sand or shingle on coastal or estuarine beaches, near the high-tide mark Occasionally, the birds will also utilize salt marsh or grassy areas for nesting (Smith, 1991) These habitats appeared to be under extreme pressure from a number of human activities, and it is recommended that a detailed plan of management be developed, particularly emphasizing a reduction in physical disturbance's such as mowing, to help ensure the survival of this species within the Wyong Shire

Terilbah Island was the only site to record the presence of a nesting species, *Oriolus sagittatus* (Olive-backed Oriole) The absence of nesting or roosting species at most sites may be a reflection of either human disturbance or the presence of feral cats, foxes and dogs For example, twenty-nine feral cats were trapped in an area adjacent to the Colongra Swamp site, approximately 3 years ago (Wallbridge, 1998).

At the time of the survey, two large colonies of birds were present on the estuary The largest of these was *Cygnus atratus* (Black Swan), with the population estimated as being over fifteen hundred The Tuggerah Lakes estuary supports extensive, shallow beds of the seagrasses *Zostera capricornii* and *Ruppia megacarpa,* which are known to be a popular and abundant source of food for the birds (Wettin, 1981, Morris, 1992) Several environmental variables determine the distribution of *C atratus* populations, including periods of extreme drought in inland areas, which can cause the birds to migrate to coastal wetlands and estuaries (Frith, 1977, Morris, 1992)

The second largest colony was *Phalacrocorax sulcirostris* (Little Black Cormorant), with the population being estimated at over five hundred birds This is not uncommon for this species, or for the genus, as the birds will congregate wherever there is an abundant supply of small fish or other marine animals that can be caught easily (HANZAB, 1996) The estuary provides an excellent habitat for these birds, as they also commonly forage offshore

Whilst this survey recorded a number of species of birds, several migratory species that have previously been recorded were not observed due the studies restricted temporal component Morris (1992) states that over 300 species of birds have been found within the Wyong Shire, most of which were either seen on the shore of the estuary or in the adjoining fringing vegetation A number of the vegetation assemblages sampled during the survey, appeared to be greatly reduced in size and integrity due to development activities and associated disturbances (Sainty, 1998) The viability of the remaining fringing vegetation habitats and their associated avifauna appears to be under enormous pressure and it is strongly recommended that specific Plans of Management for these areas, with clear goals and objectives, be developed These Plans should be designed in association with continued sampling programs, at appropriate spatial and temporal scales, to determine whether they are a success Feedback from these surveys could also be used to focus future management decisions within the estuary's catchment

4.3.3. Nekton

The biomass of nekton (actively swimming pelagic organisms) within an estaury is generally very high The nekton of the Tuggerah Lakes estuary includes recreationally and commercially important species of fish, crabs and prawns The role of estuaries in fish production, both measured and assumed, has been a powerful contributor to the scientfic rationale for protecting estuaries from human impact (Day *et al*, 1989) Studies have been done on fish and fisheries within the Tuggerah Lakes estuary in response to assessing the impacts of power stations (Henry and Virgona, 1981, Virgona and Henry, 1987) and coal mining (The Ecology Lab, 1998) Recent reviews of the commercial and recreational fisheries of the Tuggerah Lakes estuary (Wanless 1998) and assessments of changes to fish populations using oral history (Scott, 1999) confirm the need for more rigourous qantitative spatial and temporal data on fish populations within the estuary

The estuary provides significant commercial fisheries for bream, flathead, luderick, mullet, prawns and crabs (The Ecology Lab, 1998) Commercial fish production from the estuary is the fifth largest in NSW with the recreational fishers generally targeting the same species (The Ecology Lab, 1998) Scott (1999) provides a good assessment of the commercial fish catch data for the estuary and examines the limitations of the data in terms of quantifying trends associated with anthropogenic disturbance

There are no quantititve data on the spatial and temporal variability of fish assemblages within the Tuggerah Lakes estuary (however see section on Weed Harvester) Wyong Shire Council has now incorporated the quantitave assessment of fish assemblages at a number of spatial and temporal scales within the estuary

4.3.4. Benthic Invertebrates

The abiotic components of an estuarine system include factors such as depth, sediment particle size and distribution, wave action and velocity, temperature, salinity, and the concentrations of dissolved oxygen, nutrients and other chemicals Interactions between these variables and the biological assemblages are complex and can be modified, however, it is the abiotic factors, which will ultimately determine whether or not an organism can exist, and therefore be found within a system (Putman and Wratten, 1984)

In a shallow estuarine environment such as the Tuggerah Lakes, the sediments play a structural role in terms of providing specific habitat requirements for certain organisms, and can act as a significant sink or source of nutrients (Boynton *et al.*, 1997, Bourguès, 1998)

Generally, a large fraction of the inorganic nutrients entering an estuary from major tributaries or storm water runoff, is taken up by the algae (particulary phytoplankton) and converted to organic forms of nitrogen and phosphorous (Boynton *et al*, 1995) A large portion of this organic material ends up on the bottom sediments either directly by deposition or indirectly by zooplankton or suspension-feeder grazing (Boynton, 1997) This organic particulate matter is either stored and buried in depositional areas of the estuary or is consumed by the benthic fauna (Boynton, 1997)

Benthic fauna are the assemblages of animals living on or in the muddy and sandy sediments of the estuary floor These organisms range in size from the minute bacteria and protozoans to larger colonial animals termed the 'macrobenthos', which are considered to be those animals that are retained on a 0 5 mm sieve (Poore, 1992) Also included in this bottom community are the interstitial meiofaunal animals, which vary in size between 0 1-0 5 mm (Higgins and Thiel, 1988, Coull, 1997)

As well as having a major role in nutrient cycling processes, benthic organisms serve as a food source for higher trophic organisms such as fishes and birds They are highly sensitive to anthropogenic disturbance, which can make them an ideal management tool for the assessment of the effects of potential catchment management strategies (Warwick, 1988, Coull, 1997) The strong inter-relationships that exist between the bacterial, meiobenthic and macrobenthic assemblages are complex and quantitative descriptions of these processes are scarce, despite their importance, particularly in Australian waters (Nielson and Jernakoff, 1996, Coull, 1997)

Previous work done in the Tuggerah Lakes estuary includes that by Powis (1973), who identified a total of 33 macroinvertebrate species The major objectives of the study by Powis (1973) were to examine the effects of the power station and weed clearing operations on macrobenthic assemblages Powis (1973) concluded that the Munmorah power station changed the structure of the benthic community but not species diversity The weed clearing operations were found to greatly reduce both the number of species and the total number of individuals within experimental plots and it was suggested that this reduction in the abundance of benthic macroinvertebrates could lead to a reduction in fish populations

Of the food guilds represented by the macrobenthos, suspension-feeders and deposit-feeders generally dominate the macrofauna (Poore, 1992) Suspension-feeders (including sponges, mussels, oysters and clams) can have a major influence on water clarity as they filter out particulate organic materials from the water column Due to their considerable filtration capacity, suspension-feeding bivalves have caused major changes in the growth rates of phytoplankton populations with consumption sometimes greater than production (Cloern, 1992, Nielson and Jernakoff, 1996) Suspension-feeders can also promote the flux of ammonium from the sediments through mortality and excretion or bioturbation processes (Moss, 1988, Nielson and Jernakoff, 1996)

Deposit-feeders consume benthic organic material and may bioturbe or bioirrigate the sediment through their burrowing and feeding activities This can indirectly promote nitrification by increasing oxygen penetration into sediments and by increasing bacterial activity (Aller, 1982, Fukuhara and Sakamoto, 1987, Bird, 1994) Nitrification in turn promotes denitrification, with both processes leading to the consumption of ammonium and the production and subsequent loss of nitrogen gas from the sediments, representing an important sink for nitrogen in estuarine sediments (Koike and Mukai, 1988, Nielson and Jernakoff, 1996)

Meiofauna, despite being identified as a suitable ecological group for monitoring the effects of pollution and being an integral part of estuarine food webs, have largely been ignored due to their difficult taxonomy Like the macrofauna, meiofauna play a major role in mineralization and nutrient cycling however, it is thought that their role is more a stimulatory effect on the benthic microbial community (Tietjen, 1980, Coull, 1997) Tietjen (1980) proposed four ways that meiofauna stimulate bacterial growth. i) by mechanical breakdown of detrital material which increases its surface area to volume ratio making it more reactive to bacterial action, ii) by direct excretion of nutrients, making them available for microbial use, iii) through the production of slime/mucous cases which attracts and sustains bacterial growth, iv) through physical reworking of the sediments which can redistribute deposited organic matter back to the sediment-water interface As well as promoting nutrient cycling, meiofauna are an important source of food for a variety of organisms (Coull, 1997) Many predator life cycles, for example juvenile fish and prawns and birds, have obligatory meiofaunal feeding stages (Coull, 1997)

Previously, studies on the benthic macroinvertebrate assemblages of the estuary have focused on the effects of the Munmorah power station (see Powis, 1973, Powis and Robinson, 1980, MacIntyre, 1990) The power station uses water from Lake Munmorah as a coolant for condensors and discharges this effluent into Bugewoi Lake, raising the temperature and producing an artificial current around the discharge area Small changes in community structure have been detected however, it would appear that the effects of the effluent were localised to shallow waters around the discharge area, where the temperature was usually about 4ºC above ambient

Powis and Robinson (1980) examined differences in the structure of communities throughout the estuary to determine whether there were correlations between substratum and seagrass type. They classified the estuary into four groups: 1) seagrass species growing in muddy sand, 2) mud substratum, 3) seagrass species growing in mud or mud sites adjacent to seagrass beds and 4) sand substratum and/or seagrass growing in sand. Unvegetated areas were characterised by low fauna diversity and abundance. The bivalves *Theora fragilis* and *Notospisula trigonella* dominated mud substrata whilst another bivalve species, *Sanguinolaria onuphria,* was common in sandy substrata. The 'seagrass on muddy sand' habitat type was dominated by the filter-feeding polychaete *Owenia fusiformis* whereas *Tellina deltoidalis* and the omnivorous *Ceratonereis erythraeensis* dominated the 'seagrass on mud' habitat. It was concluded that the faunal composition of muddy areas did not vary significantly between the three lakes. These muddy areas were comprised of a high percentage of clays and silts (78-95%) which can greatly restrict the recruitment of animals that require a firm medium in which to settle or burrow (Powis and Robinson, 1978; The Ecology Lab, 1998).

As part of the COAL Australia EIS, The Ecology Lab sampled demersal fish and benthic macroinvertebrate assemblages in the deep habitats of the estuary. Deep habitats were defined as unvegetated habitats where the depth of water was three meters or greater and sampling was done on two occasions; December 1997 and June 1998 (The Ecology Lab, 1998). The polychaete families Magelonidae and Ophelidae and the bivalve *Theora fragilis* were found to represent 21%, 15% and 12% of the total abundance, respectively. The assemblages and populations of benthic macroinvertebrates differed among locations however differences could not be related to sediment particle sizes determined for each location. The location situated closest to The Entrance was generally distinct from the two other locations sampled and it was assumed that these differences were most likely related in some way to distance from the ocean (The Ecology Lab, 1998). Generally, the most abundant taxa listed within this study did not vary considerably from those listed in previous studies (Powis and Robinson, 1980; MacIntyre, 1990; Courtney, 1992), however, the rank abundance of taxa varied.

4.3.4.1. Methods

Benthic macroinvertebrate assemblages from within open water and seagrass habitats in the Tuggerah Lake estuary were sampled in February 1998 using a nested sampling design (Cummins *et al*, 2000) The study was designed to provide a description of the distribution and abundance of macrobenthic assemblages and to establish their variability at different spatial scales. The sampling design incorporated three scales (location, habitat and sites) and samples were collected from six locations although only the data from Tuggerah Lake (TL), Tuggerah Bay (TB), Chittaway Bay (CB) and The Entrance (TE) are presented here (Figure 56) Sites were approximately $50m^2$ and situated randomly within openwater and seagrass habitats Three replicate samples were taken from within each of two sites at each of the locations Sediments were collected by SCUBA to a depth of 10cm with corers made from 15cm diameter PVC pipe Samples were placed into plastic bags and fixed in 10% buffered formaldehyde in seawater In the laboratory, samples were sieved through a 1mm mesh and the contents placed in labelled plastic bags and preserved in 70% ethanol solution Samples were later identified and enumerated to the lowest practicable taxonomic level, for instance, to family level for polychaetes and to order for crustaceans

Data were transformed using the double-square root transformation to reduce the weighting given to abundant taxa and increase the weighting given to rare taxa (Clarke and Warwick, 1994) Two-dimensional nMDS ordinations were constructed and the significance of any apparent differences among locations or habitats was determined using one-way ANOSIM Sites were first pooled to increase the power of the pairwise comparisons (n =6) The SIMPER procedure was then used to examine the contribution of faunal groups to the similarities (and dissimilarities) among locations and habitats (Clarke and Warwick, 1994)

Analysis of variance (ANOVA) tests were used to test the following hypotheses i) significant differences exist in the structure of benthic macroinvertebrate assemblages within seagrass and openwater habitats; ii) macroinvertebrate assemblages vary significantly among locations within Tuggerah Lake The locations were treated as fixed, habitats were fixed and orthogonal, whilst sites were nested within both habitats and locations.

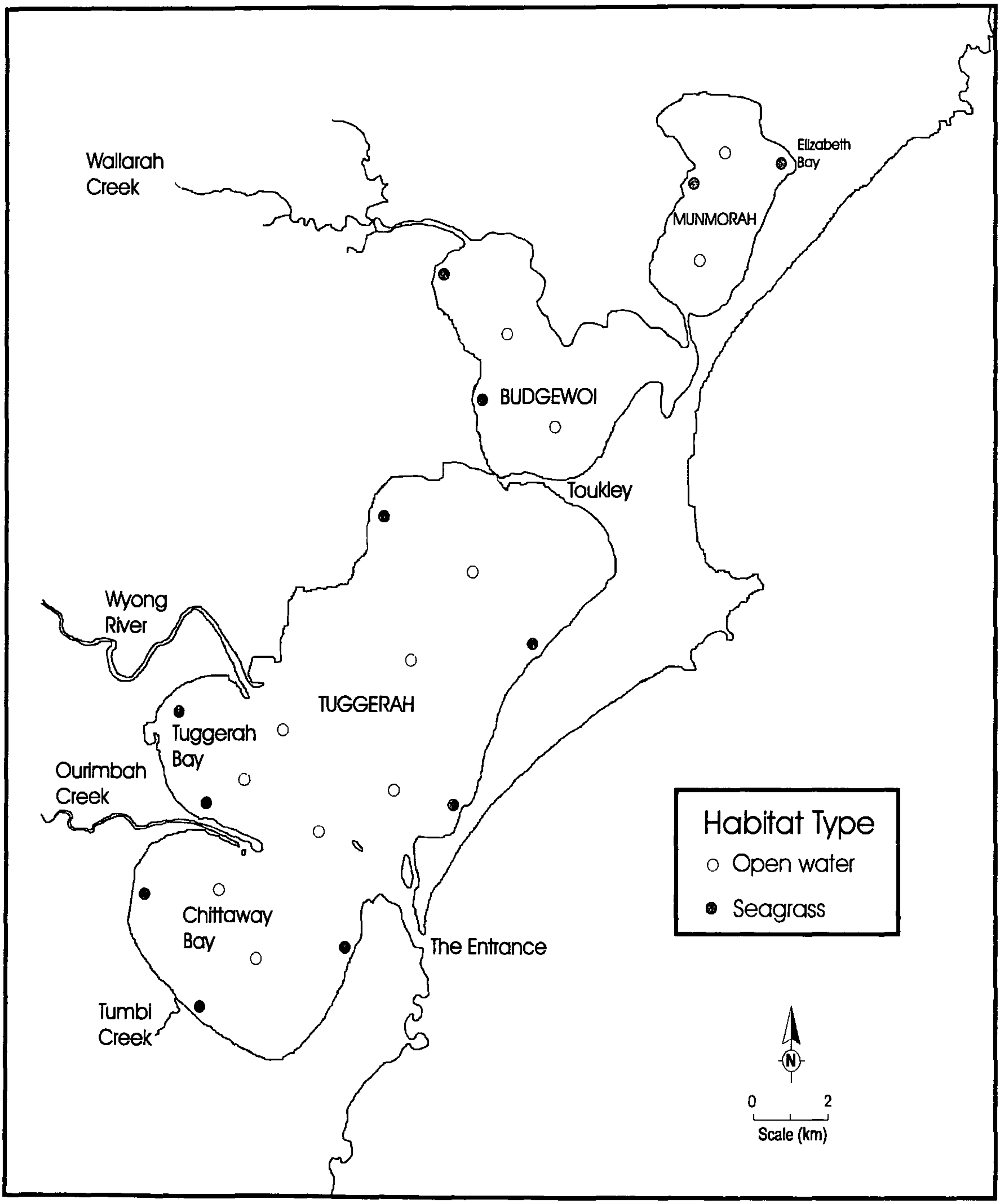


Figure 56. **Macrobenthic sampling sites within seagrass and open water habitats**

4.3.4.2. Results

A total of 1131 animals representing 41 taxa (Table 13) were identified from within the seagrass and open water habitats (Cummins *et al*, 2000) Polychaetes were the richest and most abundant taxa however their numbers varied among openwater and seagrass habitats (Figure 57) Open water habitats were characterised by low faunal richness and abundance and by the presence of two polychaete families, Magelonidae and Maldonidae Seagrass meadows had considerably higher numbers of taxa and total numbers of individuals, when compared to the open water habitats Polychaetes, specifically capitellid worms numerically dominated assemblages sampled from sediments within seagrass beds (Figure 57) The next most numerically dominated taxa were the gastropods (Figure 57)

The total number of individuals and species richness were significantly greatest in samples collected from within seagrass beds, compared to the open water habitat (Figure 57). Seagrass meadows within Tuggerah Bay had significantly greater numbers of individuals and taxa than all other locations (Figure 57) The number of polychaetes varied significantly among sites, however their numbers were considerably highest in the seagrass beds in Tuggerah Bay (Figure 57) The number of bivalves did not vary significantly between locations or habitats, however the number of gastropods was significantly higher in seagrass meadows (Figure 57)

A non-metric multidimensional scaling (nMDS) ordination grouped the samples into two clusters, which distinguished benthic macroinvertebrate assemblages within the seagrass habitat from those in the openwater habitat (Figure 58) There appeared to be no clear separation of samples into groups that readily distinguished between the four locations (Cummins *et al*, 2000) ANOSIM tests confirmed that there were significant differences in the structure of assemblages within openwater and seagrass habitats (Cummins *et al*, 2000) Pairwise comparisons revealed there was little variation among locations sampled within the openwater habitat however, assemblages within seagrass beds varied significantly among the four locations (Cummins *et al*, 2000). SIMPER analyses identified two polychaete families, Magelonidae and Maldonidae, and one gastropod species, *Nassarius burchardi* (Family Nassariidae) as the taxa, which contributed most to the similarity of samples collected within the openwater habitat Capitellid worms were ranked highly for all groups of samples collected within seagrass habitat in each of the 4 locations (Cummins *et al*, 2000)

Table 13. Macroinvertebrate taxa identified from the estuary

ANNELIDA

Polychaeta
Capitellidae (*Notomastus* sp)
(*Capitella capitata*)
Cirratulidae
Eunicidae
Lumbrineridae
Magelonidae
Maldanidae
Nephtyidae (*Nephtys australiensis*)
Nereididae (*Ceratonereis aequisetis)*
Opheliidae (*Armandia intermedia*)
Orbiniidae *(Scoloplos (scoloplos) simplex)*
Oweniidae(cf *Owenia fusiformis*)
Pilargiidae
Serpulidae
Spionidae
Syllidae

Terebellidae
Oligochaeta
Nemertina
Actiniara
Sipuncula

CRUSTACEA
Mysidacea

Amphipoda
Coraphiidae (*Caprella* sp)
Melitidae (*Melita* sp)
(*Orchestia* sp)
Phoxocephalidae (*Limnoporeia yarrague*)
Paracalliopidae (*Paracalliope australis*)
Paracorophium sp

Isopoda
Anthuridae (*Cyanthura hakea*)

Decapoda
Alpheidae
Grapsidae (*Ilyograpsus paludicola*)

MOLLUSCA

Gastropoda
Amphibolidae (*Salinator fragilis*)
Aplysiidae (*Phyllaplysia* sp)
Haminoeidae (*Haminoea* sp)
Hydrobiidae (*Potamopyrgus antipodarum*)
Littorinidae (*Bembicium auratum*)
Marginellidae (*Cystiscus* sp)
Muricidae (*Bedeva hanleyi*)
Nassariidae (*Nassarius burchardi*)
Naticidae (*Conuber sordidum*)
Neritidae (*Smaragdia souverbiana*)
Potamididae (*Velacumantis australis*)
Pyramidellidae (*Linopyrga cerea*)
Trochidae (cf *Prothalotia comtessei*)
Trochidae (*Austrocochlea porcata*)

Bivalvia
Arcidae (*Anadara trapezia*)
Galeommatidae (*Arthritica helmsi*)
Laternulidae (*Laternula* sp)
Mactricidae (*Notospisula trigonella*)
Mytilidae (*Xenostrobus securis*)
Semelidae (*Theora fragilis*)
Tellinidae (*Tellina deltoidalis*)

INSECTA
Chironomidae

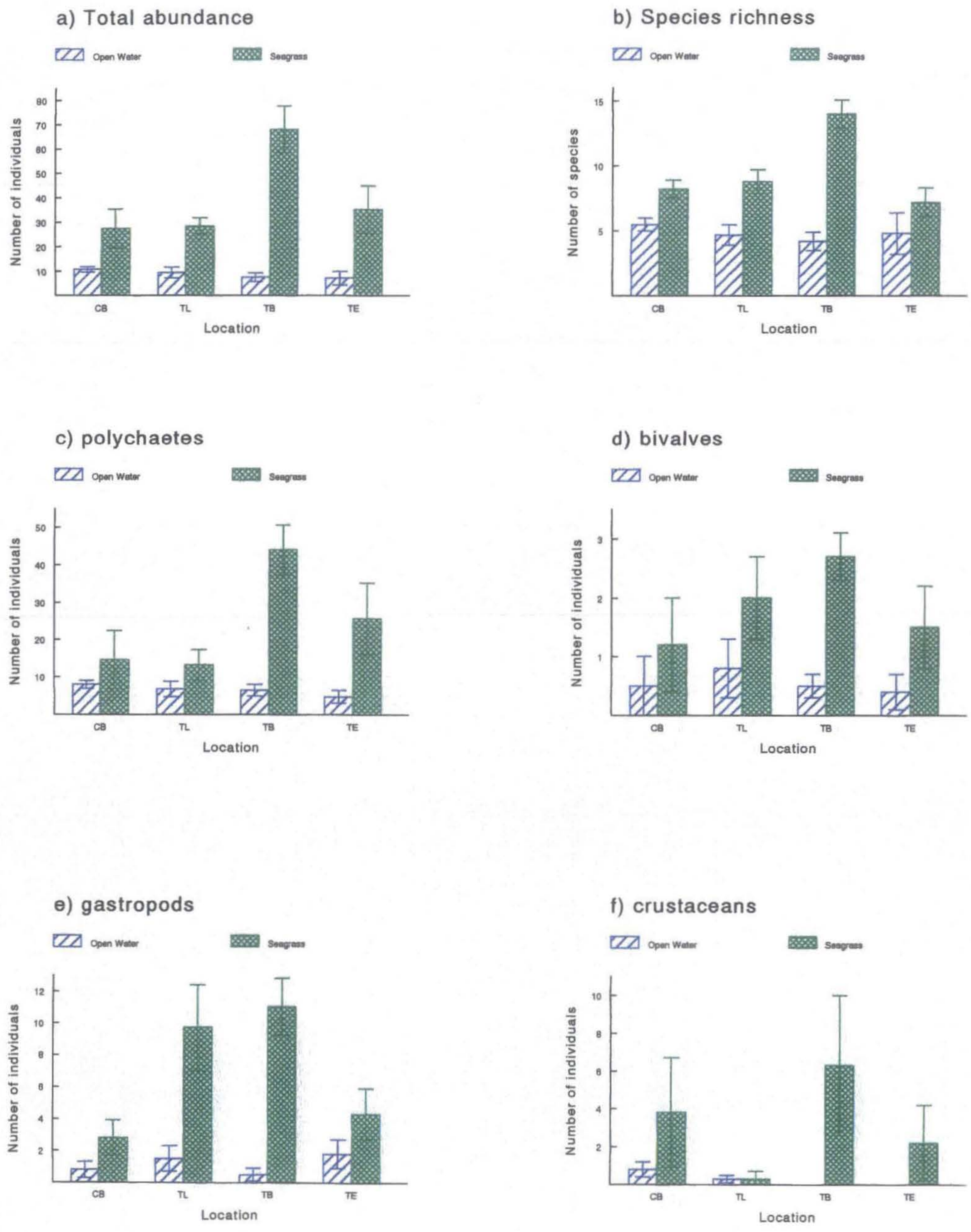


Figure 57. Mean (± SE) richness and abundance of benthic invertebrates from within seagrass and open water habitats in Tuggerah Lake (TL), Chittaway Bay (CB), Tuggerah Bay (TB) and The Entrance (TE)

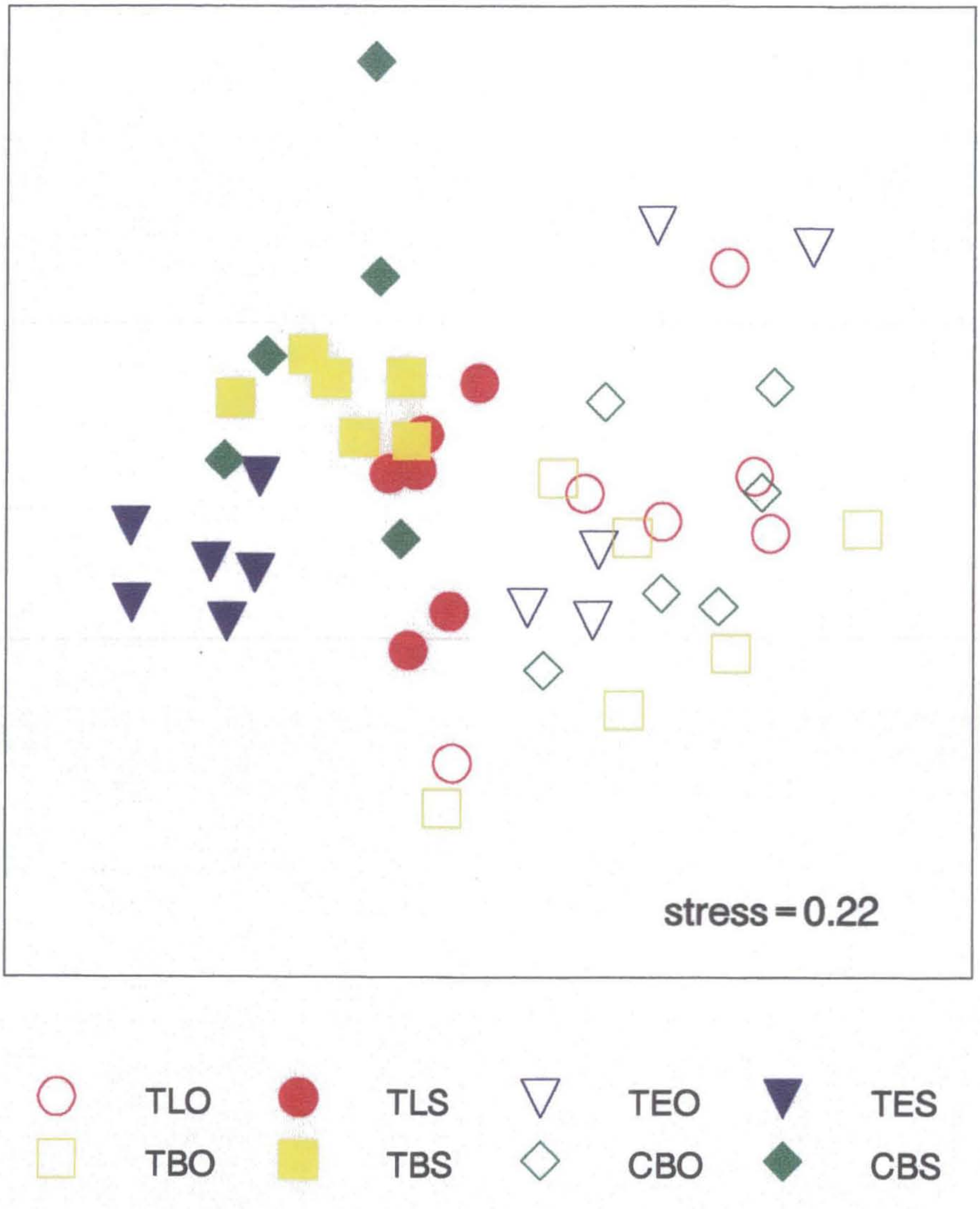


Figure 58. nMDS ordination of invertebrate sites within seagrass and open water habitats

4.3.4.3. Discussion

Significant variation in the structure of benthic macroinvertebrate assemblages among open water and seagrass habitats was found Generally, open water habitats were characterised by low fauna diversity and abundance, whilst seagrass habitats were diverse and had considerably greater numbers of individuals. Species present in the open water habitat were mostly from deposit-feeding groups Sediments within the openwater zones were comprised of a high percentage of clays and silts (78 –95%) and it has been shown that a number of species, particularly suspensions feeders, are unable to colonise within these areas as a lack of stability and resuspension of the silt may cause “choking” or “smothering” (Rhoads and Young, 1970, Bloom *et al*, 1972, Powis and Robinson, 1980) As well as contributing to habitat complexity (allowing greater coexistance of taxa), seagrasses contribute to a more stable substratum (by binding together sediments) They can also increase oxygen supply to the sediments via their root systems, thus increasing the depth of the redox-potential discontinuity layer or by providing an abundant food-supply and protection from predation (Young *et al.,* 1976)

Seagrass meadows within Tuggerah Bay had significantly greater species richness and abundance than all other locations As well as having the most extensive area of seagrass meadow within the estuary, the foreshores of Tuggerah Bay are relatively undisturbed Development of foreshores at The Entrance, Chittaway Bay and Tuggerah Lake include a number of recreational areas and water-frontage properties Human related disturbances to these foreshore areas include stormwater drains that discharge directly into the lake and physical disturbances such as beach-cleaning activities to remove drift-macroalgae and seagrass wrack These activities can significantly alter water qualtiy and substratum characterisitcs, subsequently impacting benthic community structure (Powis, 1975, Daley, 1997) It has been well documented that the diversity and abundance of macrobenthic communities are highest in stable, undisturbed habitats and become more depauperate in unstable regions of constant disturbance (Pearson and Rosenberg, 1978, Boesch and Rosenberg, 1981, Austen *et al*, 1989)

The most abundant taxa listed within this study did not vary considerably from those listed in previous studies (Powis and Robinson, 1980, MacIntyre, 1990, Courtney, 1992, The Ecology Lab, 1998), however the rank abundance of taxa varied Estuaries are complex ecosystems and respond to a number of interacting physical, chemical and biological processes Major fluctuations in salinity can certainly alter the distribution and abundance of stenohaline species There have been significant fluctuations in salinity in the estuary over the past 30-40 years (see water quality section) and Powis and Robinson (1980) implicated major floods in 1974 to a fish kill and the destruction of considerable areas of seagrass meadows Anthropogenic disturbance around the estuary includes power station operations, dredging, harvesting, net-hauling and increased loads of nutrients and suspended particulate matter from catchment based runoff The effects of both natural and anthropogenic disturbances on the structure of benthic assemblages require studies that take into account appropriate spatial and temporal scales Despite wide fluctuations in their distribution and abundance the macrobenthic assemblages within the estuary remain consistent in their relative species composition over time Further studies on the benthic assemblages will be reported in the management study report

4.3.5. Zooplankton

Zooplankton are small, floating or weakly swimming animals, which occur in all estuaries and along with the phytoplankton and bacterioplankton constitute the planktonic community Zooplankton play significant roles in trophic transfer and nutrient cycling in aquatic ecosystems Zooplankters are effective grazers of phytoplankton, keeping microalgal populations in check Waste products from grazing are either recycled within the water column or sedimented to the bottom for utilization by epibenthic and benthic organisms In estuarine environments, zooplankters provide an essential food source for many taxa, in particular, larval and juvenile fish

Surveys that include assessments of zooplankton and phytoplankton abundance and distribution may shed some light on the potential grazing impact of zooplankton They also provide an effective means for monitoring the presence of undesirable bloom-forming species, such as the large and ubiquitous heterotrophic dinoflagellate, *Noctiluca scintillans* (up to 2 mm diam), which is known to produce red tides in local coastal waters Some zooplankton taxa have limited tolerances to particular environmental conditions (e g. salinity, temperature) and thus may be used as indicator species of changes in the chemical and/or physical environment

Planktonic interactions and processes within the Tuggerah Lakes estuary are currently little understood Previous studies include a series of phytoplankton surveys (Cheng, 1994 and prior reports) and only one major investigation of the zooplankton some 20 years ago (Hodgson, 1979) This study of zooplankton was the first to describe their distribution and abundance at various spatial and temporal scales and was run concurrently with the phytoplankton monitoring program

4.3.5.1. Methods

Zooplankton samples were collected from 16 sites in the Tuggerah estuary, at the same spatial and temporal scales as the phytoplankton program (from May 1997 to November 1998) Zooplankton and phytoplankton samples were taken at the same time from a mixed water sample of about 8-L, which was collected using a clear plastic pole sampler (2-m long, 60-cm diam) and emptied into a bucket To sample the zooplankton, a 2-L volume of seawater was taken from the bucket and poured through a 110 µm mesh zooplankton net All zooplankters retained by the mesh were collected in an attached receiving jar and fixed with 3-5% formalin. This method was repeated three times at each site The fixed zooplankton samples were then transferred to the lab for microscopic identification and enumeration The contents of a total of 480 samples were counted and the data were statistically analysed using univariate and multivariate techniques

4.3.5.2. Results & Discussion

The zooplankton were representative of those found in the 100-2000 µm size fraction, and included many benthic larvae and immature stages of other zooplankton A total of 44 different zooplankton types were identified Commonly occurring types included crustacean nauplii, juvenile and adult copepods (calanoids, cyclopoids and harpacticoids), cladocerans, polychaete larvae, early developmental stages of many other benthic animals, small medusae, chaetognaths and the heterotrophic dinoflagellate, *Noctiluca scintillans* Tintinnids (loricate ciliates), though at times abundant, were not included in the total counts as most were too small to be retained by the net used for this study (110 µm mesh)

The estuary exhibited seasonal trends in both zooplankton and phytoplankton densities (Redden and Blacklock, 1999) During most of the year, the average zooplankton abundance was <100 individuals per litre, with the lowest densities observed in the winter months of both 1997 and 1998 Increased abundance was apparent in early spring (October 1997 and November 1998), with highest abundance observed in December 1997 (>200 per litre) Zooplankton peaks in December 1997 and November 1998 lagged behind observed phytoplankton peaks in July 1997 and July-August 1998, respectively This trend is typical for temperate coastal waters and reflects differences in reproductive rates While phytoplankton cells may double as often as twice per day, zooplankton typically produce eggs which hatch days to weeks later

For the purposes of examining general trends in zooplankton composition, the 44 categories observed were grouped into one of six main types crustacean nauplii (mostly copepod larval stages), copepods (juveniles and adults), polychaete larvae, other benthic larvae, the large dinoflagellate *Noctiluca scintillans,* and “others” (Figure 59)

Nauplii numerically dominated the zooplankton in the 100-2000 µm size class, with representation over the 18 month period ranging from 48% to 74% of total zooplankton abundance (Figure 59) Their dominance indicates that copepods are reproducing year-round Individuals grouped under “copepods” (primarily cyclopoid and harpacticoid taxa) were observed in highest relative abundance in the spring months, following a peak in the density of phytoplankton, the main food source for zooplankton Polychaete larvae, which occurred year-round, appeared in highest numbers during the late summer and fall The category “other benthic larvae” comprised a large number of taxa, with representatives occurring throughout the year In winter, when zooplankton abundance was low, benthic larvae comprised a large fraction of the total zooplankton observed The large dinoflagellate, *Noctiluca scintillans*, appeared in highest numbers in samples collected in winter and early spring

An analysis of zooplankton abundance with habitat type revealed no significant difference in total abundance between seagrass sites and open water sites (Figure 60). However, the relative composition of zooplankton taxa, were at times different between habitats In particular, polychaetes and other benthic larvae were generally more abundant in open water sites than in seagrass beds

Although total zooplankton abundance varied little with habitat type, there were significant differences in abundance between the locations at Tuggerah Entrance, Tuggerah Lake, Budgewoi Lake and Lake Munmorah (Figure 61) Notably, the abundance of zooplankton in the Tuggerah Entrance location was significantly lower than all other locations (Figure 61) This result may be due to a diluting effect of tidal exchange in the Entrance area and/or greater predation by zooplankton-feeding fishes The highest zooplankton densities were often observed in samples collected from Budgewoi Lake and Lake Munmorah, the two lagoons least affected by coastal mixing processes Interestingly, *Noctiluca* was most abundant in Tuggerah Lake and the Tuggerah Entrance area, reflecting its coastal origin and likely transport into the estuary via tidal exchange and advection

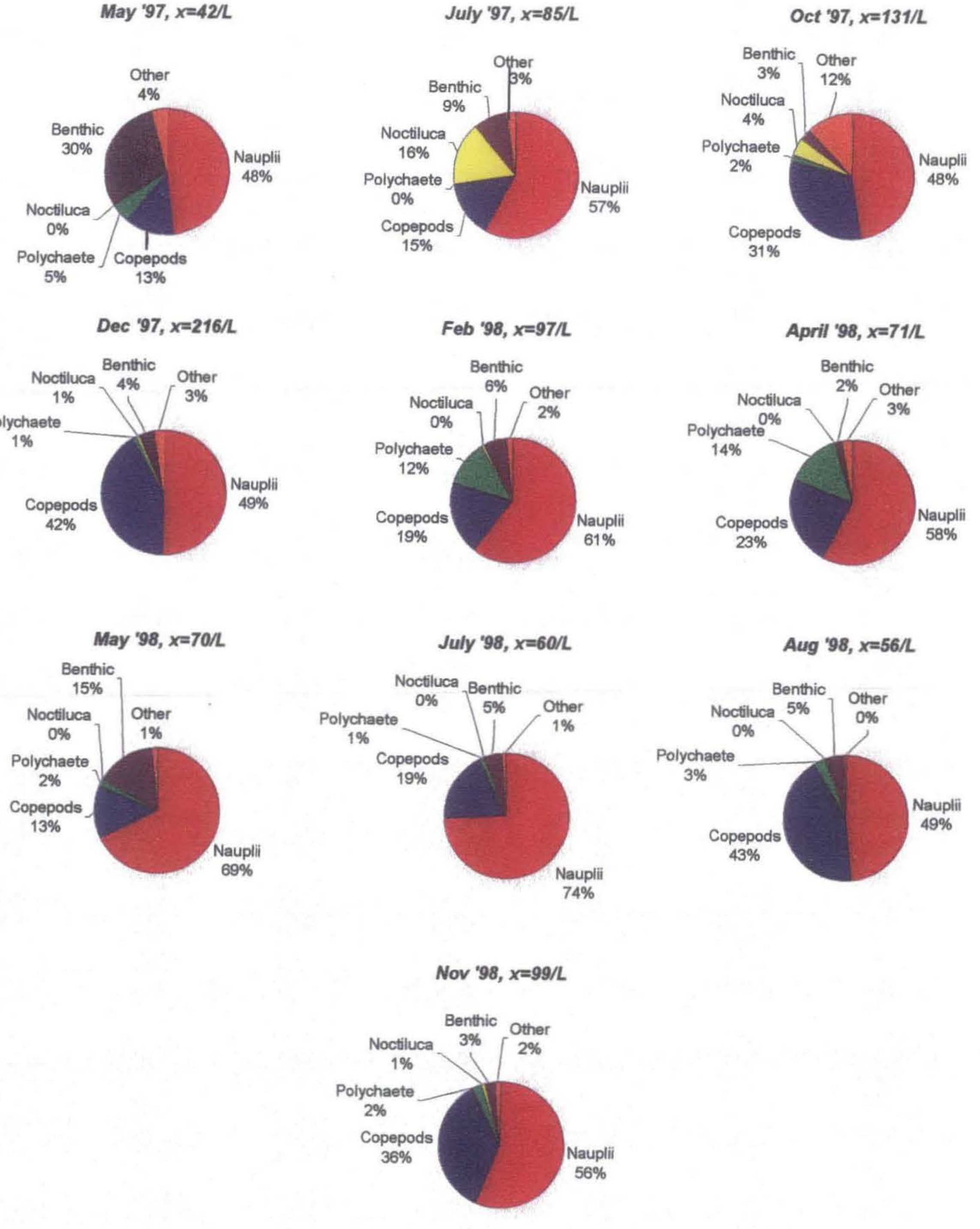


Figure 59. **Pie graphs showing percentage composition of broad zooplankton groups (nauplii, copepods, polychaete larvae, other benthic larvae, *Noctiluca scintillans* and all others) for individual sampling dates over the period May 1997 – November 1998. Each pie graph represents the mean composition from 16 sites, with 3 replicates per site (n=48).**

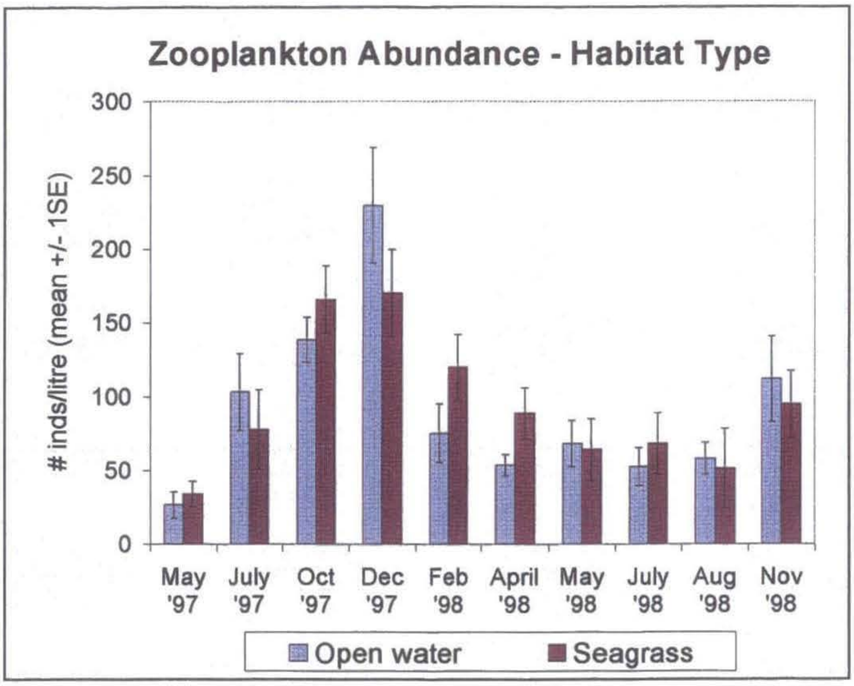


Figure 60. **Abundance of zooplankton (mean # individuals/litre ± 1SE) for each habitat type, for the period May 1997 - November 1998. Each bar represents 8 sites (n=24 samples).**

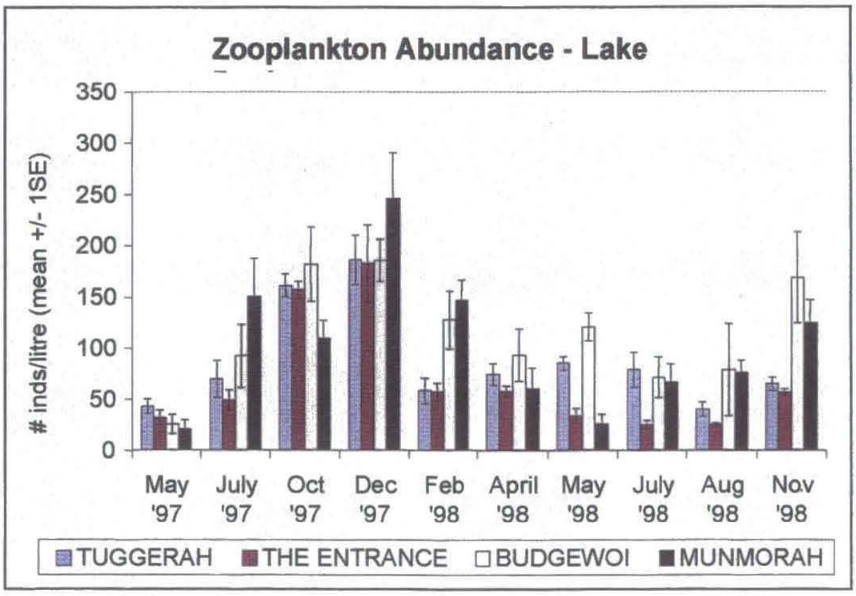


Figure 61. **Abundance of zooplankton (mean # individuals/litre ± 1SE) for each Lake region, for the period May 1997 - November 1998. Each bar represents 4 sites (n=12 samples).**

5. ECOLOGICAL PROCESSES AND DISTURBANCE

5.1. Variability in Patterns and Processes

All ecosystems experience spatial and temporal variation in their physical, chemical and biologogical components This variabilty is introduced into a system from interactions between these components and disturbance from the natural environment Variation in natural systems can also be caused by anthropogenic disturbance Some examples in estuaries are stormwater runoff, dredging and fishing Ecological systems are rarely in equilibrium because of changes associated with natural disturbance and in heavily populated coastal estuaries by anthropogenic disturbance Patterns of variation in biological assemblages have received considerable attention in the scientific literature In estuarine systems significant pattterns of change of macroalgae or phytoplankton populations (e g massive increases in biomass or changes to the structure of the assemblage) are generally associated with some form of anthropogenic disturbance, e g eutrophication There are many examples of estuaries where increased human activity has lead to increased primary productivity associated with the disturbance What is not clear is whether this increase in populations is due to natural or anthropogenic disturbance What is required is a framework by which observations associated with natural patterns of variability can be discerned from those caused by humans The detection of environmental impacts in marine systems has been dealt with in great detail over the last few years (Underwood, 1997) The Tuggerah Lakes estuary has had its fair share of distubance with development and subsequent eutrophication There are currently numerous sources of anthropogenic disturbance to the estuary Whether they cause environmental impact has never really been quantified

5.2. The Tuggerah Lakes Restoration Project

The Tuggerah Lakes Restoration Project was a program established by the NSW State Government and Wyong Shire Council in response to community pressure to “clean up” Tuggerah Lakes (WSC, 1998) The program involved dredging to keep the entrance open, foreshore reclamation and removal of nutrient ladden sediments from within the shallow seagrass meadows (Figure 62), and the construction of stormwater treatment zones around the estuary (Patterson Britton & Partners, 1992) The impacts of the actual works on physical, chemical and biological processes within the estuary were never evaluated The restoration program and its value to the estuary have been questioned by environmental managers and there are mixed feelings within the general community as to its overall worth as a solution to the problems that the Tuggerah Lakes were experiencing during the 1980’s

Overall, it is difficult, if not impossible to assess the positve or negative impact of the restoration project on the estuary, because no quantitative data were ever collected either before or after There are many reports of fish kills associated with the physical works and the dredging did cause disturbance to acid sulphate soils The restoration project was essentially a "band aid solution" to what is considered to be anthropogenic disturbance from the catchment Nutrients delivered to the estuary from the wider catchment and from local subcatchments were considered to be the cause of eutrophication in the first place The source of the nutrient problem was never addressed in the restoration project but has been and is continuing to be dealt with by environmental management of the catchments (WSC, 1998)

5.3. Munmorah Power Station

The Munmorah Power Station was commissioned in 1967, and obtains its cooling water from Lake Munmorah and discharges into Budgewoi Lake There have been numerous studies and investigations into the effects of the Power Station on the ecology of the Tuggerah Lakes estuary (Powis 1973, Higginson, 1973, Henry and Virgona, 1980) Batley *et al* (1990) and Thresher *et al* (1993) reviewed the effects of power station operations on the ecology of the estuary It was considered that the power station had substantial ecological impacts in Budgewoi Lake within one kilometre of the outfall, with changes to sediments, benthos, macrophytes and water quality (Thresher *et al*, 1993) Elevated temperatures of surface waters in Budgewoi Lake were obvious, however there were insufficient data to assess whether the station has caused effects on the growth of seagrasses It was recommended that experiments be done to ascertain effects associated with increased temperature Light, salinity and sediment composition were not affected by the power station, however it was thought that increased water temperature could lead to increased nutrient release rates (fluxes) from the sediments Particulate ash from the station was high in Lake Munmorah whilst zinc, lead, copper and antimony were also high There was no evidence of bioaccumulation in seagrass or other bioata (Batley *et al*, 1990)

5.4. Coal Mining and Subsidence

Subsidence due to coal mining has been a problem in the Wyong Shire for many years especially in the northern areas around Lake Munmorah The effects of recent mine subsidence to the foreshores and freshwater wetland at Colongra (Lake Munmorah) was evaluated by Duchatel (1998) Generally, four hectares of foreshore wetland was subsided by 900mm allowing saline water to flow into the freshwater swamp behind the more elevated foreshore (Figure 63) Widespread mortality of plants and associated wildlife were predicted and management strategies to deal with the problem have been recommended (Duchatel, 1998)

COAL Australia has been undertaking exploratory drilling under the Tuggerah Lake with a view to mining in the future Assessment of the environmental effects of these operations is being done by COAL Australia in conjunction with consultants ERM Mitchell McCotter Wyong Shire Council and ERM Mitchell McCotter have done some collaborative studies to gain baseline data on some of the more important ecological components that may be affected by subsidence The results of these studies will be reported in an EIS by ERM Mitchell McCotter for Coal Australia however, the management plan for the Tuggerah Lakes estuary will need to evaluate potential effects of mining Important issues associated with subsidence include the effects on fringing wetland habitats and seagrass meadows Seagrass meadows are important for commercial and recreational fisheries within the estuary as many fish species depend on these meadows at some stage in their life history Within these seagrass meadows there are also many invertebrate species, which are important to the ecology of the estuary. In general, mine subsidence could potentially alter the mean depth of seagrass habitats causing a net loss in seagrass within the estuary Significant seagrass meadows occur within Tuggerah Bay and any increase in the overall depth of this area could cause changes to seagrass and fisheries An hypothesis of increased depth leading to decreased seagrass and changes to invertebrate assemblages is currently being examined by a series of manipulative field based experiments where sediment and seagrasses are being translocated to deeper water to mimic the effect of subsidence This work will be reported within the management studies Furthermore, if sections of Tuggerah Lake are “made deeper” there is greater potential for stratification of the water column, which could lead to lower oxygen levels within “deeper pools” Depending on the scale of subsidence there is potential for greater nutrient release from sediments under these conditions This is all conjecture until the mining surveys and plans are completed and the managers of the estuary have a better understanding about which areas may be mined and the extent of potential subsidence is known

Figure 62. Swamp dozers removing sediment and macrophytes as part of the restoration project

Figure 63. The effects of mine subsidence on the foreshore at Colongra Wetland

5.5. Environmental Flows

Environmental flows are the stream flows that are required to maintain natural stream conditions and these flows are thought to be essential for the "health" of instream biota The Tuggerah Lakes estuary relies on inflows from its tributary rivers and creeks to provide freshwater input and brackish/freshwater habitat (The Ecology Lab, 1999) The water supply system for Wyong consists of a small storage dam at Mardi reservoir and weirs and pumping stations at Ourimbah Creek and Wyong River, which pump to Mardi Dam (The Ecology Lab, 1999) It is thought that the instream ecology of both Wyong River and Ourimbah Creek are under some stress from reduced flow (The Ecology Lab, 1999), which has ecological implications for the receiving waters of the estuary The water authority of Gosford and Wyong Shire is currently evaluating options for management of environmental flows in the waterways within its sphere of operations (The Ecology Lab, 1999) An environmental flow strategy (Muston, 1999) and a review of the water supply activities and baseline ecological data (The Ecology Lab, 1999) have now been completed Wyong Shire Council are collecting data on the aquatic ecology of the streams and rivers that feed into the Tuggerah estuary with a view to quantifying the effects of managing environmental flows in their areas of operation (Towell, 1999)

5.6. Potential Bioindicators of Estuarine Health

The use of organisms as 'indicator species' has been attempted in a wide variety of applications, ranging from the microbial level to the ecosystem Biological indicators are organisms that by their habitat and interactions with the environment provide an easily measurable, easily interpreted indicator for assessing the state of an ecosystems health A number of bioindicators are being assessed as part of the estuary management program for the Tuggerah Lakes estuary These include phytoplankton, macroalgae and benthic assemblages To assess the success of catchment management strategies, it has been recommended that additional locations be sampled in external reference estuaries such as Lake Macquarie and Brisbane Waters

5.6.1. Epiphytes as Indicators of Nutrient Status

Aside from the established biological monitoring programs, Wyong Council in collaboration with the University of Newcastle are currently examining the concept of using artificial substrata as tools for assessing the nutrient status of an estuary This collaborative study examines the use of epiphytes (the algae and animals that grow on other organisms or structures) as potential indicators of estuarine health The concept has been borrowed from research and management strategies that are currently being investigated in the eutrophic Chesapeake Bay in America (Boynton *et al*, 1998)

A pilot study was done where arrays were deployed at a number of spatial scales within the estuary and adjacent to major tributary inflows (Davis *et al*, 1999) Each array had a number of plastic "Myolar Strips" attached and were deployed at depth of approximately 1 5m Individual strips were collected at random from the arrays over a twelve-week period, and estimates of epiphytic growth made at a number of spatial scales At the same time water samples were collected for analysis of the nutrients nitrogen and phosphorus The biomass of epiphytes at each location was assessed and correlations with water quality made The pilot study showed that epiphytes could potentially be a usefull technique in assessing the nutrient status of the estuary and a twelve-month program of epiphyte sampling has begun The results of this study will be reported in the management studies and in the scientific literature

5.6.2. Seagrasses and Light Climate

Declining populations of seagrasses within NSW coastal estuaries have been recorded due to habitat destruction and deteriorating water quality Light is the primary limiting factor for seagrass growth and therefore any reduction in light quality will cause a reduction in the depth to which seagrasses may grow. The NSW Environment Protection Authority have completed a study of a number of NSW estuaries to determine the potential of using seagrasses and light climate as indicators of estuarine health (Doherty *et al*, 1997) The aim of the study was to assess the use of seagrass depth limitation as a sensitive indicator of estuarine "health" Seagrass depth range was determined and water samples were analysed for nutrients, total suspended solids, turbidity and light (Photosynthetic Active Radiation) The study investigated the maximum depth penetration of the seagrass *Zostera* spp in several estuaries along the coast of NSW By using the seagrass as integrating light meters, light regimes and associated water quality can be assessed and ecological information inferred Tuggerah Lake was included in this study and a number of important findings of relevence to the management of the estuary were identified The results of the study showed that seagrass maximum depth appeared to be a sensitive indicator of some water quality variables, with applications for water quality management Tuggerah Lake was found to have the smallest depth range for seagrass growth and was one of the most turbid estuaries examined, with mean turbidity levels of 4 47NTU's Light attenuation coefficients (Kd) were calculated for the estuary and were generally high The EPA study showed maximum seagrass depth penetration in waters of low turbidity, Kd and nutrients and progressively shallower depth limits with declining water quality Light regime modelling in conjunction with limited *in situ* mapping of seagrass depth penetrations may be an efficient means of assessing ecosystem health and establishing protection and restoration goals Wyong Shire Council is considering adopting the measurement of photosynthetic adaptive radiation (PAR) as part of its long-term monitoring activities for the estuary

6. ESTUARY MANAGEMENT ISSUES

6.1. Introduction

The primary aim of the estuary process study was to establish the patterns and processes occurring within the estuary and identify potential management studies that may need to be done A number of “scoping workshops” were run within the monthly estuary management committee meetings and the results obtained were summarised to identify the major management issues that would need to be dealt with during the management study Input from a number of community meetings were used to help identify potential issues that would need to be addressed in the development of the estuary management study and plan

6.2. Scoping of the Management Studies

6.2.1. Introduction

To assist the development of the Estuary Management Plan, the Estuary Management Subcommittee ran a number of workshops at its meetings to identify and investigate the key management issues for the estuary The initial session asked what were the major issue areas (sets of issues) that should be addressed? Subsequent committee meetings took one issue area and asked two key questions (1) what management **options** should be considered and (2) what were the key **uncertainties** that must be evaluated? In the event, it was much easier to identify the options than to articulate the uncertainties that could be explored to help us make choices about which policies to adopt

6.2.2. Overview of Problems and Issues

The points raised were organised into groups, and the groups divided roughly into Pressure, State and Response issues, as this framework facilitates diagnosis of problems and development of management options (Walkerden, 1999) In general the issues can be summarised into the following key points, which will be addressed in the estuary management study and plan

- Ecologically sustainable management of estuarine beaches, foreshores and seagrass meadows
- Protection of ecologically sensitive habitats, eg Budgewoi Sandmass and Tuggerah Bay

- Managing potentially elevated nutrient and sediment loads to the estuary from increased urbanisation and development in the catchments
- Identification and management of those nutrients responsible for excessive aquatic plant growth
- Implications of periodic dredging of rivers and the tidal delta at The Entrance
- Practical and ecological implications of a second entrance and/or break walls, to alter existing estuarine mixing and flushing
- The management of both recreational and commercial fisheries
- Potential ecological effects of mine subsidence
- The feasibility of using "Bioindicators" to quantify whether management targets for the estuary are attained

6.3. Management of Estuarine Foreshores

6.3.1. Beaches and Reserves

Wyong Shire Council has responsibility for maintaining and regularly cleaning public foreshores around the Tuggerah Lakes estuary This is done to improve visual amenity and is considered important for tourist areas such as at Canton Beach. Seagrass and macroalgae wrack and dangerous objects such as broken glass and syringes are removed using a tractor and rake A foreshore maintenance and beach cleaning procedure manual has been prepared by Council, and is regularly reviewed and updated (WSC, 1998) Council has been collecting seagrass wrack from public foreshores for many years, however the potential environmental impacts associated with these operations has never been quantified Potential effects include the physical disturbance of the strucure of the beach and the fauna and flora that live there. A study is currently being done by the University of Newcastle on the effects of beach cleaning on estuarine beach fauna and avi-fauna Wyong Council in collaboration with the Centre for Ecological Impacts on Coastal Cities (EICC) have also begun preliminary investigations into the ecological processes associated with seagrass wrack and saltmarsh The results of these investigations will be reported in the management study

6.3.2. Fragmented Saltmarsh Habitats

Saltmarshes and fringing wetlands are important in the nutrient cycling process in NSW coastal estuaries and are important feeding and nursery habitats for many birds, fish, invertebrates, and a range of fauna Around fifty percent of these habitats have been destroyed in NSW, through the direct results of development and the indirect effects of anthropogenic disturbance These habitats are generally high on the shore of estuarine intertidal mudflats and are usually located behind mangrove forests They are usually dominated by salt-tolerant species of grasses, sedges, rushes, forbs, shrubs and small trees (Sainty and Roberts, 2000) Although there has been considerable urban development around the Tuggerah Lakes estuary, fringing saltmarsh and wetland vegetation can still be found in some undeveloped areas (Sainty, 1998) Saltmarshes are frequently inundated by seawater because of tidal action, however, in the Tuggerah estuary, the tidal range is quite small Flooding and long-term changes to mean water levels in the estuary are generally the mechanisms by which these particular habitats become inundated

No data existed on the smaller fragmented saltmarshes around the estuary These fragmented habitats are important to the ecology of the estuary and their protection or enhancement needs to be considered in conjunction with public amenity A study was done to identify existing fragmented saltmarsh/wetland habitats and outline methods to maintain or enhance them (Duchatel, 2000) These data were essential to assist in formulating management options for foreshore maintenance on Council reserves that accounts for all stakeholders and users, whilst balancing the ecology of the estuary The information from this investigation will be vital for the Tuggerah Lakes Estuary Management Plan The project outcomes will include a semi-quantitative assessment of the remaining fragmented/disturbed saltmarsh habitats and make recommendations on management of the existing fragmented/disturbed saltmarsh habitats

6.3.3. Effects of the Weed Harvester

As part of the Lakes Restoration program a mechanical weed harvester was commissioned to remove floating seagrass and macroalgae wrack from shallow seagrass meadows, in high priority areas around the estuary NSW Fisheries issued an experimental permit to collect wrack on the basis that environmental monitoring was done, where the effects of the harvester on seagrasses, benthic and nektonic assemblages was examined This research into the potential impacts of the harvester is being done as part of a Post Graduate degree at the University of Newcastle A monitoring program has been in place since August 1997, with regular sampling occurring during each summer and winter seasons The harvester did not begin operation until late 1998, so essential "before" data were collected for two winter and one summer period. "After" data now includes one summer and winter period and future work will provide further summer/winter data

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The dominant seagrass species was *Zostera capricornii*, with *Halophila ovalis* and *Ruppia megacarpa* spread throughout a variety of areas The project has provided two years of seasonal data on *Z capricornii* from each of the three lakes Variables include the number

The dominant seagrass species was *Zostera capricornii*, with *Halophila ovalis* and *Ruppia megacarpa* spread throughout a variety of areas. The project has provided two years of seasonal data on *Z. capricornii* from each of the three lakes. Variables include the number of shoots, number of leaves per shoot, leaf lengths and biomass, all of which have not been previously been recorded. Significant spatial variation and seasonal trends were observed for some variables, with generally greater seagrass biomass during the warmer months (Figure 64). During winter the seagrass appeared to "die-back" producing less biomass and shorter leaf lengths (Figure 65). It is possible that the longer leaves are "sloughed" from the shoot in late summer, contributing to floating wrack mats and decreasing the average leaf lengths in winter (Casey, 1999).

The richness and abundance of fish assemblages in the estuary generally increased in summer (Figures 66 & 67). Infaunal macroinvertebrates were also sampled during winter 1997/1999 and summer 1998 and seasonal trends were observed (Casey, 1999). The amount of by-catch and live seagrass being collected by the harvester was assessed in an experiment (Casey, 1999). The results indicated that negligible amounts of live seagrass and associated fauna were collected, however recent observations are that by-catch from the harvester may be larger and dependent on the operator and the location. Furthermore, it was found that turbidity and nutrients in the water column were significantly increased during harvesting, primarily due to the turbulent action of the paddlewheels. Daley (1997) found similar results in an experiment on the effects of manually raking seagrass wrack, where nutrients were elevated by an order of magnitude in the water column.

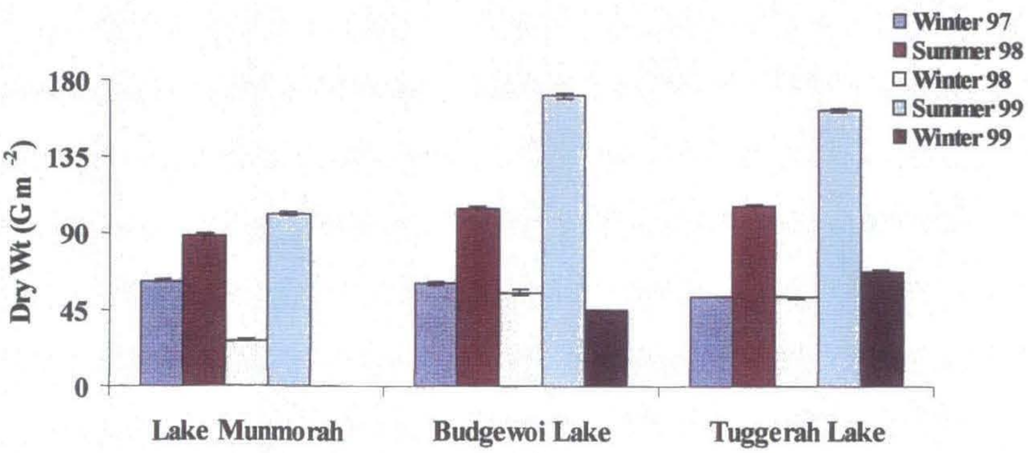

Figure 64. **Seasonal trends in the abundance of *Zostera capricornii***

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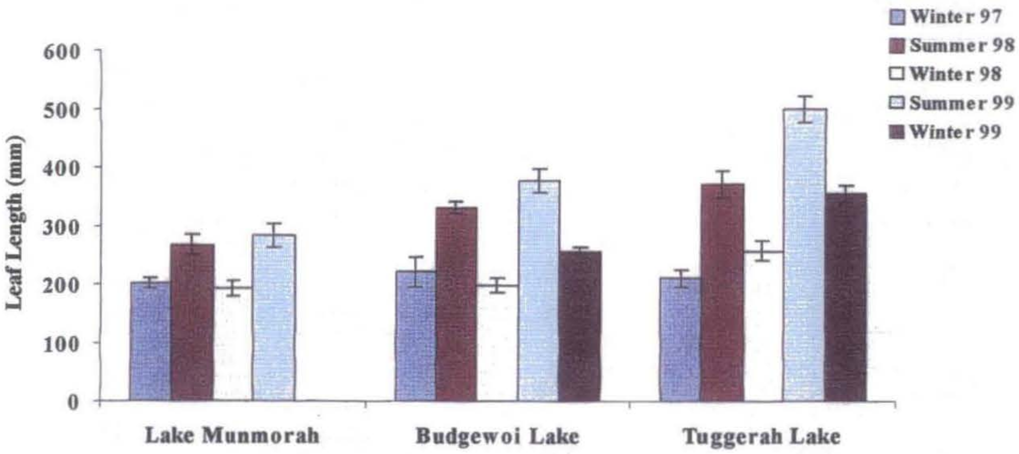

Figure 65. Seasonal trends in *Zostera capricornii* leaf lengths

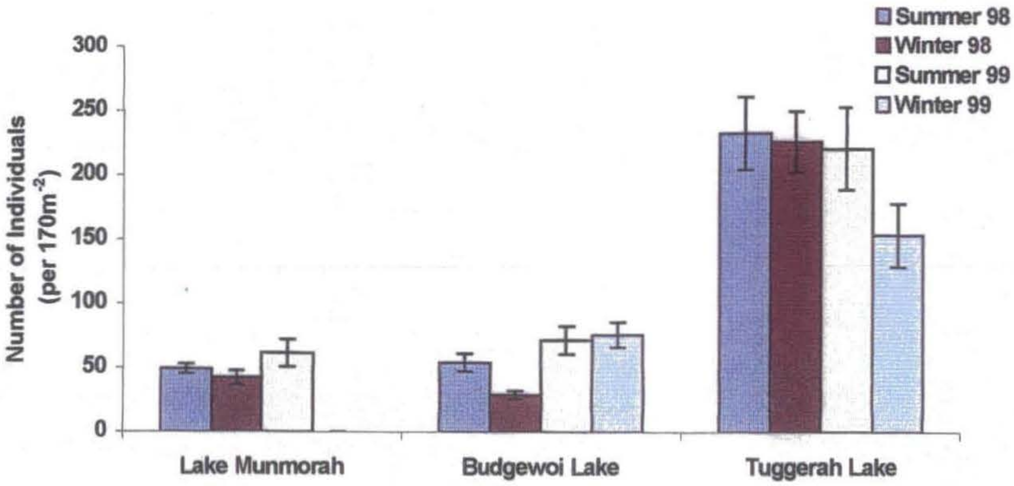

Figure 66. Seasonal trends in the abundance of fishes

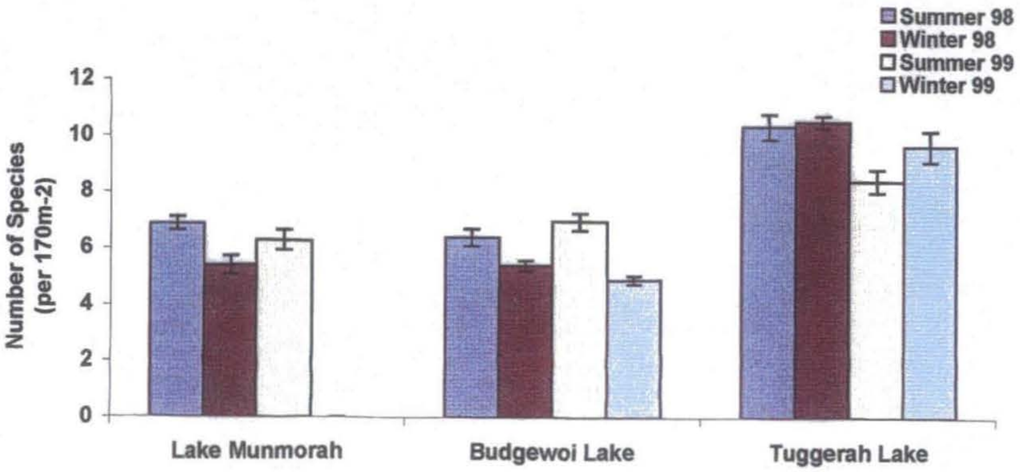

Figure 67. Seasonal trends in the species richness of fishes

6.3.4. Ecologically Sustainable Foreshore Management

In New South Wales, many areas of saltmarsh have been cleared and re-establishment or restoration of these habitats can be problematic (Chapman and Underwood, 1997) There are remnant patches of saltmarshes around the Tuggerah Lake estuary, some of which appear to be quite healthy (Sainty, 1998) There are also very large patches of disturbed foreshore, which probably once contained saltmarsh (Duchatel, 2000) Observations have been made that seagrass wrack washed onto beaches may assist the establishment and/or growth and survival of saltmarsh plants This may be because they provide a structure, which helps to reduce erosion and dessication of the soil and may provide nutrients to what are essentially nutrient-poor sediments To test these observations, a series of manipulative experiments are being done by the EICC in collaboration with Wyong Shire Council These experiments were designed to test hypotheses regarding the role of seagrass wrack in the establishment and growth of saltmarsh Further experiments are examining how seagrass wrack may be used to assist saltmarsh restoration programs Finally, saltmarsh may assist in the recycling process in estuaries and removal of these habitats may have critically altered the natural breakdown of seagrass wrack in the estuary These management experiments are the first step in addressing the role of saltmarsh and fringing wetlands as nutrient recyclers in the estuary and in guiding the development of ecologically sustainable foreshore management

6.4. Managing Nutrients and Sediments

Wyong Shire Council currently monitors the ambient nutrient concentrations within the water column of the estuary and at the major river inflows at a number of spatial and temporal scales (Cummins *et al* , 1999) Groundwater contributions have also been examined (Kerry, 1999), as well as the flux rates of nutrients between the sediments and the water column Nutrients (nitrogen and phosphorus) and sediments enter the estuary by various pathways, including riverine sources, urban runoff (stormwater), groundwater, atmospheric deposition (nitrogen), and ocean exchange The estuary is the receiving waters for most of the larger catchment based runoff and localised urban stormwater runoff Excessive nutrients and sediments can alter the ecological status of receiving waters and in many cases lead to eutrophication A stormwater management plan which incorporated catchments draining to the Tuggerah Lakes estuary was developed by Wyong Shire Council (Dickinson, 1999) The estuary was subjected to high levels of nutrient enrichment (eutrophication) in the past, from various sources including septic systems and poor land-management-practices Large-scale blooms of various macroalgae (e g *Chaetomorpha*, *Enteromorpha* and *Ulva*) were common during the 1980's leading to the Lakes Restoration Program Blooms of macroalgae still occur at small-scales, generally in shallow vegetated seagrass meadows in close proximity to stormwater drains (Cummins *et al*, 2000)

6.4.1. Stormwater Treatment Zones

As part of the Tuggerah Lakes Restoration Project, some 37 gross pollutant traps (GPT's) and 200 stormwater treatment zones (STZ's) were constructed around the foreshores of the estuary at existing stormwater discharge points These structures were designed to remove sediments and other gross pollutants and nutrients from stormwater prior to discharge into the estuary The STZ's are regularly maintained by Wyong Shire Council, but their effectiveness in terms of sediment and nutrient removal was questioned by Sainty and Hunter (1997) and by Dickinson (1997) Observations have been made that particularly coarse material has formed alluvial fans in front of some stormwater drainage lines Some of the coarse material has been identified as gravel having a particle diameter of approximately 2mm or more (Dickinson, 1997) The fact that such coarse material exists suggests that the GPT's are not trapping fine material if the coarse material is passing through in larger flows (Dickinson, 1999) Furthermore, the size of the mini-wetlands at the end of the stormwaters drains were too small, in terms of the volume of water they must treat, and their physical design allows water to pass straight through the macrophytes without any chance of nutrient uptake (Sainty and Hunter, 1997)

6.4.2. Experimental Manipulations of STZ's

A number of STZ's have been identified for upgrading which would make them more efficient at nutrient and sediment removal Council was successful in obtaining funding from the National Heritage Trust (NHT) for a collaborative management experiment with the EICC, to assess local aquatic assemblages in response to upgrading STZ's in the estuary The objective of the study was to quantify the ecological response to upgrading STZ's within shallow seagrass meadows immediately adjacent to stormwater point sources The project outcomes will include a quantitative assessment of whether there is efficient nutrient and sediment removal, whilst documenting the ecological response of the aquatic assemblages within the receiving waters Six STZ's along the western shoreline of Budgewoi Lake have been selected where the manipulative experiments are to be done At each of the STZ's a number of variables are being measured including water quality, benthic infauna, seagrasses, macroalgae and nutrient uptake in the deployed bivalve *Xenostrobis securis*

6.4.3. Nutrient Limitation

The major plant nutrients nitrogen and phosphorus are important for the growth of macroalgae (Bayne *et al.*, 1999; Cummins *et al.*, 2000). Temperature, light, salinity, and the effects of grazing invertebrates and fish also potentially interact with the growth of macroalgae. Wyong Shire Council is investigating the possibility of retrofitting or upgrading a number of sub-catchment stormwater treatment trains and devices to help control nutrients entering the estuary (Dickinson, 1999). To assist in the design of these stormwater upgrades it was necessary to establish which nutrients need targeting so that efficient designs can be developed for the stormwater treatment devices. A nutrient limitation study on the growth of macroalgae has begun with a laboratory and field based experimental approach (Bayne *et al.*, 1999). The results of this collaborative research between the EICC and Wyong Shire Council will be reported in the management study.

6.5. Dredging of the Tidal and River Deltas

Maintenance dredging is currently done to keep the entrance channel open and river deltas navigable. The overall effect of maintenance dredging on the ecology of the estuary will be assessed, as will the potential impact of larg-scale dredging proposals such as the Budgewoi sandmass. The effects of dredging on benthic and seagrass communities will also be assessed with the aid of management experiments as part of the estuary management study.

6.6. Entrance Management

what model?

what data?

Wyong Shire Council currently maintains an open entrance channel to the sea primarily to elleviate the effects of severe flooding in low-lying developed areas around the estuary. The entrance channel is kept open by Council's dredge and the resultant spoil from the dredging is relocated to the northern end of the entrance. Hydrodynamic and water quality monitoring suggest that the benefits of dredging to the flushing of the estuary are minimal and the effects on estuarine ecology are not known. Twin breakwalls at the entrance and opening a second entrance in the north-east section of Budgewoi Lake (Budgewoi Sandmass) have been suggested as a way to increase tidal exchange and flushing. The AEAM program was used to model these scenarios and found that these options would not have the desired "flushing" effects (Walkerden and Gilmore, 1996). Furthermore, the environmental implications of opening a second entrance have not been examined and a full examination of

I doubt calibrated model?

the ecological implications would be required and is beyond the scope of this study Given that the modelling showed that a second entrance would not result in "flushing the lakes", it is considered that this option be a low priority, however further discussion on this management option will need to be done as part of the estuary management plan

6.7. Fisheries Management

The Tuggerah Lakes estuary is the fifth largest commercial and seventh largest recreational fishery within NSW With increasing population pressures in the catchment, there have been suggestions that the fishery cannot be sustained into the future (Wanless, 1998) A review of historical and recent catch records showed that fish catches fluctuated from year to year with a decline in total catches (Wanless, 1998) The fishery has been examined for the effects of operating the Lake Munmorah Power station and the addition of another power station at Chittaway Point (Ruello, 1978, Henry and Virgona, 1980, Virgona and Henry, 1983) The open water habitats of the estuary are where the majority of the primary target species can be found (The Ecology Lab, 1998), whilst the seagrass beds are thought to be nursery grounds for larval fishes and other invertebrates (Bell and Pollard, 1989). Commercial fishing within the estuary has been ongoing since the early 1900's Records have been kept for at least 50 years by NSW Fisheries in the form of catch return forms, submitted each month by the commercial fishers The present number of commercial fishers using the estuary on a regular basis is 44, compared with 60 in 1984 (Wanless, 1998) The recreational fishery is a multi-species, multi-gear, small boat and shore based fishery, targeting a diverse range of species in NSW estuaries (Fletcher, 1998) Fishing effort by recreational anglers is thought to be intense with recreational surveys having been done for more than 30 years (Fletcher, 1998) It has been estimated that at least one third of the population engage in recreational fishing at least once per year, on a casual basis, and recreational fishing is still quite popular within the estuary The effects of fishing in the Tuggerah Lakes estuary will be further explored in the estuary management study. Although conflict between commercial and recreational anglers is minimal, there have been calls by the community to ban commercial fishing The conservation of biological diversity of fish and marine vegetation and the protection of threatened species, populations and ecological communities and key fish habitat are primary objectives under the Fisheries Management Act (Fletcher, 1998) Fisheries habitat loss, potential eutrophication and entrance management all need to be explored in the management study.

a graph would be helpful?

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6.8. Ecologically Sensitive Habitats

— what about aquatic habs?

6.8.1. Tuggerah Bay

Tuggerah Bay has been identified as an important ecologically sensitive habitat within the Tuggerah Lakes estuary (Sainty, 1998) There has been very little development around the shoreline of Tuggerah Bay, so much of the fringing wetlands are relatively undisturbed Physical disturbance to the saltmarshes does occur through horse riding, four-wheel driving and motorcycling activities (Riley, 1998) Wyong Shire Council has attempted to "seal off" the area so that disturbance to the saltmarsh and fringing wetlands is minimised The seagrass meadows within Tuggerah Bay are rich and support prolific birdlife, invertebrates and fish assemblages (Daley, 1997, Mackey, 1998; Bryant, 1999, Casey, 1999, Cummins *et al.*, 2000). Tuggerah Bay will be targeted within the management study as an ecologically sensitve area which may need protection and further investigations will be done to ascertain its value to the entire estuary These include an assessment of the role of seagrasses to invertebrate and fish assemblages and the development of a management plan specific for Tuggerah Bay

6.8.2. Colongra Wetland

Colongra wetland is situated within Lake Munmorah on land currently owned by Delta Electricity, which is to be donated to the National Parks and Wildlife Service The wetland is perched above Lake Munmorah and is considered significant within the area because of its relative isolation, lack of urban development and as an important water bird habitat (Duchatel, 1998, Sainty, 1998, Mackey, 1999, Wallbridge, 1999) Recent mine subsidence in the area has caused some problems for the wetland and associated fringing flora and fauna (Duchatel, 1998) A plan of management for the wetland will need to be considered, within the estuary management study, which takes into account all stake-holders and remedial management strategies

6.8.3. Budgewoi Sandmass

The Bugewoi sandmass is a relic tidal delta that was once open to the sea and is the result of marine sands being deposited into the estuary through tidal exchange and storm events The sandmass is a valuable ecological area within the estuary because it provides non-tidal areas for feeding and roosting for many migratory and local waterbirds (Mackey, 1999, Bryant, 1999) There have been proposals to mine the sandmass and a number of Environmental Impact Studies have been prepared (Resource Planning Pty Ltd, 1991, Cheng, 1997) The estuary management study will be focussing on this area as a sensitive habitat and examining the potential ecological effects of any proposed mining or future development

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9. Appendix 1

Past and present members of the Tuggerah Lakes Estuary and Coastal Management Subcommittee

Mr D Armstrong (Coal Australia)
Cr J Axford (Chairperson, Wyong Shire Council)
Mr T Bagnat (National Parks and Wildlife Service)
Mr B Bell (Wyong Shire Council)
Cr G Best (Wyong Shire Council)
Cr F Brennan (Wyong Shire Council)
Mr B Buggy (Tuggerah Lakes Catchment Management Committee)
Mr K Byles (Tuggerah Lakes Commercial Fishing Association)
Mr P Carter (NSW Fisheries)
Mr C Clarke (NSW Fisheries)
Mr R Cooke (Department of Land and Water Conservation)
Mr J Cowden (Community Representative)
Mr J Daly (Central Coast Regional Development Corporation)
Mr A Denniss (Tuggerah Lakes Commercial Fishing Association)
Ms B Durkin (Central Coast Environment Council)
Mr J Fisher (Waterways Authority)
Cr K Forster (Wyong Shire Council)
Mr R Gibson (Tuggerah Lakes Catchment Management Committee)
Mr B Gray (Department of Land and Water Conservation)
Mr D Green (Department of Land and Water Conservation)
Mr W Green (Community Representative)
Mr R Hempstead (Community Representative)
Mr D Holland (Tuggerah Lakes Catchment Management Committee)
Mr P Jackson (Delta Electricity)
Mr N Kelleher (Department of Land and Water Conservation)
Ms S Lynch (Waterways Authority)
Mr S Northard (Tuggerah Lakes Catchment Management Committee)
Mr P Plunkett (NSW Fisheries)
Ms E Robinson (Central Coast Regional Development Corporation)
Mr G Sharrock (Delta Electricity)
Mr P Smith (Delta Electricity)
Mr K Southwell (Community Representative)
Mr V Szarkun (Community Representative)
Cr W Thompson (Wyong Shire Council)
Mr D Tracey (Community Representative)
Mr G Walkerden (Wyong Shire Council)
Dr K Zimmerman (Central Coast Campus, University of Newcastle)

10. Appendix 2

Members of the Tuggerah Lakes Technical Peer Review Panel

Professor Hal Cogger (Central Coast Campus, University of Newcastle)
Professor Alistar Gilmour (Macquarie University)
Dr Alan Jones (Australian Museum)
Mr Neil Kelleher (Department of Land and Water Conservation)
Dr Peter Roy (University of NSW)
Mr Geoff Sainty (Sainty and Associates)
Dr Peter Scanes (NSW Environment Protection Authority)
Dr Adam Smith (NSW Fisheries)
Mr Alan Morris (National Parks and Wildlife Service)
Professor Tony Underwood (EICC, University of Sydney)