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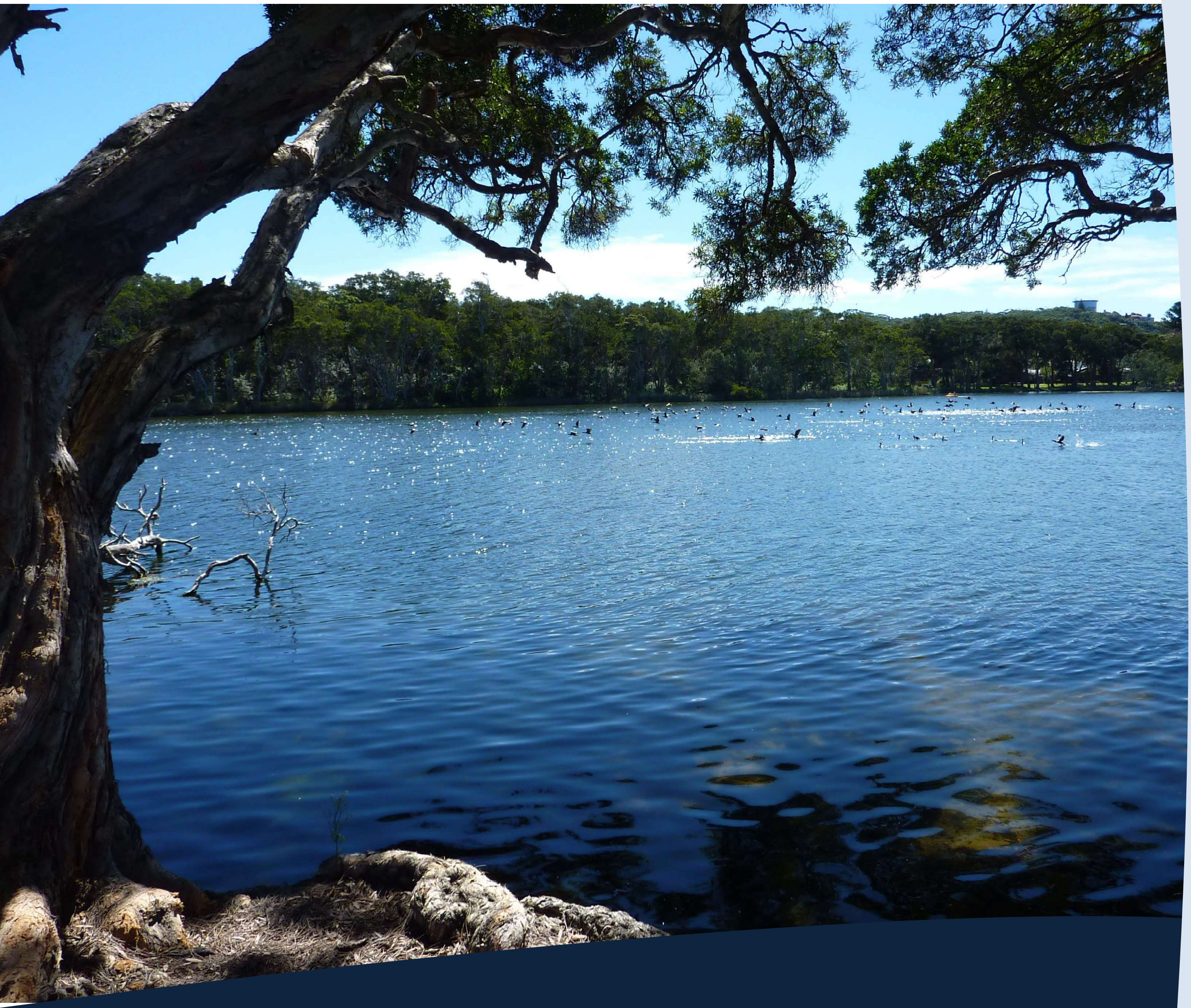

Gosford Coastal Lagoons Processes Study

Volume 1 – Main Report

LJ2713/R2472/V2

Prepared for Gosford City Council

July 2010

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Shaping the Future

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Executive Summary

This study has been undertaken by Cardno Lawson Treloar in association with the University of Newcastle for Gosford City Council (GCC).

This Processes Study focuses on the four coastal lagoons, **Figure 1.1**, that enter the Tasman Sea:

- Wamberal Lagoon,
- Terrigal Lagoon,
- Avoca Lagoon, and
- Cockrone Lagoon.

The study area comprises the tidal waterways, foreshores and adjacent land of each of the four lagoons, including their respective catchments. Processes occurring in the wider catchment are considered only where they impact directly on lagoon processes.

The project brief (issued in March 2008) identified a number of issues of concern, derived from the outcomes of a workshop attended by representatives of the community, local and State Government and special interest groups. Further investigations undertaken for the purposes of this study have assisted in gaining a greater appreciation of these issues. An overview of some of the key issues is provided in this executive summary.

Artificial Entrance Management

One of the key human influences on lagoon processes is the timing of lagoon openings, with the entrance berm actively managed for flood mitigation purposes. Based on the water level analysis in **Section 4.6.1**, it is apparent that management of the entrance has had a significant impact on lagoon hydraulics, with flow on effects for water quality, sediment transport and ecological processes. The let out (or breakout) levels in the entrance management policy are determined primarily by the desire to prevent inundation of surrounding property. Hence, development patterns and existing floor levels are the key determinants of entrance management practices and take precedence over ecosystem responses. Historical development of low lying lands around the foreshores has resulted in let out levels being set at relatively low levels when compared to the Highest Astronomical Tide (HAT) occurring in the adjacent Tasman Sea. For Wamberal, Avoca and Cockrone Lagoons the let out levels are more than 1 m higher than HAT giving a reasonable level of confidence that there is sufficient freeboard to both convey extreme floods from the lagoon to the ocean and avoid inundation by extreme ocean levels that arise during Storm surges. The adopted let out level for Terrigal Lagoon is only 0.15 m higher than HAT making it susceptible to inundation from the sea as well as catchment flooding. The management of the entrance berm requires break out on a regular, approximately monthly basis. This artificial opening of the entrance has likely resulted in significant modification of the natural range of water levels such that the variation in water levels is much less than those observed for the other three lagoons. While current entrance management practices would also be having a similar effect on the hydraulics in the other lagoons, the magnitude of the impact is much greater in Terrigal Lagoon.

While the entrance management policy identifies other issues of concern (e.g. odours after breakout, water quality and the exposure of habitat for the Green and Golden Bell Frogs at Avoca) in relation to lagoon water levels, the implementation of the policy focuses on Council's obligations to mitigate risk to life and property from flooding. In moving forward with the management process for the coastal lagoons, it is recommended that the desired environmental values be articulated and options for adjusting the entrance management practices towards facilitating the desired ecological values while meeting the flood mitigation imperatives be assessed. Based on discussion provided on water quality (**Section 5.2.3**) and threats to lagoon ecology (**Section 6.5**), it is suggested that the entrance management regime for Avoca and Cockrone Lagoons could be amended to permit breakouts at lower water levels following a period of significant build up of algal mats .

Water Quality

Generally, the day to day water quality of the lagoons appears acceptable in terms of both aquatic ecosystem health and for recreational use, but periodic declines in water quality can occur. The limited available data collected as part of Council's compliance monitoring does not provide sufficient resolution of processes to enable the cause and effects of particular practices/processes to be assessed. Understanding of the likely responses is based largely on information from similar lagoons and informed speculation. Sewer overflows and stormwater runoff may be contributing nutrient loads beyond the natural catchment loads to the lagoon systems leading to a tendency towards eutrophication of the lagoons that may be evidenced by the establishment of large expanses of algal mats. It is thought that the water quality issues (odours and fish kills) observed after a breakout are dependent upon the antecedent conditions prior to breakout. In the case of Avoca and Cockrone Lagoons, it is thought that the persistence of elevated water levels for extended periods of time prior to a breakout event in combination with high levels of algal biomass lead to rapid decline in water quality immediately following the breakout. Council may wish to consider management of lagoon water levels and timing of breakout events with a view to minimising these water quality issues.

Management of Foreshore Crown Land

Management of foreshore land is important in relation to recreational access and amenity. Access to the foreshores is variable, and even where Crown land does exist on the foreshore, access is not always possible by foot. There is a suggestion that foreshore and fringing vegetation has been lost and subject to degradation as a result of access by the public to the lagoon foreshores, or for the purposes of enhancing the recreational amenity of the lagoons. In some locations this has involved the replacement of native vegetation with grassed open space. Uncontrolled access, be it due to a lack of formal paths or by people deviating from the designated pathway, has also resulted in damage to vegetation. Other negative impacts on lagoon water quality can result from methods of managing vegetation, which can include ‘over-mowing’ of grassed areas, whereby mowing extends beyond the boundary of the grassed area and infringes on native vegetation. In addition, as noted in **Section 8**, it is understood that there have been instances of deliberate removal of native vegetation by residents in order to enhance views and/or provide access. Management should target public education, as well as proper planning for and control of recreational use of the lagoons.

Climate Change

The study has also included some additional investigations on the potential impacts of climate change on the lagoons and discussion is provided on the likely berm response and changes in lagoon water levels. The projected sea level rise (SLR) of 0.4m by 2050 (i.e. HAT increases by 0.4 m) is likely to increase the low range of water levels and groundwater levels around the lagoons by a similar 0.4 m. Given that current entrance management regime is expected to continue, the future maximum water levels would be tied to the present day flood mitigation levels and hence the range of water levels would decrease by roughly the 0.4 m to 2050. This scenario assumes that there would be sufficient operating range in the lagoons to accommodate the reduced range. Results indicate that while the freeboard above HAT is sufficient to accommodate SLR effects in Avoca, Wamberal and Cockrone Lagoons, clearly, the Terrigal Lagoon let out level of 0.25 m below HAT would not be sustainable..

The decrease in minimum water levels and hence operating range would lead to the three “mostly closed” lagoons transitioning towards more open conditions, i.e. more frequent breakouts and probably slightly longer open periods of tidal influence. The current entrance management of Terrigal Lagoon, however, will need to be carefully considered in terms of the options available to mitigation potential flooding. The current strategy will not be appropriate as a flood mitigation action under the 2050 SLR scenario. The projected increase in the intensity of rainfall events will likely lead to more flash flooding with more rapid increases in lagoon water levels, possibly necessitating faster response to breakout events.

The projected decrease in water level range in Avoca, Wamberal and Cockrone Lagoons will also have implications for lagoon water and ecosystem response.

Conclusion

The study has been undertaken as required under the NSW Rivers and Estuaries Policy and in accordance with the Estuary Management Process outlined by the NSW Government (1990). It is intended that the information detailed in this report will aid Council in providing a basis for moving forward with the development of the Gosford Coastal Lagoons Management Study and Plan.

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Glossary and Abbreviations

Ambient	Refers to the immediate surrounds. In the case of water quality, this refers to chronic or 'push' conditions.
Amenity	Those features of an area that foster its use for various purposes.
Animal	Any animal, whether vertebrate or invertebrate, and at whatever stage of development.
ARI	Average Recurrence Interval
ASS	Acid Sulfate Soil(s)
Biota	Living organisms.
Bird	Any bird that is native to, or is of a species that periodically or occasionally migrates to Australia, and includes the eggs and the young thereof and the skin, feathers or any other part.
BOD	Biochemical Oxygen Demand
BoM	Bureau of Meteorology
CAMBA	China Australia Migratory Bird Agreement
Catchment	The area draining to a site. This always relates to a particular location and may include the catchments of tributary streams as well as the main stream.
CCS	Coastal Carrier System
CCCEN	Central Coast Community Environment Network
CEMC	Coastal and Estuary Management Committee
CLAM	Coastal Lake Assessment and Management Tool
CMA	Catchment Management Authority
COSS	Coastal Open Space System
DCP	Development Control Plan
DECC	Formerly the Department of Environment and Climate Change; now known as the Department of Environment, Climate Change and Water.
DECCW	Department of Environment, Climate Change and Water (now DECCW and DII)
DII	Department of Industry and Investment. Incorporates NSW Fisheries.
DoL	Formerly Department of Lands; now Land and Property Management Authority
DoP	Department of Planning
DPI	Formerly Department of Primary Industries; now Department of Industry and Investment.
DWE	Department of Water and Energy
Ecosystem	A community of living organisms, together with the environment in which they live and with which they interact.
EEC	Endangered Ecological Community as identified under the TSC Act or the EPBC Act.
Endangered Fauna	Protected fauna of a species under Schedule 1 or 2 of the *Threatened Species Conservation Act*, 1995.
ENSO	El Niño – Southern Oscillation
EPA	Environment Protection Agency, also referred to as the Climate Change and Environment Protection Group, DECCW.
EP&A Act	NSW *Environmental Planning and Assessment Act, 1979*
EPBC Act	Commonwealth *Environmental Protection and Biodiversity Conservation Act, 1999.*
Epiphytic	A plant that grows on another plant, but does not derive any nourishment from it.

ESD	Ecologically Sustainable Development
Eutrophication	The over-enrichment of a water body with nutrients, leading to the excessive growth of plants and plankton and the depletion of oxygen.
Fauna	Any mammal, bird, reptile, amphibian or fish.
Fish	All or any of the varieties of marine, estuarine or freshwater fishes (whether indigenous or not) and their young, fry and spawn and unless contrary intention be expressly stated, or the context otherwise requires, includes crustacea, oysters and all marine, estuarine and freshwater animal life.
FM Act	*Fisheries Management Act 1994*
GCC	Gosford City Council
GIS	Geographic Information Systems, computer-based spatial data management tools.
GPSO	Gosford Planning Scheme Ordinance
GPT	Gross Pollutant Trap
Habitat	The places in which an organism or community lives.
HCRCMA	Hunter-Central Rivers Catchment Management Authority
ICOLL	Intermittently Closed and Open Lake or Lagoon
IDO	Interim Development Order No. 122
Invertebrate	Animal without a backbone or notochord.
IPCC	Intergovernmental Panel on Climate Change
ICOLL	Intermittently Closing and Opening Coastal Lakes and Lagoons
JAMBA	Japan Australia Migratory Bird Agreement
LALC	Local Aboriginal Land Council
LEP	Local Environment Plan
LG Act	*Local Government Act, 1993*
LGA	Local Government Area
LPMA	Land and Property Management Authority; formerly Department of Lands
MHL	Manly Hydraulics Laboratory
MHWS	Mean High Water Springs
MHWN	Mean High Water Neaps
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MSL	Mean Sea Level
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
NPWS	National Parks and Wildlife Services; part of DECCW
NSW	New South Wales
OSSM	On-Site Sewer Management (septic system)
PASS	Potential Acid Sulfate Soils
Riparian Vegetation	Vegetation growing along banks of rivers.
ROKAMBA	Republic of Korea Australia Migratory Bird Agreement
Runoff	That proportion of rainfall that drains off the lands surface.
Seawall	Wall built parallel to the shoreline to limit shoreline recession.
Sea Waves	Sea waves are generated locally and move in the same direction as the surface wind.
Sedimentation	The act or process of depositing sediment, especially by mechanical means of matter suspended in a liquid.
Semi-diurnal tides	Tides with a period, or time interval between two successive high or low waters, of about 12.5 hours.
SEPP	State Environmental Planning Policy

Sewage	Refuse liquids or waste matter carried off by sewers.
Shoreline Recession	A net long-term landward movement of the shoreline caused by a net loss in the sediment volume.
SLR	Sea Level Rise
SOI	Southern Oscillation Index
Swell Waves	Waves that have travelled into the observation area having been generated by previous winds in other areas.
Tides	The regular rise and fall of the sea level in response to the gravitational attraction between the sun, moon and Earth.
TN	Total Nitrogen
TP	Total Phosphorous
TSC Act	*NSW Threatened Species Conservation Act, 1995*
TSS	Total Suspended Solids
Vertebrate	Animal with a backbone or notochord.
WSUD	Water Sensitive Urban Design

1 Introduction

This study has been prepared by Cardno Lawson Treloar in association with the University of Newcastle for Gosford City Council (GCC).

The study has been informed primarily by the *Gosford Coastal Lagoons Data Compilation Study* (Cardno, 2008a).

1.1 The Study Area

The Gosford Local Government Area (LGA) is located on the NSW Central Coast and encompasses significant waterway areas and open coast beaches. This Processes Study focuses on the four coastal lagoons, **Figure 1.1**, that enter the Tasman Sea:

- Wamberal Lagoon,
- Terrigal Lagoon,
- Avoca Lagoon, and
- Cockrone Lagoon.

The study area comprises the tidal waterways, foreshores and adjacent land of each of the four lagoons, including their respective catchments. Processes occurring in the wider catchment are considered only where they impact directly on lagoon processes.

A summary of the key characteristics of each of the coastal lagoons is provided in **Table 1.1**. All four of the lagoons are classed as Intermittently Closed and Open Lakes or Lagoons (ICOLLs). These summary characteristics have been sourced primarily from investigations undertaken as part of this study. Where indicated, information has been sourced from National Land and Water Resources Australia (NLWRA) (1998).

The project brief (issued in March 2008) identified a number of issues of concern, derived from the outcomes of a workshop attended by representatives of the community, local and State Governments and special interest groups. These issues of concern include:

- Illegal interference with the lagoon entrances;
- The effect of artificial entrance management practices on lagoon ecology;
- Timing of lagoon openings with respect to community needs, and species recruitment and biodiversity;
- Natural opening regimes;
- The emission of odours after entrance breakout;
- Siltation (e.g. particularly for Terrigal and Avoca Lagoons);
- Sedimentation associated with tributaries;
- Paucity of data on sedimentary characteristics;
- ASS risk;
- Management of foreshore Crown land;
- Foreshore access;
- Foreshore erosion;
- The prevalence of artificial foreshores, often associated with a lack of public access;
- Water quality as it relates to both aquatic ecosystem and human health. Issues include eutrophication, the potential for algal blooms and faecal contamination;

- Sewer overflows and stormwater runoff;
- Algal mats;
- Fish kills;
- Flooding;
- Green and Golden Bell Frogs at Avoca frog pond;
- Loss of riparian vegetation and dune vegetation;
- Weeds present in some locations, particularly in association with creeklines;
- Natural succession of native vegetation; and
- Implications of climate change.

It is intended that this Processes Study will enhance our understanding of the function of these lagoon systems and provide additional baseline information to inform ongoing management of these issues in the future.

Table 1.1: Summary of Key Characteristics – Gosford Coastal Lagoons

Key Characteristics	Wamberal	Terrigal	Avoca	Cockrone
Estuarine				
Classification*	ICOLL / Wave Dominated	ICOLL / Wave Dominated	ICOLL / Wave Dominated	ICOLL / Wave Dominated
Waterway Area* (note: variable depending upon water level)	$4.6km^2$	$5.7km^2$	$10.1km^2$	$3.5km^2$
Avg. Bed Level (m AHD)	0.9-1.0	0.5-0.7	0.8-0.9	0.4-0.6
Avg. Annual Siltation Rates (mm/yr)	0.22	0.35	0.21	0.18
Water Levels (m AHD)	Min: 0.21 Median: 1.67 Mean: 1.59 Max: 2.89	Min: 0.10 Median: 0.92 Mean: 0.89 Max: 2.09	Min: -0.05 Median: 1.23 Mean: 1.26 Max: 2.845	Min: -0.05 Median: 1.79 Mean: 1.73 Max: 3.10
Volume at Mean Water Level (ML)	448	176	644	306
Volume at Entrance Opening Trigger Level (ML)	924	274	1,282	685
Trigger Level for Entrance Opening (m AHD)	2.40	1.23	2.09	2.53
Managed Berm Height (m AHD)	2.6-2.7	1.7	2.7-2.8	3.3-3.5
Avg. No. Openings Per Year	2.9	12.9	3.5	2.4
Avg. Flushing Time (days) when open	4.4	2.4	7.4	7.4
Max. Flushing Time (days) when open	29.9	4.5	35.1	40.2
Avg. Duration Entrance Open (days)	10	8	21	9
Catchment				
Catchment Area	655ha	892ha	1,187ha	722ha
Catchment Land Use	31% urban 36% rural 24% forest 9% waterway	36% urban 44% rural 16% forest 3% waterway	25% urban 21% rural 45% forest 9% waterway	9% urban 16% rural 69% forest 6% waterway
100 year ARI catchment flood levels	3.1m AHD	2.9m AHD	3.2m AHD	3.8m AHD
Annual Catchment Inflows (ML/year)	Avg. year 2,180 ML Dry year 1,230 ML Wet year 5,200 ML	Avg. year 3,500 ML Dry year 1,990 ML Wet year 7,970 ML	Avg. year 3,420 ML Dry year 1,850 ML Wet year 9,050 ML	Avg. year 1,740 ML Dry year 879 ML Wet year 5,340 ML

Key Characteristics	Wamberal	Terrigal	Avoca	Cockrone
Avg. Annual Loads of TSS ('000 kg/year)	Avg. year 228 Dry year 148 Wet year 453	Avg. year 387 Dry year 252 Wet year 752	Avg. year 297 Dry year 193 Wet year 633	Avg. year 101 Dry year 65.9 Wet year 260
Avg. Annual Loads of TN ('000 kg/year)	Avg. year 4.6 Dry year 4.9 Wet year 9.4	Avg. year 7.8 Dry year 4.9 Wet year 15.5	Avg. year 6.1 Dry year 3.7 Wet year 13.7	Avg. year 2.2 Dry year 1.3 Wet year 6.0
Avg. Annual Loads of TP ('000 kg/year)	Avg. year 0.6 Dry year 0.4 Wet year 1.2	Avg. year 1.0 Dry year 0.6 Wet year 2.0	Avg. year 0.8 Dry year 0.5 Wet year 1.6	Avg. year 0.2 Dry year 0.2 Wet year 0.6
No. EECs Present	4	4	5	6
SEPP14 Wetlands	Present	Present	Present	Present
No. Identified Sewer Overflow Points	5	12	10	3

*These characteristics have been derived from the 1998 National Land and Water Resources Audit (NLWRA, 1998).

1.2 Estuary Management Process

The *NSW Coastal Policy* (1997) has a central focus on the Ecologically Sustainable Development (ESD) of the coastal zone. ESD refers to development that uses, conserves and enhances the community's resources so that the ecological processes on which life depends are maintained and the total quality of life now and in the future can be improved. The four principles of ESD are:

- Conservation of biological diversity and ecological integrity
- Inter-generational equity
- Improved valuation, pricing and incentive mechanisms
- The precautionary principle.

One of the NSW Coastal Policy's strategic directions is the preparation and implementation by local Councils of detailed management plans for estuaries in accordance with the Estuary Management Policy, as defined in the *Estuary Management Manual* (NSW Government, 1992). The policy outlines a structured management process leading to the implementation of an Estuary Management Plan. In developing the plan all values and uses of the estuary are considered. The plan aims to be a balanced long-term management framework for the ecologically sustainable use of the estuary and its catchment.

The Estuary Management Manual recommends an eight step process in order to implement an Estuary Management Plan, as follows:

1. Form an Estuary Management Committee;
2. Assemble existing data (data compilation study);
3. **Undertake an Estuary Processes Study;**
4. Undertake an Estuary Management Study;
5. Prepare a draft Estuary Management Plan;
6. Review Estuary Management Plan;
7. Adopt and implement the Estuary Management Plan; and
8. Monitor and review the management process as necessary.

Council has previously commissioned an Estuary Processes Study for the coastal lagoons, which was prepared by Marine Pollution Research Pty Ltd in 1994, and Council subsequently developed the *Coastal Lagoons Management Plan* (GCC, 1995). Council is now seeking to update these studies as identified under step 8 of the Estuary Management Process. In seeking to update the relevant management documents for the coastal lagoons, GCC has been working through the Estuary Management Process from the beginning. This new Estuary Processes Study and any subsequent Management Study and Plan will supersede these historic documents.

GCC has formed an Estuary Management Committee through their Coastal and Estuary Management Committee (CEMC) and an updated Data Compilation Study has been undertaken (Cardno, 2008a) in compliance with steps 1 and 2 respectively. It should be noted that the Data Compilation Study should be read in conjunction with this report, which expands upon the information provided in previous stages of the estuary management process.

This document has been prepared to meet the requirements of the third stage of the Estuary Management Process, the Estuary Processes Study (shown highlighted above).

The development of the *Gosford Coastal Lagoons Estuary Processes Study* has been overseen by Council's CEMC. The Committee is chaired by Council and has a membership that includes representatives of a range of State government agencies, non-government organisations, special interest groups and the community. The Terms of Reference for the CEMC include:

- Provide advice and recommendations as to an integrated, balanced, responsible and ecological sustainable use of the City's estuaries, coastal and aquatic environments, including foreshore areas.
- Promote cooperation between the State Government, Local Government and estuary users in the development and implementation of Estuary and Coastal Zone Management Plans.
- Advise and recommend on how to improve the management of the City's estuaries, coastal and aquatic environments through environmental planning frameworks.
- Advise and recommend on how to implement Estuary, Coastal and Aquatic Environment Management Plan actions.
- In undertaking the Committee's duties, include sustainable climate change adaptation and mitigation actions as a response to climate change. In the implementation of this duty, ensure consistency with Council's Climate Change Policy.

The final point was adopted at a meeting of the Committee on 15 December 2009.

1.3 Study Objectives

The overall aim of the study is to document the key physical, chemical and ecological processes that characterise each of the lagoons, and to describe the interactions between processes, including human influences on the lagoons.

The main objectives of this study are broad in their scope and include:

- To identify and document the physical and chemical functioning of the lagoons, as well as related processes and interactions, through investigation, data collection and comprehensive modelling.
- To identify and document the biological functioning of the lagoons and related processes, covering flora and fauna, species composition and distribution, the productivity and health of ecosystems, the range and sensitivity of habitats, and rare and endangered species.
- To define baseline conditions of estuarine processes and interactions on which management decisions can be made.
- To review the existing and strategic land use activities that may potentially impact on the management needs of the lagoons.
- To undertake any further data collection or monitoring to aid the subsequent stages of the estuary management study and formulating an estuary management plan for the lagoons.

1.4 Methodology Overview and Report Structure

This Estuary Processes Study utilised a range of methodologies, including:

- A review of existing literature, including studies and reports held by GCC,
- A search of a range of relevant databases, as outlined where relevant,
- Computer modelling of runoff and water quality processes in the catchment using the MUSIC software program (refer to **Section 3.9** and **Appendix E**),
- Computer modelling of estuarine hydraulics, estuarine morphology and siltation and estuarine water quality, all using the DELFT3D software program (**Sections 4 and 5, Appendix F**),
- Field-based ecological studies and associated laboratory and statistical analyses, utilising a range of techniques (**Section 6** and **Appendix D**),
- Records of bird sightings held and maintained by the Birds Australia (**Section 6.4.2**),
- Compilation and review of available published information on cultural heritage (Indigenous and European) and presentation of the data relevant to this study (**Section 7**),
- Compilation and review of published information on recreational usage and presentation of the data relevant to this study (**Section 8**), and
- Compilation and integration of the information gathered for consideration of interactions between processes, undertaken by the Cardno project team of environmental engineers and scientists (**Section 9**).

Further details of the methods used in the preparation of this study are provided in the relevant report sections and appendices.

Site inspections of the study area were undertaken by kayak and land in January 2009. In addition, an entrance breakout event at Cockrone Lagoon, consisting of mechanical breaching of the entrance berm by Council for flood mitigation purposes, was observed on 3 February 2009. A photolog of the study area is provided in **Appendix A**. Additionally, some components of the study, for example the ecological investigations, involved further visits to the study area.

Mapping was prepared by the study team based on GIS data provided by GCC, DECCW, the Department of Industry and Investment (DII - Fisheries) and the Lands and Property Management Authority (LPMA), as well as those GIS layers created by Cardno based on investigations by the study team.

2 Consultation

2.1 Overview

Consultation was undertaken with a range of stakeholders, community members and the CEMC throughout the study to both inform the stakeholders on progress and seek input on a range of identified issues. Key elements of the consultation program included:

- Direct stakeholder engagement via correspondence,
- A public information session, and
- Periodic meetings with the Committee.

Further details are provided in **Sections 2.2 - 2.3**.

2.2 Stakeholder Consultation

At the outset of the project, a letter regarding the project was sent to the following stakeholders:

- Central Coast Community Environment Network (CCCEN),
- Darkinjung Local Aboriginal Land Council (LALC),
- Department of Environment and Climate Change (DECC), (now Department of Climate Change and Water)(DECCW), including the Coasts and Estuaries Division, National Parks and Wildlife Service (NPWS) and Environment Protection Authority (EPA),
- Department of Lands (DoL, now Land and Property Management Authority or LPMA),
- Department of Planning (DoP), including the NSW Heritage Office,
- Department of Primary Industries (DPI, now Department of Industry and Investment or DII),
- Department of Water and Energy (DWE, now Office of Water at DECCW),
- Gosford City Council,
- Hunter-Central Rivers Catchment Management Authority (CMA),
- NSW Maritime, and
- Surfrider Foundation.

The letter distributed to each of these organisations consisted of an introduction to the study, advising of the objectives of the project and seeking inputs from stakeholders.

A copy of the form letter is provided in **Appendix B**, as are copies of any stakeholder correspondence (letters or emails) received. In some cases, discussions were held via telephone and an effort has been made to distil the content of those discussions where possible.

A summary of responses received is provided in **Table 2.1**.

Table 2.1: Summary of Stakeholder Responses Received

Stakeholder	Addressed in Report:
CCCEN	
➢ The CCCEN has prepared a Rehabilitation Plan for Cockrone Lagoon. ➢ Rehabilitation Plans for Avoca and Terrigal are currently available in draft form. ➢ As NPWS are the governing body for Wamberal Lagoon, there is no intention to prepare a Plan for that location. However, CCCEN intends to support NPWS with their plan and any on-ground works.	**Section 6**
Darkinjung LALC	
➢ No key issues identified with respect to the coastal lagoons. ➢ In general, the LALC is concerned about the potential impacts of climate change on Aboriginal sites and has worked on a project with the CMA regarding erosion of midden sites.	**Section 7.2**
DECCW – NPWS	
➢ A Plan of Management has been developed for the Wamberal Nature Reserve (a copy of the Plan was provided). ➢ With respect to Aboriginal cultural heritage, NPWS assumes that all the lagoons would have some significance as historical food and water sources. There are some sites surrounding the lagoon and there currently exist some management issues in relation to midden erosion and impacts of visitation of these sites.	**Section 3.3.2** **Section 7.2**
DECCW - EPA	
➢ Whilst there have been water quality issues due to sewer overflows in the past, the EPA is not aware of any ongoing issues.	**Section 3.8**
LPMA	
➢ Information was provided regarding land tenure and Crown lands around the lagoons.	**Section 3.3.1**
DoP	
DoP advised that the following issues should be given consideration as part of the study: ➢ Impacts associated with increased urban development in coastal lagoon catchments, particularly stormwater impacts and pet faecal matter; and ➢ Impacts associated with climate change / sea level rise.	**Sections 3.2, 3.9 and 4.10**
DII - Fisheries	
➢ Historic fisheries data was provided to inform the ecological studies.	**Section 7**
Office of Water (formerly DWE)	
No issues identified. Matter referred to DECCW.	

Stakeholder	Addressed in Report:
GCC	
➢ Land use in the catchment will not be subject to any intensification under the new LEP. Rural areas will retain the same densities and uses. ➢ The draft LEP zones the waterbodies of the lagoons W1 – Natural Waterways.	**Section 3.2.1**
Hunter Rivers CMA	
No response received.	
NSW Maritime	
➢ Avoca Lagoon has one Hire and Drive licence (Aquamuse) that has been operating in the lagoon since 2002. Aquamuse hires out small paddle-craft such as canoes. The operator uses a small outboard motor on their rescue vessel. ➢ Terrigal Lagoon has two Hire and Drive licences; Terrigal Paddle Boats (since 2002) and Terrigal Water Sports (since late-2007). Both operators hire out paddle-craft. ➢ Council has erected signage prohibiting motorised craft and NSW Maritime has received no complaints regarding unauthorised vessels in the lagoons to date.	**Section 9**
Surfrider Foundation	
No response received.	

2.3 Community Consultation

Community consultation was undertaken via a media release and a community newsletter. Copies of these materials are provided in **Appendix B**.

A community information session was held on 22 May 2010 to provide details of the study findings. The presentation was also used as an opportunity to seek feedback from the community in relation to management issues for each lagoon for consideration in later stages of the management planning process.

3 Catchment Characteristics

3.1 Overview

As identified in Haines (2006), catchment processes are one of two key drivers of ICOLL functioning, the other being the entrance condition. The principal catchment processes that will affect each of the lagoons are the spatio-temporal variations in stormwater runoff and pollutant loads (e.g. nutrients and sediments) delivered to the waterway. The climate, soil types, terrain and development condition will all affect the volume and rate of runoff, as well as the sediment loading in the runoff and the type and mass of contaminants delivered to the lagoons.

The magnitude of influence that catchment inflows will have on estuarine processes is dependent upon the relative sizes of the lagoon waterway and the catchments. Where the surface area and volume of a lagoon is large relative to the catchment size, catchment inflows will generally have a lesser impact on the lagoon (and vice versa). For the four Gosford Lagoons the ratio of annual inflow to lagoon volume and catchment area to lagoon area presented in **Table 3.1** indicate that the lagoon processes are strongly influenced by the catchment inflows.

There are a number of creeks draining into each of the lagoons. However, many of these drain small sub-catchments (<1km^2) and are un-named, intermittent watercourses. Therefore, there are few tributaries that may be referred to as "major tributaries" (**Table 3.1**).

Table 3.1: Ratio of Annual Inflow to Lagoon Volume and Catchment Area to Lagoon Area for each Lagoon

Lagoon	Catchment Size	Major Tributaries	Avg. Ann. Inflow (ML) / Vol (ML)	Catchment Area / Lagoon Area (ha)
Wamberal	6km^2	Forresters Creek	4.9	12.3
Terrigal	9km^2	North Arm Creek	19.9	32.6
Avoca	10km^2	Saltwater Creek	5.3	17.5
Cockrone	7km^2	Cockrone Creek Merchants Creek	5.7	19.6

Figure 3.1 shows the extent of the catchments and sub-catchments for each of the four lagoons and their respective tributaries.

This section of the report considers those catchment processes that have an impact on the physical, chemical and biological processes operating in the lagoons.

3.2 Catchment Land Use

3.2.1 Historical Land Use

An analysis of the trends in historical land use has been undertaken using historical aerial photographs provided by GCC in electronic format for the following years:

- 1954,
- 1964,
- 1983, and

- 2007.

1954

The predominant land use in 1954 was rural, with a number of what appear to be orchards and other rural properties located throughout the study area. In some parts of the coastal strip there exist residential properties, although whether these are permanent residences or holiday homes is not clear. Interpretation of the aerial photography is difficult, however it appears that many of the roads through the study area were unsealed at this time. There are a number of pockets of vegetation, commonly associated with ridgelines, creeklines and dune vegetation. The lagoon entrances were closed on the day the aerial photographs were captured.

The Wamberal Lagoon catchment is extensively forested, particularly around the lagoon foreshores and following the coastline to the north of Forresters Creek. There are some scattered buildings located to the north of the lagoon and there are a number of tracks or informal roads crossing the dunes towards the beach. Orchards and other agricultural lands predominate in the western part of the catchment, where larger patches of cleared land occur. Residential lands on larger blocks are confined largely to those coastal lands between Wamberal and Terrigal Lagoons. The Entrance Road, Tumbi Road and Ocean View Drive are present.

The Terrigal Lagoon catchment is generally more extensively developed for rural land uses, with a number of orchards and other agricultural lands present. Wetlands and other vegetation are present around what is now the Terrigal Memorial Country Club and the reserve located around the tributaries to the western arm of the lagoon. Residences on large blocks are visible along Ocean View Drive and Terrigal Drive near the coast. The Ocean View Drive and Willoughby Road bridges are in place at this time.

The western and south-western portions of the Avoca Lagoon catchment are largely forested with some isolated cleared lands, not unlike they appear in recent years. Orchards are also present in this catchment, while other rural lands are being utilised for other agricultural activities. Expanses of exposed substrate are visible in the lagoon due to lower water levels at the time the photograph was taken. As with the other lagoons, residential lands are located closer to the coastline. Scenic Drive, Avoca Drive and Cape Three Points Road are all visible.

The Cockrone Lagoon catchment is largely forested and rural lands occur in scattered patches throughout the catchment. Agricultural uses include orchards. The Scenic Road and Lakeside Drive are visible. Residential lands are concentrated immediately to the south of the entrance near McMasters Beach. The dune between what is now Tudibaring Parade and the beach is poorly vegetated.

1964

The lagoon entrances were all closed on the day the aerial photographs were captured.

To the north of Wamberal Lagoon and east of Forresters Creek residential development is occurring as evidenced by the presence of additional dwellings on large blocks and recent clearing of land. Some additional residential development has also occurred between

Wamberal and Terrigal Lagoons propagating further westward of that present in 1954 and around the junction of Ocean View Drive and The Entrance Road. Apart from this development in the immediate coastal strip, there do not appear to have been any significant changes in land use patterns in the Wamberal Lagoon catchment since 1954.

In the Terrigal Lagoon catchment there is a similar process of land use intensification due to an increase in the extent of residential development on large blocks, concentrated in the immediate coastal strip and around parts of the lagoon foreshore. However, the wetlands in the upper reaches of the lagoon do not appear to have been infringed upon in the period 1954 – 1964.

Much of the north, western and southern portions of the Avoca Lagoon catchment remain forested with scattered rural lands. However, residential development is intensifying along the coastal strip and around the region of Hillside Road and The Round Drive. Bradleys Road, Lake Shore Drive and Easter Parade are present but very few residences are present in this location at this time.

For Cockrone Lagoon, more road and residential development has occurred along the coastline around the lagoon entrance, including the southern area around Tudibaring Parade and down to Warri Crescent. To the north of the lagoon entrance residential subdivision has commenced, with the road system largely present, although few residences had been constructed.

1983

By 1983 extensive residential development has occurred in the study area resulting in a sharp intensification of land use over the period since 1964. This includes not only an increase in the extent of development but also an increase in development densities. Some formerly rural lands have now been converted to residential land use, primarily closer to the coast.

Most of the residential development in the north of the study area has occurred to the east of The Entrance Drive. In the Wamberal Lagoon catchment, residential development has also occurred west of The Entrance Drive, near the reservoir. Much of the foreshore vegetation appears to have been retained, except along Bell Drive.

Residential development has occurred around the entirety of Terrigal Lagoon and the Country Club is now present. This development was undertaken in the floodplain, thereby impacting on catchment hydrology, as well displacing wetlands that previously occurred at that location. In addition, a significant portion of the lagoon was reclaimed for the purposes of residential development on the north-eastern foreshore. It is thought that this occurred in the 1970's.

Development around Avoca Lagoon is concentrated around the northern, eastern and southern shorelines. In some locations this has resulted in displacement of some of the vegetation near the lagoon shoreline, more so in the south.

Residential development around Cockrone Lagoon has occurred largely east of The Scenic Road, displacing some formerly rural lands and some forest in these locations.

2007

Patterns of land use in the study area do not appear to have undergone significant change since 1983. What little development has occurred relates to an increase in the extent of residential areas to the southwest of Terrigal Lagoon towards Picketts Valley at the expense of pre-existing rural lands.

Summary

Based on interpretation of the historical aerial photography over the last 50 years, it is apparent that there has been a shift from formerly rural land uses to increasing residential development of the study area. The presence of agricultural activities in the study area in the 1950's and 1960's would likely have resulted in some negative impacts on lagoon water quality through increased sediment and nutrient loads associated with clearing of formerly forested areas. The use of any fertilisers or pesticides for agricultural purposes may also have resulted in soil and water quality impacts.

Progressively through the 1970's and 1980's land use underwent a period of intensification for residential land use. This would have involved the clearing of more vegetation and a general increase in impervious areas, which would have the effect of changing stormwater runoff patterns (i.e. timing of flows). Water quality would continue to be impacted, particularly during the construction phase, which coincided with a time during which strict implementation of erosion and sedimentation controls would not have been common practice. Conversely, the sealing of informal roads would have decreased sediment loads associated with runoff from roads. It is understood that the reticulated sewage system was not extensively adopted until the 1990's, and until that time there were water quality issues resulting from the wide-spread use of septic systems (GCC, 1995).

It is likely that the implementation of improved catchment management practices in recent years (in addition to the construction of the sewage system) have resulted in an improvement in the quality of stormwater runoff entering the lagoons. However, delivery of flows into the lagoons would still be quicker than that which would have occurred in a less developed (or natural) catchment condition.

In addition, past land use decisions have had a significant impact upon current management practices due to the development of low lying lands. For example, parts of the foreshore lands of Terrigal Lagoon are now threatened by inundation at water levels of 1.23m AHD. This has necessitated a relatively high degree of management intervention by Council through the implementation of an Entrance Management Policy for flood mitigation purposes. Over the past 50 years each of the lagoons has been subject to artificial breaching of the beach berm to mitigate flooding of foreshores and infrastructure. This management activity has had a profound impact on the processes in the lagoon and is discussed further in **Section 3.7.**

3.2.2 Current Land Use

GCC has in place two key planning instruments that guide land use planning in the study area including:

- The Gosford Planning Scheme Ordinance, and
- Interim Development Order No. 122.

The *Gosford Planning Scheme Ordinance* (GPSO) is the principal planning instrument for Gosford urban areas and Interim Development Order No 122 (IDO 122) is the principal planning instrument for the non-urban areas. The planning instruments guide the type of development permitted in different parts of the Gosford LGA through land use tables, corresponding to the zoning of each parcel of land. The GPSO and IDO 122 also set out subdivision and density requirements, and development controls relating to the bed of natural waterways. Heritage conservation is also considered with Schedule 8 of the GPSO and Schedule 2 of the IDO 122 listing items/sites of heritage significance. There have been over 460 amendments to Council's planning instruments.

The DoP has issued a Standard Instrument (LEP template) as part of planning reforms aimed at standardising planning throughout the state. The Draft Gosford LEP 2009 has been prepared in accordance with this Standard Instrument. It was placed on public exhibition by Council from 10 February 2010 to 5 May 2010. The Draft Gosford LEP 2009 will replace the GPSO and IDO 122 once gazetted.

Figure 3.2 shows the existing land use zoning for the study area. It is noted that commercial and industrial land uses are not present in the study area. The predominant land use zonings relate to residential conservation and scenic protection zonings.

Mapping of land use zonings and available aerial photography captured in 2007 have been analysed to develop a map showing the general consolidated land use types present in the lagoon catchments (**Figure 3.3**), including:

- Residential (urban) land use,
- Rural land use, and
- Forested land.

Table 3.2 provides details of the relative proportions of these land use types in each of the lagoon catchments. The more developed, urban residential areas are concentrated largely in the eastern portion of the study area near the coast and around the lagoon foreshores.

The Wamberal and Terrigal Lagoon catchments are subject to similar levels of urbanisation, with around one third of the catchment developed for residential urban land uses. However, of these two catchments, Wamberal has a higher proportion of forested land (24%) use due to the presence of the Wamberal Lagoon Nature Reserve.

Cockrone Lagoon has the lowest proportion of developed catchment. Around 69% of the catchment is categorised as being forested land (**Table 3.2**).

Table 3.2: Land Use Types for the Wamberal, Terrigal, Avoca and Cockrone Lagoon Catchments

Lagoon	Total Catchment Area (ha)*	Urban	Rural	Forested	Waterway
Wamberal	654.8	31%	36%	24%	9%
Terrigal	892.3	36%	44%	16%	3%
Avoca	1,186.6	25%	21%	45%	9%
Cockrone	722.3	9%	16%	69%	6%

*Calculated from GIS data.

The mapping of land use types provided in **Figure 3.3** was prepared for the purposes of modelling of catchment runoff characteristics. Catchment hydrology is discussed further in **Section 3.9**.

3.2.3 Future Land Use

A search of Council's Development Application tracking system and DoP Major Projects Register (for projects proposed under Part 3A of the *Environmental Panning and Assessment Act 1979*) did not reveal any records of proposed developments that are likely to result in a significant change of land use within the study area (search undertaken 12/1/10).

In terms of strategic land use planning, the NSW Department of Planning (DoP) has been implementing planning reform in NSW whereby local Council's are required to re-assess their land use zoning and prepare a new Local Environment Plan (LEP) in accordance with the Standard Instrument. GCC has been developing a Standard Instrument LEP for the Gosford LGA in consultation with DoP and the Draft Gosford LEP 2009 was on public exhibition until 5 May 2010. Advice from Council (pers. comm., T. Mackenzie, Cardno – M. Bowman, GCC, 14/01/10) confirmed that the land use intensity and land use types proposed in the Draft LEP are generally consistent with that currently occurring in the catchment. The lagoon waterways are at present zoned W1 – Natural Waterways and the zone W1 objectives are:

- To protect the ecological and scenic value of the waterways,
- To prevent development that would have an adverse impact on the natural values of waterways in this zone,
- To provide for sustainable fishing industries and recreational fishing,
- To make provision for aquaculture.

Coincident with these planning reforms, DoP has also released the *Central Coast Regional Strategy* (DoP, 2008). The Strategy covers the Gosford and Wyong Shire LGAs and has been developed by the NSW Government as a long-term land use plan for the region. The regional strategy contains policies and actions designed to cater for the region's projected housing and employment growth over the period to 2031 and outlines how and where future development should occur. The DoP has set a target for Gosford LGA to accommodate an additional 16,500 dwellings by 2031, although the general growth centres identified in DoP (2008) within which these additional dwellings are proposed are located in close proximity to the train line around Gosford and Woy Woy, away from the immediate study area and as such are not expected to influence the lagoon areas.

The recently released guidelines for sea level rise projections (NSW Government, 2009) may affect land use planning of low lying areas. It is not yet clear whether these issues will be incorporated into planning instruments.

3.3 Foreshore Land Use and Land Tenure

Land tenure has been mapped in **Figure 3.4**, which shows publicly accessible lands including:

- Crown land (**Section 3.3.1**),

- National Parks (**Section 3.3.2**), and
- Community lands (**Section 3.3.3**).

The assessment of land tenure has focussed on those publicly accessible lands.

3.3.1 Crown Land

Crown land is land vested in the Crown and managed by the NSW LPMA under the *Crown Lands (CL) Act 1989*. Crown lands are managed by the LPMA for public recreation and enjoyment, environmental conservation and heritage conservation purposes. In many parts of the State, coastal lands commonly include Crown lands. In addition, any land below the mean high water mark (MHWM) is also classed as Crown land. As a result, the LPMA is one of the major landholders in the coastal zone.

Under the *CL Act 1989* Crown lands may be:

- Held under tenure (lease or licence) for public purposes;
- Community managed reserves;
- Reserved for environmental purposes;
- Crown public roads; or
- Managed reserved lands.

Management of Crown land may be undertaken by the LPMA, by a Trust manager (which may be Council) or by Council on behalf of the LPMA.

When referring to Crown lands, tenure is defined as the holding of land under the *CL Act 1989*. There are three general types of arrangements under which Crown land may be held under tenure:

- ***Lease*** – form of tenure generally for exclusive occupation and use of Crown land for a specific term and under specific conditions as outlined under the provisions of the CL Act. Leases are designed with terms to suit the purpose of the lease. A lease may be forfeited for non-compliance of conditions, or may expire because the term has lapsed. A lease is also transferrable with the consent of the Minister. Generally, leases will require land assessments.
- ***Licence*** – provides the right to occupy or use Crown land under the provisions of the CL Act. A licence may not necessarily confer exclusive use by a licensee. It is not transferrable and may be revoked at the will of the Minister without compensation.
- ***Permissive Occupancy*** (PO) – PO agreements with the Minister are pursuant to the CL (Continued Tenures) Act 1989. Under the CL Act, only leases or licences will be issued in the future and permissive occupancies will be progressively terminated in favour of a licence or lease.

Where an individual or organisation proposes to undertake an activity, build a structure or use Crown land, they are required to apply for a tenure from the LPMA. This includes the issue of domestic waterfront licences for the use of submerged and tidal Crown land where there is direct access to Crown land. This type of licence would cover facilities such as jetties, boatsheds or boat ramps. In the case of these domestic waterfront licences, the

LPMA aims to ensure that the waterway is not overcrowded and that the public's right of access to the foreshore is maintained.

An audit of Crown lands was undertaken with the assistance of the LPMA in order to summarise land tenure, but also to gain an indication of public access to the lagoon foreshores. Crown lands within the study area are shown in **Figure 3.4**.

3.3.2 National Parks Land

National Parks are dedicated under the *National Parks and Wildlife Act 1977* (NP&W Act) and are managed by DECCW. There are three National Parks falling within the bounds of the study area: Wambina Nature Reserve, Wamberal Lagoon Nature Reserve and Bouddi National Park (**Figure 3.4**). There are Plans of Management in place for the Wamberal Lagoon and Wambina Nature Reserves. Within National Parks and Nature Reserves, some types of activities are permitted and others are not. This also applies to recreational activities. Nature Reserves generally have a high conservation value and fewer activities are permitted in these areas. National Parks also have a conservation value, but they are also maintained for recreational usage and a greater range of activities are permitted in these lands.

3.3.3 Community Land

Community lands are public lands vested in or otherwise under the control of Council as identified under the *Local Government Act 1993*. This excludes land identified under the CL Act (i.e. Crown lands). Community land is open to the public and may include parks, reserves and sports grounds. The extent of community land within the study area is shown in **Figure 3.4**.

Council has established a Coastal Open Space System (COSS), being lands that have been set aside and are actively managed by Council as continuous open space areas in order to achieve multiple objectives relating to nature conservation, ecological connectivity, scenic quality and recreational usage. The lands have either been acquired by or dedicated to Council, and are managed in accordance with Council's *Draft COSS Strategy* (GCC, 2010).

The purpose of the COSS Strategy is to implement the Gosford Community's Vision 2025, and the State Government's planning priorities and legislation by identifying the strategic directions and the major actions required to conserve and preserve a sustainable Coastal Open Space System. The COSS Strategy has been prepared to provide a strategic planning rationale for the operation and management of the COSS. A number of actions are identified within this strategy that, when implemented, will assist in the operation and management of the COSS (GCC, 2010).

The extent of COSS lands has been overlaid (blue hatching) on community lands in **Figure 3.4**.

3.3.4 Native Title

Native title is the recognition by Australian law that Indigenous people have rights and interests in their land that come from their traditional laws and customs. Generally, native title cannot supersede the rights held by others, for example, native title may not be conferred over freehold land. However, native title does provide recognition of the rights and interests held under traditional law and custom. According to the Native Title Tribunal, native title rights and interests may include rights to:

- Live on the area,
- Access the area for traditional purposes, e.g. for camping or to undertake ceremonies,
- Visit and protect important sites and places,
- Hunt, fish and gather food or traditional resources like water, wood and ochre, or
- Teach law and custom on country.

As stated by the Native Title Tribunal, in some cases native title may confer the right to possess and occupy an area to the exclusion of all others (i.e. to have 'exclusive possession).

Native title may be conferred under the Commonwealth *Native Title Act 1993* or the NSW *Land Rights Act 1983*.

Indigenous Land Use Agreements (ILUAs) may also be established. ILUAs are voluntary agreements between native title holders and others about the ongoing use of land and water; they effectively explain how native title can co-exist with other interests within the determination area.

A review of the mapping provided by the Native Title Tribunal indicates that there are no active native title claims within the study area. Given that native title has not been conferred for any lands within the study area, there are no operational ILUAs present.

3.4 Topography, Geology and Soils

3.4.1 Topography and Landscape Character

Catchment topography for the study area has been mapped in **Figure 3.5**.

The topographical variation and vegetated ridgelines and upper slopes have long been recognised and protected through appropriate planning controls to preserve the visual backdrop of the City. The COSS, which has been in operation since the early 1980's, is a key feature in maintaining the environmental and visual qualities of these lands, whereby the most important lands are progressively brought into public ownership. Other vegetated, elevated private lands play a supporting role to COSS lands to ensure environmental and scenic quality is protected together with other areas of remnant vegetation, habitat and foreshore areas playing a key role in lagoon catchment protection.

Proposed zonings under *Draft Gosford Local Environmental Plan 2009* continue to recognise the importance of both COSS and other environmentally sensitive lands, and *draft Gosford Development Control Plan* has further specific provisions (Chapters 2.1 Character and 2.2 Scenic Quality) to ensure these qualities are protected. The *Draft Gosford DCP* also ranks different landscapes in terms of their State, regional or local significance, together with describing their scenic conservation issues, development absorption capacities, visual sensitives and statements of significance. The Macmasters Beach/Copacabana coastlines are identified as being of State significance, whilst the

Avoca/North Avoca, Terrigal, Forresters Beach-Wamberal coastlines have been rated of being of regional significance (Gosford Draft DCP Part 2, Chapter 2.2).

The Wamberal and Terrigal Lagoons have relatively large floodplains (relative to their catchment size) with lower lying areas situated around the lagoon foreshores. The land surrounding the Avoca and Cockrone Lagoon waterbodies generally rise more steeply from the foreshores, except for those lands around the lagoon entrances.

In the Wamberal Lagoon catchment, the low-lying lands (0-8m in elevation) are located around the lagoon foreshores and immediately north of the lagoon waterbody. The steepest parts of the catchment are located along the western border, with peak elevations of around 145m in the northwest, overlooking the lagoon and the ocean.

For Terrigal Lagoon, the lower lying lands (0-8m in elevation) are concentrated around Terrigal Drive and Brunswick Road, where the golf course is located, and between the northern arm of the lagoon and the ocean. The steepest parts of the catchment are generally in the south, with the highest elevations of around 110m occurring in the south-western corner of the catchment.

Within the Avoca Lagoon catchment, the low lying lands (0-8m in elevation) are concentrated largely around the lagoon entrance and in the region of Avoca Beach Resort. There are some steeply sloping lands forming gullies. The highest parts of the catchment are found in the northwest where elevations reach around 190m, while more moderate elevations of around 120m occur along the southern border.

The lowest lying lands (0-8m) occurring in the Cockrone Lagoon catchment are located around the entrance and to the west along Cockrone Creek. The catchment is also fairly steep, rising to around 140m elevation in the southwest.

3.4.2 Geological and Soil Landscapes

Surface Geology

Geological mapping was sourced in electronic (GIS) format from the Department of Primary Industries (DPI, now DII). The study area primarily falls within the bounds of the Gosford-Lake Macquarie map, with the lower portion of the Cockrone Lagoon catchment falling with the bounds of the Sydney map.

The geology of the study area has been mapped in **Figure 3.6**.

Five main lithological groups are found in the study area:

- **Qa** – Quaternary Alluvium; gravel, sand silt and clay.
- **Qhd / Qs** – Sand dunes / quartz sand.
- **Rh** – Hawkesbury Sandstone; quartz sandstone and minor shale lenses (grey siltstone, claystone, laminite).
- **Rnp** – Patonga Claystone; red-brown and grey-green claystone and siltstone, grey siltstone and laminate and fine lithic sandstone (Narrabeen Group).
- **Rnt** – Terrigal Formation; lithic-quartz to quartz sandstone, siltstone, minor sedimentary breccia, claystone and conglomerate (Narrabeen Group).

The majority of the study area is underlain by the Narrabeen Group Terrigal Formation (Rnt), with Quarternary Alluvium generally associated with the lagoons and dune and barrier sands at the lagoon entrance areas.

Soil Landscapes

Soils mapping was sourced in electronic (GIS) format from DECC (now DECCW). The soil landscapes of the study area are mapped in **Figure 3.7**. Details relating to each of the soil types is provided in **Table 3.3**.

The predominant soil type in the study area is the Erina soil landscape, which is classed as an Erosional soil type. This has implications for estuarine water quality and morphodynamic processes. These erosional soils can be readily mobilised where exposed and may be transported into the lagoon during periods of high winds or rainfall events. This can lead to siltation and poor water quality (i.e. high turbidity) in the lagoon after a rainfall event. The generally erosive nature of the soils found in the study area, the Yarramalong (ya) soils in particular, mean that bank erosion may become an issue along the tributary creeks and lagoon foreshores where riparian vegetation is in poor condition or absent. Additionally, the low soil fertility may mean that some types of vegetation have difficulty becoming established.

Table 3.3: Soil Landscapes (after: Murphy and Tille, 1993)

Descriptor	Landscape Grouping	Characteristics
Erina (er)	Erosional	➢ High soil erosion hazard ➢ Localised mass movement, foundation hazard and high run-on ➢ Seasonal water logging of footslopes ➢ Strongly acid soils of low fertility.
Gymea (gy)	Erosional	➢ Localised steep slopes, some rock outcrops ➢ Extreme soil erosion hazard ➢ Shallow, highly permeable soil with very low soil fertility.
Sydney Town (st)	Erosional	➢ Very high erosion hazard, undulating and rolling hills on moderate slopes ➢ Permanent waterlogging (localised), highly permeable, strongly acid soils with low fertility.
Narrabeen (na)	Beach	➢ Severe wave and wind erosion hazard ➢ Non-cohesive, highly permeable, strongly alkaline saline soils of very low fertility.
Woy Woy (ww)	Beach	➢ High watertables ➢ Localised flooding ➢ Periodic waterlogging ➢ Very low to low soil fertility.
Norah Head (nr)	Aeolian	➢ Extreme wind and high water erosion hazard ➢ Highly permeable soils of very low fertility.
Tuggerah (tg)	Aeolian	➢ Extreme wind erosion hazard ➢ Non-cohesive, highly permeable soils with very low fertility ➢ Localised flooding and high watertables.
Watagan (wn)	Colluvial	➢ Steep slopes with occasional rock outcrop ➢ Mass movement, soil erosion and foundation hazards ➢ Seasonal waterlogging.
Woodbury's Bridge (wo)	Residual	➢ Extreme erosion hazard ➢ Localise seasonal water logging

Descriptor	Landscape Grouping	Characteristics
		➤ Low wet bearing strength and high erodibility ➤ Acid soils of very low fertility.
Wyong (wy)	Alluvial	➤ Flooding and waterlogging ➤ Stream bank erosion ➤ Strongly acid, poorly drained, impermeable soils of very low fertility with saline subsoils.
Yarramalong (ya)	Alluvial	➤ Flooding ➤ Seasonal waterlogging ➤ Stream bank erosion ➤ Low fertility.

Hydrogeology

Exchange between the lagoon waters and the local groundwater table can also occur, with the direction of exchange (exfiltration or infiltration) dependent upon the hydraulic gradient. Groundwater will typically flow downslope from the upper catchment areas towards the lagoon foreshores, with exfiltration through the banks and into the lagoon occurring when groundwater levels are higher than lagoon water levels. The rate of exfiltration will depend upon the properties of the soil along different parts of the foreshore.

The lagoon catchments are generally fairly steep with regular rainfall recharge it is likely that these groundwater levels are reasonably constant. During prolonged dry periods, however (e.g. drought) groundwater levels may drop below the lagoon water levels, creating a hydraulic head whereby there may be percolation of lagoon waters into the groundwater in the upper reaches of the lagoons.

Near the lagoon entrances loss of lagoon waters via percolation through the entrance berm is likely to occur, particularly when lagoon water levels are relatively high after periods of prolonged entrance closure. The coarser beach sands that form the berm are fairly porous and higher water levels in the lagoon can create a hydraulic head to the lower ocean levels, thereby, causing exfiltration from the lagoon waterbody through the berm to the ocean.

Rates of groundwater flow from the lagoon are estimated on the water balance assessment in **Section 4.6.4**.

3.5 Terrestrial Vegetation

3.5.1 Existing Terrestrial Vegetation

Vegetation mapping has been undertaken for the Gosford LGA by Bell (2009), as mapped in **Figure 3.8**.

Endangered Ecological Communities (EECs) identified by Bell (2009) have been mapped in **Figure 3.9**, and include:

- Freshwater Wetlands on Coastal Floodplains*,
- Kincumber Scribbly Gum Forest,
- Littoral Rainforest,
- Lowland Rainforest,
- River-flat Eucalypt Forest on Coastal Floodplains,

- Swamp Oak Floodplain Forest*,
- Swamp Schlerophyll Forest on Coastal Floodplains*, and
- Umina Coastal Sands Woodland.

A total of eight EECs can be found in the study area, with at least one EEC located within each of the four lagoon catchments. These consist primarily of small scattered patches of vegetation, except for those found in the Wamberal Lagoon catchment, where larger contiguous vegetation patches can be found associated primarily with the Nature Reserve. These EECs are protected under the NSW *Threatened Species Conservation Act 1995* (TSC Act).

Those EECs marked with an asterix in the list above are associated with estuarine/floodplain areas and are therefore key components of the vegetation fringing the lagoons. Further details of lagoon foreshore and riparian vegetation are provided in **Section 6.3.1**.

State Environment Planning Policy No. 14 (SEPP14) identifies Coastal Wetlands of State significance. The aim of SEPP14 is to ensure the preservation and protection of wetlands for the environmental and economic benefit of the State. This is achieved via a range of planning and development controls that apply under the *Environmental Planning and Assessment Act 1979* (EP&A Act). Any development or activities proposed in the study area would need to consider the presence of EECs and/or SEPP14 wetlands.

There are a number of SEPP14 wetlands located within the study area, as mapped in **Figure 3.9**. The largest extent of SEPP14 wetlands are found around Avoca and Cockrone Lagoons.

3.5.2 Changes in Terrestrial Vegetation over Time

Freewater and Gladstone (2010; **Appendix D**) provide an overview of the changes in catchment vegetation over time. A summary is provided below.

Freewater and Gladstone (2010) compared mapping of pre-1770 terrestrial vegetation (DEWHA, 2005) to vegetation mapping prepared for Gosford LGA by Bell (2003). Losses of riparian and floodplain vegetation since European settlement are estimated at greater than 25% as at 2004 based on a comparison of the available mapping.

As discussed with reference to historical land use (**Section 3.2.1**), agricultural activities within the catchment required logging and clearing of vegetation. In more recent years, residential development required further clearance and fragmentation of terrestrial vegetation. Remnant vegetation is now afforded protection under a range of mechanisms in National Parks and Reserves, on Crown land, on community lands and within COSS reserves (**Figure 3.4**).

Vegetation extents mapped by Bell (2009) provide a snapshot of the extent of vegetation in the LGA at the time of mapping and allows identification of vegetation communities deemed to be of significance. While vegetation extent mapping has covered the entire study area, assessment of vegetation quality and condition are more limited, restricted to specific areas.

Weed infestation has been identified as a significant issue, with 20% of COSS lands (at that time 2,000ha in extent) found to be impacted by weeds (Manidis Roberts, 1992). Additionally, an assessment of Gosford's rainforests found that infestation by Lantana (*Lantana camara*) had increased significantly since 1987 (Payne, 2002).

The loss of vegetation and deterioration in vegetation condition has implications for general biodiversity. Biodiversity values are closely linked to the both vegetative area and condition. In particular, biodiversity values are dependent on:

- Vegetation condition and structure (e.g. the presence of hollow-bearing trees and other refuges),
- Patch size and susceptibility to 'edge effects', and
- Connectivity between habitats.

Wildlife corridors that provide connectivity between habitats are particularly important in that they permit the movement and interaction of fauna. This is important on a range of temporal scales as it relates to, for example: access to different food sources (i.e. daily/weekly basis), seasonal migration, genetic exchange between different populations, competition and territorial expansion. Corridors also permit species to move to new areas if the habitat normally available in their usual range is lost or degraded (e.g. due to fire, flooding, development or similar). Further discussion is provided in Freewater and Gladstone (2010).

3.6 Climate

Climate is a dominant factor in the behaviour of the four lagoons and their tributary creeks with rainfall, evaporation and solar radiation being significant contributors to the processes occurring within the lagoons. Climate is discussed in this report with reference to the following variables:

- Temperature,
- Precipitation (including rainfall),
- Evaporation,
- Solar radiation (which is affected by cloud cover), and
- Wind speed
- Ocean waves

In addition to seasonal/annual climatic patterns, climate may also be influenced by long term factors such as El Niño-Southern Oscillation (ENSO) cycles (flood/drought) and global climate change (including sea level rise, temperature changes, changing rainfall, winds and wave patterns).

Climate change is discussed in **Section** 3.10

3.6.1 Climatic Summary

Current climatic conditions have been described based on an analysis of statistics obtained at two weather stations operated by the Bureau of Meteorology (BoM); the Narara Research Station (No. 06187) and the Norah Head Station (No. 061366.). The Narara Station is closest to the study area, but is located further inland beyond the local catchment. While the Norah Head Station is further away, it is located on the coastline and is therefore likely to be more representative of the study area.

A summary of the key climate statistics is listed for the Narara Research station in **Table C.1** and for the Norah Head Station in **Table C.2** (**Appendix C**).

The data provided indicate that the general climate of the study area is a warm temperate. The late summer to early winter period is generally wet and humid and the late winter-spring period is mild and dry.

Monthly average rainfall is presented in **Appendix C**. Average annual rainfall for the study area is around 1,300 mm/yr. The wettest time of the year is around February-March, while the driest is around July-October.

A comparison between the Narara (inland) and Norah Head (coastal) data shows that the coastal areas on average tend to be milder, drier and less humid than areas further inland.

3.6.2 Long Term Climatic Averages

Long term climate factors are difficult to predict. An indicator for long-period phenomena such as the El Niño-La Niña (drought/flood cycle) is the Southern Oscillation Index (SOI), which is calculated from the monthly or seasonal variations in air pressure difference between Tahiti and Darwin. El Niño periods are indicated by a strongly negative SOI (less than or equal to -10). During these times there is sustained warming of the central and eastern tropical Pacific Ocean, a decrease in the strength of Pacific Trade Winds and a reduction in rainfall over eastern and northern Australia. La Niña periods are indicated by a strongly positive SOI (greater than or equal to +10). During La Niña conditions, stronger Pacific Trade Winds occur, as do warmer sea temperatures to the north of Australia. Waters in the central and eastern tropical Pacific become cooler during these times. Together, these factors translate to an increase in the probability of rainfall in eastern and northern Australia.

The SOI provides information on the past ENSO events, but gives no clear indication of future trends. It is noted that ENSO is a long term climatic cycle and that short term processes, such as flood events, may occur within these longer term cycles.

A plot of the SOI for the last five years (source: BoM, 19/04/10) is shown in **Figure 3.10** as a guide to past drought/flood cycles. Over the previous five years there have been swings between El Niño and La Nina conditions (**Figure 3.10**). Severe droughts resulted from the weak to moderate El Niño event of 2006/2007. A moderate La Niña developed slowly during 2008.

The BoM states that the decline in the current El Niño event is consistent with climate model predictions, which suggest Pacific Ocean temperatures will cool steadily over the coming months, returning to neutral levels (i.e. tending towards neither El Niño nor La Niña conditions) by early winter 2010.

The Interdecadal Pacific Oscillation (IPO) is another long-period phenomena. IPO events are similar to El Niño events, but they tend to operate over longer time periods of 20-30 years and the observable effects are manifested primarily in the northern and southern Pacific Ocean, rather than for the tropical/equatorial Pacific. The IPO impacts on sea level pressure and sea surface temperatures in these areas. It is understood that when the IPO warms the central Pacific, the impact of El Niño and La Niña events on Australia is more moderate. Conversely, when an IPO event cools the central Pacific, El Niño and La Niña events will tend to have a stronger influence on Australia's climate.

3.7 Catchment Flooding

3.7.1 Flood Behaviour

Lagoon flooding occurs during periods of heavy rainfall and runoff from the local catchment causes the lagoon level to rise. This rise depends upon the volume of runoff, rate of stream flow to the lagoon, the volume of the lagoon and state and rate of opening (should it occur) of the lagoon entrance. This process has been considered within the catchment flood studies for each lagoon, which were not available for use in this study. The 100-year ARI flood extents, however, were provided from Council's GIS database and have been mapped for the study area in **Figure 3.11**.

Entrance scour processes play a significance role in flood levels. Changing conveyance through the entrance during a flood event is an important feature to the timing and peak of the flood. Entrance breakout simulations were undertaken as part of the physical processes investigations, **Appendix F**. These simulations were based on the 100-year ARI catchment flows and peak flood levels within each lagoon were defined. These are summarised in **Section 4.6.1.**

3.7.2 Management of Flood Risk

Flood levels in the lagoon are significantly affected by the condition of the entrance berm. Floods can re-open the entrance by overtopping and scouring a channel through the berm. If the berm level is sufficiently high, rising floodwaters can threaten lagoon foreshore properties. As a result council employs an entrance management policy that requires the entrance berm be mechanically opened to drain the lagoons before flooding threatens adjacent property.

Current Entrance Management Practices

It is understood that the lagoon entrances have been under active management by Council for flood mitigation purposes since about 1970 (GCC, 1995). Therefore, this discussion of entrance behaviour will begin with a review of the current entrance management policy *R0.14 Opening of Coastal Lagoons* (GCC, 2009).

The objective of the entrance management policy is "to mitigate flooding by opening the coastal lagoons in a manner which minimises the impacts on the environment of the coastal lagoons and the surrounding areas". It relates to the four lagoons comprising the study area. The policy document contains procedures relating to:

- Mechanical entrance opening,
- Entrance berm height management,
- Safety,
- Environmental factors,
- Monitoring of lagoon water levels,
- Notification procedures, and

- Responsible agents.

As identified above, there are two key mechanisms by which Council manages the lagoon entrances: berm scraping to maintain berm heights at manageable levels and mechanical breaching of the entrance.

Management of berm height is undertaken due to the rapid response time of the lagoons to rainfall events and aims to maximise the probability of the lagoons opening naturally prior to flooding of foreshore properties occurring. Mechanical breaching of the entrance is strictly required once the trigger water level has been reached. These berm heights and trigger water levels are provided in **Table 3.4**.

Table 3.4: Lagoon Let Out Levels & Entrance Berm Heights (after: GCC, 2009)

Lagoon	Let Out Level (m AHD)	Entrance Berm Height (m AHD)
Wamberal	2.40	2.6-2.7
Terrigal	1.23	1.7
Avoca	2.09	2.7-2.8
Cockrone	2.53	3.3-3.5

Photos of a mechanical breakout of Cockrone Lagoon undertaken by Council on 3 June 2009 are provided in **Appendix A**.

The policy recognises the need to open the Avoca entrance to facilitate the maximum run out velocity at the top of the tide thereby keeping scouring of the entrance to a minimum and enabling the entrances to close more quickly minimising ecological impacts (GCC, 2009). In addition, instruction is provided to open the entrances in the centre portion of the berm so as to avoid a meandering entrance and minimise potential bank erosion either side of the entrance channel.

Issues relating to odours following lagoon break out have been noted in relation to the exposure of mud flats in Avoca Lagoon (GCC, 2009), although it is noted that these areas are important for foraging wading birds, many of which are protected. Other identified environmental issues relate to the potential disruption of the population of endangered Green and Golden Bell Frogs (*Litoria aurea*) at Avoca Lagoon.

At present the entrance management policy actively manages the entrance primarily for flood mitigation purposes. While it identifies other issues of concern (odours, water quality and Green and Golden Bell Frogs) in relation to lagoon water levels, the implementation of the policy does not at this time actively address these issues and the extent of the impact of the current opening regime is largely unknown. While Council has an obligation to mitigate risk to life and property from flooding, they also have obligations in relation to the ongoing protection and management of a number of ecological features of the lagoons. In moving forward with the management process for the coastal lagoons, it is recommended that the desired environmental values be articulated and options for adjusting the entrance management practices towards facilitating the desired ecological values while meeting the flood mitigation imperatives be assessed. Based on discussion provided elsewhere on water quality (**Section 5.2.3**) and threats to lagoon ecology (**Section 6.5**), it may be that the entrance management regime could be amended to permit breakouts at a lower water level following a prolonged period of build up of algal mats. It is understood that entrance breakout has on occasion been initiated by residents due to flooding concerns or for recreational reasons (e.g. by surfers). This is in contravention of the entrance management policy (GCC, 2009) and would likely be identified by the authorities as an inappropriate and potentially illegal act.

3.7.3 Impact of Flood Mitigation Works

An understanding of entrance behaviour under natural conditions is difficult to ascertain due to the fact that the entrance berms (and breakout occurrence) have been artificially managed since 1970 (GCC, 1995). Furthermore, no water level data is available before this time. However, it is likely that breakout events would not occur as often without regular intervention. That is, the current management program pre-empts the natural breakout event and hence may initiate a breakout when it would not have occurred naturally.

It is important to note that the let out levels adopted in the policy (refer to **Table 3.4**) have been determined based on floor levels for local residences and properties, with the let out level reflecting the point at which properties will begin to be inundated by flood waters. Increasing flood levels would require serious consideration of options for mitigating the potential inundation of adjacent properties. Options such as raising floor levels, construction of levels, installation of pumps or through the voluntary purchase of affected properties need further consideration in light of the sea level rise projections.

Natural beach berm levels range between 2.5-3.5m AHD along the open coast beach compartments and hence it could be expected that the lagoon berms would at times tend towards these levels if uninterrupted. If this were the case the number of openings would decrease, on average.

3.8 Pollutant Sources

A number of pollutants are typically found in stormwater runoff generated from urbanised catchments. These pollutants originate from either point or non-point sources. Point sources include discrete locations where stormwater pollution can occur, for example, through discharges of trade wastes and/or sewer overflows.

Non-point or diffuse sources of pollutants do not originate from a specific location and are therefore more difficult to control. Typical examples of non-point sources include the types of activities undertaken by residents within the catchment including use of motor vehicles, car washing and gardening activities. Non-point source pollutants may include oils, heavy metals, litter, suspended solids and nutrients. While the actions of individuals within the catchment have minimal impacts when considered in isolation, cumulatively these common activities can generate substantial pollutant loadings that can then become entrained in stormwater runoff.

Licensed Premises

Under their load-based licensing program, DECCW (Environment Protection Authority or EPA) issues and administers licences for a range of premises in accordance with the *Protection of the Environment Operations Act 1997* (PoEO Act). These licensed premises may discharge waste to water either directly or indirectly. A public register is maintained of all licences and pollution notices issued by DECCW. A search of the register (undertaken January 2010) revealed two historic records for premises located within the study area:

- In 2000 a prevention notice was issued under s.96 of the PoEO Act in relation to the unauthorised receipt and disposal of landfill material for a premises in the Cockrone Lagoon catchment; and
- In 2000 a licence for treating sewage at a premises located in Wamberal was surrendered.

There are no current licences issued under the PoEO Act relevant to the study area.

Contaminated Lands

Contaminated lands may also act as an indirect point source of pollution. This may occur either directly, when stormwater runoff entrains contaminated soil, or indirectly, when groundwater intercepts contaminated soils, becomes contaminated and thereafter flows into natural waterbodies.

DECCW (EPA) maintains a register of notices issued under the *Contaminated Land Management Act 1997* (CLM Act). A search of the register (undertaken 12 January 2010) indicated that no notices have been issued under the Act for any land located within the study area.

Additionally, Council maintains a record of contaminated sites identified under the register or through the Development Application process. A review of the mapping of these sites provided by Council identified only one site known to be contaminated located within the Terrigal Lagoon catchment. However, it is noted that these two registers contain records of known contaminated lands only, and it is possible that there may be as yet unidentified contaminated sites in the study area. Council has previously commissioned a risk-based assessment of potential contaminated lands and that study identified several sites within the study area that have the potential to present a risk in terms of contamination (AWT, 2001). A list of these sites is provided in **Table 3.5**. The location of these sites has been mapped in **Figure 3.12**.

Table 3.5: Potentially Contaminated Land (Source: AWT, 2001)

Occupier	Address	Lot(s)	DP(s)	Parcel(s)	Risk
Former landfill & disposal sites – Potential contaminants, unknown contamination status					
Crown Land	Kincumber Water Quality Control Centre, Doyle Street, Kincumber	229 1	755234 877957	49413 85480	High
Motor engineers & repairs – risk based on possible contamination originating from land use practices					
Freeman Phil Mobile Auto Services	239 Hillside Rd, Avoca Beach	6	263303	30809	Moderate
Hanks Ian	86 Bluebell Dr, Wamberal	148	29639	32866	Moderate
Motor service stations & garages – risk based on possible contamination original from storage of fuel					
Caltex Oil (Aust.) P/L	Cnr Bellevue & The Entrance Rds, Forresters Beach	61	747931	48691	High
Caltex Wamberal	656 The Entrance Rd, Wamberal	0	SP16090	64483	High
E&H Car Care Avoca	14 Cape Three Points Rd, Avoca Beach	25	22167	13921	High

Sewer Overflows

Sewer overflows and/or leakages from the sewer pipe network may also act as point sources of pollution for waterways. Historically, there have been a high number of septic systems used in the catchment and it is understood that leaking or otherwise problematic septic systems have previously contributed to high nutrient loads and resultant water quality issues in the lagoons (GCC, 1995).

Connection to the reticulated system was required by Council as of 1996. Information sourced by Council for the purposes of this study however, indicates that there are currently 915 On-site Sewerage Management (OSSM) systems within the lagoon catchments, with some properties having multiple systems. From 1999 - 2003 Council's Waste Services Section undertook a comprehensive inspection of properties within the study area to assess each of the systems' performance and allocate a risk categorisation in accordance with Council's OSSM Strategy. There were only two properties located in the study area that fell into the high risk category due to the age of the systems and increased need for operational management. These properties are subject to regular inspections.

At the time the inspection of all OSSMs within the LGA was undertaken, none of the OSSM systems were found to be failing. It is considered that property owners are now aware of their responsibility to manage their OSSM systems and random inspections have not to date identified any system failures.

Overflows from the reticulated sewage infrastructure may also occur, typically during wet weather when the sewer system is unable to cope with the higher volume of flow. At these times, additional flows can enter the system through illegal connections or infiltration of groundwater. Sewage pumping stations may be established at points on the sewer network in an effort to alleviate these issues. The location of sewage pumping stations within the study area that have the potential to act as overflow points are shown in **Figure 3.12**. Council has connected a telemetry system to these sewage pumping stations to provide early warning of failures, thus allowing Council to minimise the overflow impacts when these failures occur. Other issues such as leakage from the sewer network due to cracks in the pipes may also occur, but these are difficult to identify.

Towards the end of 2010, GCC intends to begin construction of the Coastal Carrier System (CCS) upgrade - a $30 million investment to rehabilitate the major wastewater transfer system servicing Forresters Beach, Wamberal, Terrigal, North Avoca, Avoca and Kincumber. The CCS upgrade is intended to improve the reliability, performance and capacity of the current system to assist Council in:

- Protecting the community, our waterways and environment against wastewater overflows; and
- Meeting future demands in some of the Central Coast's most popular areas.

Council will build 6.5km of pipeline between North Avoca, Avoca and Kincumber to carry additional wastewater to the Kincumber Wastewater Treatment Plant.

The major wastewater pump stations at North Avoca and Kincumber will be revamped to improve the transport of wastewater to the treatment plant. Council will also upgrade two minor pump stations in Avoca.

3.9 Catchment Hydrology

When rain falls on the catchment, a range of pollutants may become entrained in the flow of stormwater and make their way into the lagoons via tributary creeks and drainage lines. Typical pollutants found in urban stormwater runoff may include:

- Gross pollutants (e.g. rubbish, grass clippings, etc.),
- Sediments,
- Nutrients (including nitrogen and phosphorous), and
- Faecal matter from animals.

The amount (or loadings) of these different pollutants will vary depending upon the specific characteristics of each catchment. For developed catchments, such as those of the four lagoons, the loadings of each of these types of pollutants in stormwater will typically be higher than would have been the case prior to development of the catchment. Depending upon the characteristics of the receiving waterbody, this may result in impacts on estuarine processes such as estuarine siltation and sedimentation, or algal blooms due to high nutrient concentrations.

Catchment Modelling

Computer modelling of stormwater runoff was undertaken for the four lagoon catchments in order to estimate the typical pollutant loadings flowing into each of the lagoons. The full report, including description of the model and the findings is provided in **Appendix E** and key findings are summarised below.

The model was used to estimate:

- Daily and average annual catchment inflows to the lagoons (in ML/year); and
- Average annual pollutant loadings of Total Nitrogen (TN), Total Phosphorous (TP) and Total Suspended Solids (TSS) delivered to the lagoons in stormwater runoff (representing key stressors for aquatic habitat values).

Estimates of annual inflows and pollutant loadings were derived for a representative average year (1995), wet year (1998) and dry year (2000) in order to give an indication of the inter-annual variation in catchment hydrology. These representative years were selected based on a statistical analysis of the historical rainfall data. In addition 16 years sequences, 1992-2008, of daily inflows for each lagoon were generated to provide the inputs to water balance models of each lagoon.

Key Findings

The volume of stormwater runoff flowing from the catchment into the lagoons is a function of both the catchment size, land use and rainfall intensity. In developed catchments with a higher proportion of hard surfaces, less runoff may be absorbed into the soil and therefore the net volume of annual runoff will be higher.

In addition, runoff from developed areas will tend to be higher in pollutants. By contrast, in forested catchments some proportion of rainfall will be absorbed into the soil and both water and nutrients will be taken up by vegetation. Vegetation can also catch suspended sediments in runoff. Hence, a highly developed catchment will typically generate higher pollutant loadings than a less developed catchment with larger areas of natural vegetation.

Comparing the four lagoons, the highest pollutant loadings are generated in the Terrigal Lagoon catchment. This is due to the large size of the catchment (being the second largest) and the degree of development of the catchment, with 80% of the catchment being developed for urban or rural land uses. It is noted that the lagoon waterway comprises only 4% of the total catchment area, which in combination with the generally high pollutant loadings, indicates a high potential for water quality issues to occur in the lagoon.

While Wamberal Lagoon catchment is the smallest in size, a number of the sub-catchments have been developed (67% of the total catchment area). As such, there is a higher proportion of impervious areas and hence a greater volume of runoff and associated pollutant loads flowing into the lagoon. Despite having a catchment almost twice the size of the Wamberal Lagoon catchment, the Avoca Lagoon catchment contributes pollutant loads not dissimilar to those modelled for Wamberal Lagoon. This is due to the high proportion of forested land (46%) and lower proportion of urban land use (25%).

The Cockrone Lagoon catchment generates lower pollutant loads than all other catchments. This is due to the small catchment size and the low percentage of impervious area. In addition, the Cockrone Lagoon catchment has a high proportion of forested land (69%), which generates lower pollutant concentrations.

The modelling also provides information about how pollutant loadings to the lagoons may change under different climatic conditions. It is noted that the total pollutant loadings entering the lagoons in a wet year and are about three times higher than the loadings in a dry year.

3.10 Climate Change

3.10.1 Climate Change Science

Two studies of the potential impacts of climate change on the local area have been undertaken:

- CSIRO (2007) – Assesses the impact of climate change on the Hunter-Central Rivers
- Blackmore and Goodwin (2009) – Provides summary statistics for the coastal portion of the Hunter – Central Coast region, including the study area.

CSIRO (2007) Hunter – Central Rivers CMA Study

CSIRO (2007) states that the CMA has experienced a warming of 1.3˚C since 1950 and a decline in rainfall of about 50mm per decade in the east. These changes in the climatic variables are thought to be due, at least in part to human activities.

In general, CSIRO (2007) predicts that the Hunter-Central Rivers CMA will be warmer, and although predictions relating to rainfall patterns are uncertain, given the likely increase in rates of evaporation, the CMA will also likely be drier. Increases in the incidence of extreme weather conditions such as heat waves, bushfire and extreme winds are also anticipated.

A summary of the predicted changes for a range of climate variables in the Gosford coastal zone for the years 2030 and 2070 compared against a 1990 base year is provided in **Table 3.6**. It is noted that these values have been calculated for the entire CMA, which includes a sizable area inland from the coast. It is likely that the coastal areas would differ from these regional predictions due to local climatic factors such as proximity to the ocean and topographic effects.

Table 3.6: Projected Climate Change in the Hunter-Central Rivers CMA (after: CSIRO, 2007)

	2030	2070
Temperatures		
Average	+0.2 to +1.6 ˚C	+0.7 to +4.8 ˚C
Rainfall		
Annual Average	-7 to +7%	-20 to +20%
Extreme Rainfall[1]	-10 to +12%	-7 to +10%
Evaporation	+1 to +13%	+2 to +40%
No. of Droughts per Decade[2] (approx. 3 at present)	1 to 5	1 to 9
Wind		
Extreme Winds	-5 to +8%	-16 to +24%

[1]Defined as 1 in 40-year 1 day rainfall total. Values represent a range in seasonal projections from a limited set of climate models. [2]The values for drought represent monthly drought frequencies.

The range of values listed in **Table 3.6** provides an indication of the level of uncertainty associated with the climate predictions. Nonetheless, the changes in climatic conditions of increasing temperature and evaporation into the future will likely impact upon the processes occurring in the lagoons.

CSIRO (2007) includes a literature review and discussion of the implications of the report findings. The key points relevant to this study have been summarised below:

- Decreases in average annual rainfall will likely translate in a decrease in environmental flows.
- In combination with increased evaporation rates and higher temperatures, this will likely lead to declines in water quality (e.g. higher incidence of algal bloom conditions).
- The quality of groundwater may suffer due to rising sea levels and saltwater infiltration.
- Factors such as an increase in atmospheric carbon dioxide levels will benefit some vegetation, while other factors such as increased temperatures or harder frosts may negatively impact some vegetation.
- Climate change impacts will place further pressure on ecosystems already being impacted by human activities.
- Some native species may become displaced due a shift in their climatic range, which may permit opportunistic invasive species to move into new areas.

- Potential increases in sea level rise, storm surges and coastal inundation may result in erosion (depending on shoreline type) and therefore displacement of foreshore vegetation.

Blackmore and Goodwin (2009) Hunter – Central Coast Regional Study

The findings of Blackmore and Goodwin (2009) are summarised in a climate profile for the Gosford LGA. The region was broken down into three sub-regions or zones, with the study area identified as being located in the coastal zone.

The study undertook both an analysis of historical climatic data for the region and further modelling to examine the impact of climate change on the LGA. The changes in climatic patterns under climate change conditions are reported for the period 2020-2080.

Temperatures

A regression analysis of historical temperatures for the period 1970-2007 showed that there had been an increase in average temperatures for the study area, with additional overall increases in average temperatures forecast for 2020-2080 (Blackmore and Goodwin, 2009). Similarly, a statistically significant increase in maximum temperatures has also been observed since 1970, and average maximum temperatures are expected to generally increase during autumn and winter. The results of the analyses are shown in **Table 3.7**.

Table 3.7: Projected Climate Change in the Gosford Coastal Zone - Temperatures (after: Blackmore and Goodwin, 2009)

	Summer	Autumn	Winter	Spring
Historical (1970-2007)				
Minimum Temperature	+ 0.5 °C	+ 0.8 °C	+ 1.2 °C	+ 1.0 °C
Maximum Temperature	+ 0.9 °C	+ 0.5 °C	+ 0.9 °C	+ 1.4 °C
Future (2020-2080)				
Minimum Temperature	- 0.9 °C	+ 1.4 °C	+ 1.3 °C	- 0.2 °C
Maximum Temperature	- 0.2 °C	+ 1.1 °C	+ 1.3 °C	- 0.7 °C

Rainfall

An analysis of historical rainfall data from 1948-2007 shows that there has been a statistically significant decrease in annual rainfall of approx. 274mm (Blackmore and Goodwin, 2009).

It is noted that both annual and interdecadal variability are imposed on top of these historical records associated with the IPO. During that time period there have been two phases in the IPO which would have influenced rainfall patterns; a negative (La Niña-like) phase from 1948-1976 and a positive (El Niño-like) phase from 1977-2007 (Blackmore and Goodwin, 2009). A stepwise change in rainfall patterns is observable between IPO periods.

It is thought that rainfall patterns for 2020-2080 are likely to stay within the boundaries of known variability (**Table 3.8**), although during this period they will return to the generally wetter and more variable 1948-1977 phase of the IPO.

Table 3.8: Projected Climate Change in the Gosford Coastal Zone - Rainfall (after: Blackmore and Goodwin, 2009)

	Summer	Autumn	Winter	Spring
Historical (1970-2007)				
Rainfall per year	-46mm	No change	-52mm	+4mm
Future (2020-2080)				
Rainfall per year	No change	No change	-13%	+15%

Wind Speed

No real change in average annual wind speeds has been observed over the period 1970-2007 (**Table 3.9**). For the period 2020-2080, seasonal shifts in wind speed will cancel each other out leading to no net change on an annual basis (Blackmore and Goodwin, 2009).

Table 3.9: Projected Climate Change in the Gosford Coastal Zone – Wind (after: Blackmore and Goodwin, 2009)

	Summer	Autumn	Winter	Spring
Historical (1970-2007)				
Wind speed	+ 1.4km/hr	+ 0.6km/hr	-2.0km/hr	-0.4km/hr
Future (2020-2080)				
Wind speed	-0.1km/hr	+ 1.5km/hr	-0.2km/hr	-1.4km/hr

Extreme Events

Blackmore and Goodwin (2009) also considered projected changes in extreme events for the period 2020-2080, including major storms (such as east coast lows), flood events and extreme temperatures, defined as those events that fall within 95%ile.

The analysis found that the projected frequency of weather events for extreme storm events was likely to increase, indicating a higher probability of occurrence for east coast lows during autumn/winter. High rainfall (flood) events are predicted to increase in frequency in summer and autumn and decrease in winter and spring. An increase in extreme temperatures during summer and autumn is also predicted, which would have implications for bushfire risk as well as human health.

3.10.2 Policy Development

State Government Initiatives

The NSW Government recently released a Sea Level Rise Policy Statement (DECCW 2009a) outlining their objectives and commitments to communities affected by sea level rise. The primary objective of the Policy Statement is to minimise the cost of climate change by:

- Promoting an adaptive, risk-based approach to managing sea level rise impacts,
- Providing guidance to local Councils to support their sea level rise adaptation planning,

- Encouraging appropriate development on land projected to be at risk from sea level rise,
- Continuing to provide emergency management support to coastal communities during times of floods and storms,
- Continuing to provide updated information to the public about sea level rise and its impacts.

In support of this policy statement, the NSW Government has adopted the following sea level rise planning benchmarks. For an increase above 1990 mean sea levels of 40cm by 2050 and 90cm by 2100, these values were established through careful consideration of available sea level rise projections and take into account the uncertainty associated with the projections.

Gosford City Council Initiatives

In December 2009, Council resolved to adopt a sea level rise planning level of 0.9m that is consistent with NSW State Government Sea Level Rise Policy Statement to 2100. The resolution included the following:

- Council adopt 0.9m as its sea level rise planning level for the year 2100 with an assumed linear increase from 1990 levels as the basis for Council staff to proceed with risk assessment, policy development, and strategic planning decisions.
- The sea level rise planning level is used in all relevant strategic processes and Council commit to reviewing all relevant strategic documents to incorporate the adopted sea level rise planning level to enable management options for development controls to be developed.
- The sea level rise planning level is used in all relevant asset management and capital works project planning processes to enable proper consideration of potential sea level impacts in all relevant decisions.
- A notation be placed on planning certificates pursuant to s149(5) of the *Environmental Planning & Assessment Act 1979* that the land is within the 0.9m sea level rise extent as identified on the most relevant map held by Council.
- The sea level rise planning level be reviewed upon the adoption of new information or policy by State Government and the process of this review involve engagement activities with the community.
- The measures already in place to address coastal risk and flood risk continue to be applied and are reviewed upon the adoption of new information or policy by State Government.

The adoption of the sea level rise planning level followed the public exhibition process between 12 August 2009 and 18 September 2009. The public exhibition included the publication of localised sea level rise information and maps that were produced to provide an indication of areas that may be potentially impacted by increases in sea level of up to 0.9m.

Council has also adopted a *Climate Change Policy* which provides the guiding principles for Council to manage its climate change risks to natural and human systems within the Gosford LGA using a combination of sustainable adaptation and mitigation measures, including community stakeholder consultation. The objectives of the Policy are:

- To provide a strategic framework, that is consistent with a whole of government, and whole of Council approach, that will assist Council prepare for, and assist the community and environment to become more resilient and adaptable to, the impacts of Climate Change.
- To undertake adaptation and mitigation actions as a sustainable response to climate change. These actions would support the known environmental, economic, social and cultural values of the local community.
- To review climate change risks and impacts (for example, sea level rise, carbon footprint, temperature increase, embodied carbon, precipitation change, and storm, bushfire, drought and flood events) as further reliable information becomes available.
- To provide Council and the public with objective information that will assist in understanding the problem, alternatives, opportunities and/or solutions.
- To continue to undertake research and to participate in opportunities that will improve climate change management capacity.
- To comply with applicable legal requirements and implement any relevant state government policies, guidelines and/or directives.
- To recognise Gosford's proportionate contribution to Australia's historic emissions and associated moral obligations.

Council is now working to ensure the objectives and commitment statements of the *Climate Change Policy* are incorporated into strategic planning and decision making processes, along with the operations of Council.

3.11 Summary of Key Characteristics and Management Implications

A summary of the key findings and management issues identified in relation to catchment processes is outlined below:

- ***Catchment Management Practices:*** The study area has gone through a period of development, initially for agricultural uses prior to the 1950's, and more recently for residential land use during the 1970's and 1980's. The change in land use patterns that have necessitated the introduction of entrance management policy through this period would likely have impacted on the lagoons. Whilst significant changes in patterns of land use in the future are considered unlikely, there may still exist opportunities to further improve catchment management practices.
- ***Catchment Pollutant Loads:*** The catchment (MUSIC) modelling indicates that there are significant pollutant loads being delivered to the lagoons via catchment runoff. While this would be a natural process, development of the catchment would have altered the hydrology and quality of stormwater inflows. This is likely to be a significant contributor to water quality issues in the lagoons. The Terrigal Lagoon catchment has the greatest pollutant loading and should be targeted in the first instance for any activities that seek to address these issues. This may be achieved through the implementation of Water Sensitive Urban Design principles within the catchment.
- ***Sewer Overflows:*** The introduction of a reticulated sewage system to the study area would have resulted in a large reduction in contamination within the lagoons. Significant gains have been made through pro-active ongoing management of OSSM systems, and it is recommended that these activities continue to be

supported into the future. In terms of the reticulated sewer system, Council is currently in the process of upgrading the CCS and this will achieve further water quality improvements through improved capacity and a reduction in the incidence of sewer overflows.

- ***Contaminated Sites:*** There exist in the lagoon catchments several sites identified as having a high level of risk in terms of acting as sources of contamination. The types of sites identified have the potential to act as sources of heavy metals and hydrocarbons, which can impact on human and environmental health. Where contaminated sites are identified, the potential for migration of contaminants off-site via stormwater runoff, aeolian transport of sediments or groundwater infiltration should be considered.
- ***Climate Change:*** It is anticipated that climate change will lead to increased temperatures, evaporation rates, more extreme rainfall patterns and therefore extreme catchment inflows to each of the four lagoons. This will have implications for both flows and loads to the lagoons.

4 Physical Processes

4.1 Overview

This section of the report provides a discussion of various facets of the physical (hydraulic and morphological) processes occurring in the four study lagoons. Much of the information in this section (except where otherwise identified) has been derived from a technical report prepared by Cardno Lawson Treloar, which is provided in full in **Appendix F**. Additional information has been obtained from a variety of sources.

4.2 Intermittently Closed and Open Lakes and Lagoons (ICOLLs)

ICOLLs are common along the south-east portion of the NSW coastline. Of the approximately 130 estuaries located on the coastline identified by DECCW, 70 have been classified as ICOLLs greater than 1 ha in size (Haines and Thom, 2007). It has been estimated that around 70% of these ICOLLs are closed most of the time (Haines, 2006).

In terms of physical processes, the key driver of the ICOLL system is the entrance condition. The entrance berm is the sand bar that separates the lagoon from the ocean during periods when the entrance is closed. When the entrance is closed, both catchment inputs and in-lagoon processes are the key influences on factors such as circulation and water quality.

As described in the preceding chapter rainfall events lead to stormwater runoff that flows into the lagoons raising lagoon water levels. Following inflow events water levels gradually decrease due to evaporation from the water surface and seepage through the berm, particularly at higher lagoon water levels. Successive inflows will eventually cause the water levels to rise above the berm crest height and overtop the berm initiating scouring of the berm sands to form a channel connecting the lagoon to the ocean. During this breakout process, significant volumes of water and water borne constituents flow out of the lagoon. This entrance breakout process typically occurs over a period of hours. The frequency with which the entrance breaks out is therefore determined by rainfall patterns in the catchment and the volume or capacity of the lagoon that is in turn determined the berm height prior to breakout.

When the entrances are open, coastal processes play a more significant role in the hydrodynamics of the lagoons. Tidal processes influence lagoon water levels and exchange of lagoon and ocean waters, thereby influencing water quality and circulation patterns in the lagoons. During this time, however, the action of coastal waves and currents that drive littoral sediment transport will also gradually begin to fill in the entrance channel and re-build the berm. The sand that previously formed the entrance berm gets deposited in the nearshore zone as an ebb tide delta during the entrance breakout event. During flood tides both cross-shore and long-shore currents transport this sand from this nearshore area into the open lagoon entrance channel, where the lower energy environment leads to deposition and formation of a flood tide delta. In this manner, more and more sand is deposited back into the lagoon entrance and the berm re-builds. The duration of entrance open conditions is determined by these coastal processes, and in high energy coastal environments such as those occurring in the study area, the lagoon entrances will typically close over a period of days to weeks. As the channel accretion process progresses, the magnitude of tidal exchange gradually decreases, until the berm crest exceeds ocean high tide and blocks the ocean waters from entering the lagoon.

Following blockage of the ocean tides the berm continues re-building due to long-shore and cross-shore transport and may ultimately reach heights in excess of 3m AHD, in line with the natural beach berm features in the vicinity of the lagoon entrance. Catchment inflow events during the open period or soon after closure when the berm crest is relatively low can lead to additional scour and prolong the open condition. The entrance condition reflects a balance between these two sediment transport forces: catchment inflows and coastal processes.

The natural balance between these competing processes is interrupted by mechanical opening of the lagoons before/during heavy rainfall events. Past land use and development in low lying areas around the foreshores of the lagoons has resulted in a practice of entrance management for flood mitigation. The four Gosford lagoons are subject to such practices based on trigger levels set to mitigate foreshore flooding and inundation of infrastructure. These aspects are discussed further in **Section 4.5**.

4.3 Lagoon Bathymetry

The bed form topography or bathymetry of the lagoons has been surveyed by DECCW and the data provided for use in this study. The bathymetry represents a key input for use in modelling of physical processes.

The lagoon bathymetry for Wamberal, Terrigal, Avoca and Cockrone Lagoons is shown in **Figures 4.1**. **Figure 4.2** shows the relationship between water levels and water surface area and water volume (hypsographic curves) under entrance closed conditions for all the lagoons assuming the berm height is at a maximum of 4 m. A range of water levels are also shown to highlight the dynamic range of levels and volumes. The lagoons are generally broad, shallow basins, with typical bed levels of:

- ***Wamberal Lagoon:*** -2.05 to 3.07m AHD; predominant depth 0.9-1.0m AHD.
- ***Terrigal Lagoon:*** -3.10 to 1.02m AHD; predominant depth 0.5-0.7m AHD.
- ***Avoca Lagoon:*** -3.98 to 5.96m AHD; predominant depth 0.8-0.9m AHD.
- ***Cockrone Lagoon:*** -1.30 to 2.90m AHD; predominant depth 0.4-0.6m AHD.

As lagoon water levels decline, expanses of the bed become exposed until the subsequent inflows inundate exposed areas.

AWACS (1994) provide estimate maximum berm heights based on surveys of back beach areas undertaken by Public Works:

- ***Wamberal and Avoca Lagoons*** - berm levels of 3.0m AHD are common, with a level 3.5m AHD achievable over time;
- ***Terrigal Lagoon*** – berm levels of 2.5m AHD could be expected, with a level of 3.0m AHD achievable over time; and
- ***Cockrone Lagoon*** – berm level of 3.5m AHD likely and a level of 4.0m AHD is possible.

The entrance morphology of Terrigal Lagoon is somewhat different to the other lagoons as evidenced by its lower average berm height and more frequent opening regime.

Furthermore, the entrance at Terrigal Lagoon is located towards the southern end of the beach compartment, as opposed to the other three lagoon entrances which are located toward the centre of their respective beach compartments. The presence of elevated ground (rock cliff) on the southern bank adjacent to the entrance channel limits the annual supply to the Terrigal Lagoon entrance.

Due to its alignment within the beach and greater protection from the predominant south to south-easterly swells the Terrigal Lagoon entrance responds a little slower than the other lagoon entrances. The entrance berm at Terrigal is subject to less offshore forcing (i.e. long-shore and cross-shore transport) than the other lagoons and berm re-building is likely a much slower process for this Lagoon. Under natural conditions this slower rate of re-building could translate to a higher rate of entrance breakouts than the other three lagoons. However, this process also needs to be viewed in the context of active management of the entrances by Council (refer to **Section 4.5.1**) where the natural open/closed cycles have been modified for at least the past 40 years.

4.4 Bed Sediment Characteristics

This section provides a summary of the available information on sediment grain size, historic extraction and reclamation works, sediment quality and Acid Sulfate Soils (ASS).

4.4.1 Sediment Grain Size

There is a range of different sedimentary environments found within the lagoons and the distribution of these different environments is the result of different sediment sources and different environmental processes that move these sediments around the lagoon.

There are two general categories of sediments in estuaries: fluvial sediments and marine sediments. Fluvial sediments are derived from the catchment, where they become entrained in stormwater runoff and flow via the tributary creeks into the lagoon. During periods of entrance closure, fluvial inputs from the surrounding catchment are trapped in the lagoons. Marine sediments are generally sandier/coarser sediments that are deposited in the lagoon via tidal inflows and waves. These two types of sediments have different properties and will play a role in shaping lagoon processes.

Silts and muds are generally defined as being those sedimentary particles being <63µm (0.063mm) in size. These sediments are generally derived from fluvial inputs. Coarser sediments are defined as being sand and having a marine origin. Being the interface between the terrestrial and marine environments, lagoon sediments are typically a combination of sediment types, with muddier sediments associated with creek deltas and coarser marine sediments located closer to the lagoon entrance.

Sediment sampling undertaken by Edwards and Gladstone (2008) and reproduced in Freewater and Gladstone (2010; **Appendix D**) provides an overview of the current geomorphic environments in the four coastal lagoons. The total number of sediment samples analysed were: 13 for Wamberal Lagoon, 12 for Terrigal Lagoon, 15 for Avoca Lagoon and nine for Cockrone Lagoon. The distribution of sedimentary environments in the lagoons has been inferred based on the analysis of these samples. Sediments were categorised as follows:

- Coarse sand = 2.0-0.6mm,

- Medium sand = 0.2-0.6mm,
- Fine sand = 0.2-0.06mm, and
- Coarse Silt = 0.02-0.06mm (i.e. 20-60µm).

In Wamberal Lagoon, the sediments were generally found to be predominantly sandy. Coarse sands likely to be of marine origin have been deposited in deeper parts of the lagoon with coarse silts found in the upper lagoon associated with the outlet of Forresters Creek. Mapping also identifies some rock outcropping in the region of Remembrance Drive and offshore in this location.

The samples collected in Terrigal Lagoon identify a predominantly fine sand environment, with some medium sand sampled from locations near where Lake View Drive and Bundara Avenue run along the foreshore. No rock outcropping was observed.

Similarly, Avoca Lagoon sediments comprise primarily fine sand, with some coarse sand sampled from sites located in the upper portions of the northern and western arms of the lagoon. No rock outcropping was observed.

Samples analysed for Cockrone Lagoon show an accumulation of coarse silts in a delta formation near the outlet of Cockrone Creek. Sediments otherwise comprise fine sand, except for the northern part of the lagoon near Kincumber, where a single sample was analysed as having medium sands. A small area of rock was mapped along the southern bank near the entrance. Rock armouring has been placed in this location.

Sediment grain size analysis has previously been undertaken by Cheng (1992) and WMA (1995), however the results have not been reported herein due to the relatively small number of samples analysed and/or the significant time lapse since sampling was undertaken.

Of particular interest to the modelling components of this study were the sediment grain sizes that affect mobility of sediments within the entrance berm. Sediment data for the entrance berms and the relevant sources are identified in **Table 4.1**.

Table 4.1: D50 Grain Sizes at Entrance Berms

Lagoon	Sediment Grain Size (D50, mm)
Wamberal	0.41 (Haines, 2006)
Terrigal	0.36 (Haines, 2006), 0.37 (WMA, 1995)
Avoca	0.34 (Haines, 2006), 0.37 (WMA, 1995)
Cockrone	0.43 (WMA, 1995)

4.4.2 Historic Sediment Extraction and Reclamation Works

Historical works within two of the lagoons has resulted in changes to the morphology and distribution of sedimentary environments. There are several references to historic extraction and reclamation works for Terrigal and Avoca Lagoons. It is understood that no such works have been undertaken in either Wamberal or Cockrone Lagoons.

A summary of the available information is provided below. An attempt has been made to map the parts of these lagoons subject to the extraction and reclamation works described in **Figure 4.3**.

Terrigal Lagoon

According to WMA (1995) there was some infilling around the lagoon, mainly in the 1960's. The following sites are said to be located on reclaimed land filled with dredged material:

- The triangular-shaped area bounded by Leumeah Avenue, Ocean View Drive and Lake View Road,
- Part of Ogilvie Street,
- Lions Park,
- Rotary Park.

A comparison of the available aerial photography analysed for this study does not indicate any clear evidence of these changes. It has been reported, however, that the progress of the dredging and reclamation operations can be observed in historical aerial photographs from the mid to late 1960's and early 1970's. Foreshore reclamation is thought to have occurred over 3,500m of the 4,700m lagoon perimeter, with the primary source of fill being dredged material (WMA, 1995).

The extent of the dredging works are said to have covered approximately 15% or 4ha of the bed area to a depth of approximately -0.3mAHD, with some dredge holes to -3.0mAHD also occurring (WMA, 1995). This represents around 40,000-60,000m^3 of sediment.

Avoca Lagoon

Gale (1997) reports that dredging was recommended by the Central Coast Waterways and Coastal Advisory Sub-Committee in August 1981 for Avoca Lagoon with a view to rehabilitating and restoring the lagoon to its former condition, having been in-filled due to sedimentation as a result of development in the catchment. Subsequently, Bay River Sands Pty Ltd received approval to commercially extract the sand and sell the dredged material (Gale, 1997). A dredge lease was awarded allowing the removal of approximately 200,000 m^3 of material over five years. However, the dredge lease was extended and dredging activities in Avoca Lagoon did not cease until 1994. It is understood that there is no data available on the actual extent of dredging, but is thought to have been undertaken in the central portion of the lagoon around Bareena Island and, to some extent, up the north-eastern arm of the lagoon. However, WMA (1995) report that Council holds some hydrosurvey data showing the extent of dredging operations, said to include approximately 10% or 7.5ha of the bed surface areas to a depth of between -2.0 to -3.0m AHD. This is thought to represent approximately 100,000m^3 of material (WMA, 1995).

Gale (1997) suggests the extraction of material from Avoca Lagoon has altered the flood and entrance dynamics of the lagoon.

WMA (1995) report some foreshore reclamation upstream of the Avoca Drive Bridge as part of the sand extraction land-based operations.

4.4.3 Sediment Quality

Sediment quality can be used as an indicator of 'ecosystem health', although the effects depend on the likely degree of disturbance or bioturbation. An important aspect of bed sediment quality relates to the degree of contamination associated with adsorbed pollutants, principally when there are a high proportion of silt and clay particles within the sediments (particle sizes less than 63µm). Sediments are important as both sources and sinks of dissolved contaminants (ANZECC, 2000). As well as interacting with water quality, bed sediments represent a potential source of bioavailable contaminants, principally nutrients, including nitrogen, phosphorous and carbon, through the benthic food chain.

Sediment chemistry has important implications for lagoon management. For example, where dredging is planned, the degree of sedimentary contamination will determine the method by which dredge spoil is managed. Further, sediment quality guidelines such as those provided in ANZECC (2000) can be used as a starting point in the identification of contaminated areas requiring remediation or, alternatively, uncontaminated areas that require protection. Management of land use practices in the catchment, including the implementation of ameliorative measures, may also be considered as part of an overall management strategy.

No additional sediment quality data was collected as part of this study and available sediment quality data is summarised below. WMA (1995) provides a summary of sediment quality data collected by others for Terrigal, Avoca and Cockrone Lagoons, which is reproduced in **Table 4.2**. Data presented for Wamberal Lagoon has been sourced for Cheng (1992). The data have been compared to the ANZECC (2000) guideline values (where available). The ANZECC guidelines are provided as Interim Sediment Quality Guidelines (ISQG) Low trigger values for further investigation. The ISQG-Low values represent the point at which the concentrations of contaminants may be having an impact on aquatic ecosystem health.

Concentrations of heavy metals in surficial sediments sampled in 1991 are all well below the ISQG-Low values, except for cadmium, for which the recorded values for Terrigal, Avoca and Cockrone lagoons is higher. It is unclear if this is the lower limit of reporting for the analytical techniques available at that time or represents a contamination issue. Given the lower concentrations of other heavy metals present, the former is likely to be the case.

Table 4.2: Mean Sediment Pollutant Concentrations (after: WMA, 1995)

Pollutant (mg/kg)	Wamberal Lagoon (Cheng 1992)	Terrigal Lagoon		Avoca Lagoon		Cockrone Lagoon		ANZECC Guideline Values
		1991	1994	1991	1994	1991	1994	ISQG Low
TP	93.9	48.5	44.7	83.1	35.4	126.3	35.9	-
TN	77.8	98.3	37.0	199.1	62.9	797.8	52.8	-
Lead	BDL*	30.0	-	30.0	-	30.0	-	50
Copper	7.93	4.84	-	4.32	-	9.44	-	65
Zinc	28.2	9.58	-	11.18	-	43.78	-	200
Cadmium	BDL	3.00	-	3.00	-	3.00	-	1.5
Total Hydrocarbons	52.8	<1,000	-	<1,000	-	<1,000	-	-

*BDL = Below Detection Limit

The University of Sydney Environmental Geology Group currently has in preparation a journal article about biological health indicators of estuaries. Samples recently collected for their study show concentrations of copper, lead and zinc below the ISQG-Low value (pers. comm., T. Mackenzie, Cardno – M. Olmos, USEGG), which suggests that there is presently a low level of ecological risk associated with sedimentary contamination.

In general, it is considered likely that the sediment quality of the lagoons has been impacted over time due to the introduction of catchment-derived contaminants via stormwater runoff. Given the agricultural history of the study area, with orchards being prevalent in the 1950's and 1960's (**Section 3.2.1**) it is possible that historic contamination with fertilisers and organochlorine and organophosphate pesticides may have occurred. Assuming a decrease in application rates due to changes in land use over time, in combination with ongoing siltation of the lagoons, these contaminants (if present) would not likely be present in surficial sediments but would occur deeper in the sedimentary records. Contemporary sedimentary contamination would likely include those pollutants that are typically associated with urban areas, including the heavy metals copper, lead and zinc. The presence of petrol stations and other automotive services in the catchment also has the potential to introduce contaminants such as hydrocarbons. It is important to note that the low density development patterns within the lagoon catchments are unlikely to lead to high levels of contamination and would certainly be less than those reported for parts of Brisbane Water Estuary adjacent to urban areas (Cardno, 2008b).

4.4.4 Potential Acid Sulfate Soils

Overview

Potential Acid Sulfate Soils (PASS) are widespread among low lying coastal areas of NSW, in estuarine floodplains and coastal lowlands. These are naturally occurring sediments and soils containing iron sulfides (mostly pyrite). Where these are exposed to the air by drainage of overlying water or excavation, the iron sulfides oxidise and form sulfuric acid.

Actual Acid Sulfate Soils (AASS) are soils that contain highly acidic soil layers, the oxidation of which produces acidity in excess of the sediment's capacity to neutralise the acidity resulting in soils of pH ≤ 4.0 (DECCW, 2010). Potential Acid Sulfate Soils (PASS) contain sulfidic material that has not yet been exposed to air and oxidised. In their un-oxidised state the pH > 4.0 (DECCW, 2010).

Where ASS are oxidised, the resultant acidity may mobilise into solution toxic quantities of iron and aluminium. A part of this process is the formation of iron flocs that affect water quality and can coat streambanks, benthic organisms and the gills of fish (DII, 2010). Deoxygenation of water also occurs and the mobilisation of other compounds from the soil (such as silica) can lead to algal blooms. Buffering of acids will quickly strip calcium carbonate ($CaCO_3$) from the water and may also have impacts on calcareous organisms such as shellfish. Due to its lower buffering capacity, freshwater (pH ~6.5 – 7.7) is particularly affected by acid in comparison to ocean waters, which have a much higher buffering capacity (pH ~8.2) (DECCW, 2010). Other impacts include damage to infrastructure such as bridges and levees.

According to DII (2010), the ecological impacts resulting from acidification due to ASS include:

In the short term:

- Fish kills,
- Fish disease,
- Mass mortalities of microscopic organisms,
- Increased light penetration due to changes in water clarity,

- Loss of acid-sensitive crustaceans, and
- Destruction of fish eggs.

In the long term:

- Loss of habitat,
- Persistent iron coatings,
- Alterations to waterplant communities,
- Reduced spawning due to stress and reduced recruitment,
- Barriers to fish passage due to chemical pollution,
- Growth abnormalities and reduced growth rates,
- The production of unviable eggs,
- Increased predation and other changes in food webs,
- Higher temperatures due to persistent changes in light penetration,
- Reduced availability of nutrients, and
- The release of heavy metals from contaminated soils.

As a result, exposure of PASS can result in significant impacts on recreational fishing, commercial fishing, oyster farming and agricultural activities.

Occurrence of ASS in the Study Area

Mapping of ASS risk areas within the study area is shown in **Figure 4.4**. The mapping was prepared using data provided to Council by DECCW. Large areas corresponding to the lagoon beds and some foreshore areas are identified as being high risk for ASS. Some adjacent lands are identified as being low risk for ASS. It is noted that several areas of disturbed terrain are also identified in the DECCW mapping.

It is noted that portions of the lagoon bed identified as high risk areas that tend to become exposed when water levels in the lagoons are low. It is possible that these areas generate some small amount of acid when exposed to the air.

For Wamberal and Cockrone Lagoons, the high risk ASS areas are confined largely to the defined bed of the lagoon or public foreshore lands. Therefore, the likelihood of disturbance due to excavation is low. In the case of Terrigal and Avoca Lagoons, areas identified as being high risk for ASS coincide with private development in some locations. There is a possibility that residents may be unaware of the risk and mobilise ASS during the course of some lot-based works. The likelihood of this occurring is considered low due to the requirement for Development Assessment of certain types of activities.

As discussed in **Section 3.2.3**, land use patterns in the catchment are unlikely to change in the future. Therefore, the likelihood of mobilising large areas of ASS is low. However, ASS risk should be considered in the case of any infill or ‘brownfields’ development.

ASS should also be considered should any works be proposed as part of the Estuary Management Study and Plan.

4.5 Entrance Behaviour

4.5.1 Historical Entrance Behaviour

Council maintains a lagoon log book which records details of mechanical entrance breakout events, including:

- The date of opening,
- Height difference between the trigger water level and actual water level at time of opening,
- Height of the entrance berm above the trigger water level, and
- Time of opening and phase (spring-neap) of the tide.

Council has previously provided a copy of the lagoon log book that covers the period January 1976 to September 2007. It is understood that the log book includes mechanical breakouts of the lagoons undertaken by Council and does not include any natural entrance breakout events that may have occurred over this time. An effort was made to obtain a more up to date version of the lagoon log book for the purposes of this study however it was not available at the time of publication.

An analysis of the lagoon log book records has been undertaken and a summary of the frequency of mechanical lagoon let outs has been provided in **Table 4.3** and graphed in **Figure 4.5**.

Table 4.3: Mechanical Entrance Openings Between 1976 & 2007

	Wamberal Lagoon	Terrigal Lagoon	Avoca Lagoon	Cockrone Lagoon
Avg. No. per Year	2.7	12.6	3.2	2.5

A further analysis of the records was undertaken on the basis of total annual rainfall as being a wet, average or dry year in accordance with the methodology developed for the catchment modelling (refer to **Section 3.9**). **Table 4.4** presents both the average annual number of entrance break out events initiated by Council and the average number of days the entrance is closed between successive breakout events. This provides a more detailed description as to the variability of the entrance behaviour over time.

Table 4.4: Mechanical Entrance Openings Between 1976 & 2007 – Climatic Variation

Lagoon	No. of Entrance Breakouts per Year				Avg. No. of Days Closed (between Breakout Events)			
	All	Wet	Dry	Average	All	Wet	Dry	Average
Wamberal	2.7	4.6	1.5	2.9	134.5	79.0	247.5	125.2
Terrigal	12.6	16.6	9.5	12.9	28.6	21.7	37.7	28.0
Avoca	3.2	4.7	2.1	3.5	112.7	77.1	172.2	102.9
Cockrone	2.5	4.4	1.4	2.4	144.9	81.0	264.0	151.6

From the information presented above it is clear that entrance breakout frequency is correlated to total annual rainfall. Along the eastern seaboard, annual rainfall is in turn correlated to the SOI, as discussed in **Section 3.7.1**. It would therefore stand to reason that the frequency of breakout events is strongly correlated to the SOI index. **Figure 4.6** presents the frequency of breakout events as the number of openings in a year against the

SOI index. This shows that during negative phases of the oscillation characterised by El Niño conditions and associated with drier periods, fewer lagoon breakout events tend to be initiated by Council on an annual basis.

In terms of natural breakouts, WMA (1995) states that one quarter of all breakout events occurring between 1974 and 1993 were natural breakouts. Analysis of the lagoon water levels to determine breakout events, open periods defined by tidal flows to the lagoons and closure concur with the WMA (1995) findings.

4.5.2 Modelling of Entrance Dynamics

Lagoon entrance behaviour has a significant influence on the ecological functioning of the lagoon system. An ICOLL entrance is a dynamic area at the junction of the lagoon and ocean, subjected to a range of both catchment and ocean forces. Analysis and investigation was undertaken on the four lagoon entrances, utilising observed data and numerical modelling techniques. The results are discussed in Cardno (2010; **Appendix F**).

The previous estuary processes study (WMA, 1995) estimated entrance breakout conditions for two ARIs (10-years and 100-years) and a ‘no flood’ event. The results of these investigations are summarised in **Table 4.5**.

Table 4.5: Summary of Entrance Breakout Events (after: WMA, 1995)

Lagoon	Berm Level (mAHD)	Channel Width (m)	Invert (mAHD)	Entrance Scour (m^3)
Wamberal	N/A	N/A	N/A	N/A
Terrigal	1.2 – 1.8	35 – 60	-0.4	2,000 – 7,000
Avoca	1.2 – 3.0	25 - 75	-0.6	8,000 – 23,000
Cockrone	1.5 – 3.6	30 - 70	-0.4	2,000 – 13,000

It is noted that the shape and size of the eroded entrance following a breakout event would vary from event to event, dependent primarily on the magnitude/velocity of flows exiting the lagoon entrance. This is a result of the varying berm height, lake level, flood volume and tidal conditions. Due to this high level of natural variation, not all breakout combinations can be investigated. In lieu of this, the 100-year ARI inflow event was re-visited and modelled with the calibrated Delft3D morphological model. It is thought that the magnitude of the 100-year ARI event would provide an envelope of the majority of possible breakout shapes.

As an example the inflow hydrograph, lagoon water level, entrance channel discharge, channel bed level and bed profiles throughout the modelled breakout event for Avoca Lagoon are presented in **Figure 4.9**.

The resulting entrance conditions following the 100-year ARI storm are presented in **Figures 4.9 to 4.12** for each lagoon and summarised in **Table 4.6**. These values are indicative of the maximum amount of entrance scour that might occur in relation to a very rare catchment flood event. More regular breakout events would scour to a lesser extent.

Table 4.6: 100-years ARI Entrance Breakout Dimensions

Lagoon	Channel Width (m)	Invert (mAHD)	Entrance Scour (m^3)
Wamberal	80	-1.6	15,000
Terrigal	55	-0.6	6,750
Avoca	90	-0.5	19,600
Cockrone	75	-1.4	16,000

The 100-years ARI break out event was modelled consistent with the work previously undertaken for Avoca Lagoon (Cardno, 2007) and in order to provide information to feed into any future studies undertaken by Council, such as the forthcoming coastal hazard study and in the event Council seeks to update their flood studies for the coastal lagoons.

4.6 Lagoon Hydrodynamics

4.6.1 Lagoon Water Levels

As previously discussed (**Section 4.2**), the dominant control on water levels in an ICOLL is the entrance condition. During periods of closed entrance conditions, the water levels are dictated by catchment and groundwater inflows, evaporation and groundwater outflows (seepage), berm height and occasional wave overtopping of the entrance berm. During catchment flood events the lagoon water levels are dominated by discharges from the catchment with no tidal waters being able to penetrate through the open entrance against the flow of flood waters exiting the lagoon.

Once the lagoon entrance is open and the flood waters have subsided, the water levels within the lagoons become tidally driven for a period until the channel fills with sediment and closes. The constricted nature of the open entrance causes significant attenuation of the tides.

An analysis of historical water level records was undertaken for each of the four lagoons. The water level records were captured at 15 minute intervals over the period 1 July 1993 to 30 June 2008. The results have been presented in **Figure 4.12**, which shows the relative frequencies at which different water levels have occurred over this time. The lagoon let out levels adopted for flood mitigation (**Table 4.7**) and ocean tidal levels (MHW, MSL, MLW) have also been plotted for reference purposes. The ocean water levels shown on the graph have been taken from the Fort Denison tidal planes (**Table 4.8**).

A summary of key water level statistics is provided in **Table 4.7**.

Table 4.7: Key Water Level Statistics

Lagoon	Water Levels (m AHD)						
	Bed level max depth (m AHD)	Mean	10%ile	Median	90%ile	Max	Let Out Level
Wamberal	-1.8	1.59	0.91	1.66	2.25	2.89	2.40
Terrigal	-3.0	0.89	0.55	0.92	1.16	2.09	1.23
Avoca	-3.6	1.26	0.80	1.29	1.82	2.45	2.09
Cockrone	-1.2	1.73	1.11	1.79	2.29	2.29	2.53

Table 4.8: Tidal Planes for Fort Denison

Tidal Plane	Water Level (LAT[1])	Water Level (m AHD[2])
High Astronomical Tide (HAT)	2.1	1.18
Mean High Water (MHWS)	1.6	0.68
Mean High Water Neaps (MHWN)	1.4	0.58
Mean Sea Level (MSL)	1.0	0.08
Mean Low Water Neaps (MLWN)	0.6	-0.33
Mean Low Water Springs (MLWS)	0.3	-0.63

[1] LAT is lowest astronomical tide, [2] Australian Height Datum

The spread of water levels shown in **Figure 4.11**, indicates that most of the time the lagoons water levels are perched above the ocean levels. It is noted that the break out levels are the primary determinant of peak water level, while entrance channel breakout bed levels (**Section 4.3**) determine the lower limit of the range. Terrigal Lagoon has the lowest variation in water levels and opens with tidal flows for about 33% of time while the other three lagoons experience tidal variations less than 10% for Avoca and less than 5% in Cockrone and Wamberal Lagoons. The Terrigal pattern is a direct result of the low trigger level for this lagoon and corresponding high frequency of open entrance conditions. The other three lagoons show a greater range of variation in water level about the mean (**Figure 4.12**).

Figure 4.11 shows the water level data for each of the four lagoons against each other for comparative purposes. The green line shows the annual average water level for that year. Variations in average annual water levels from year to year likely reflect inter-annual variation in rainfall, as previously discussed with reference to the SOI. **Figure 4.12** shows periodic, often gradual, increases in water level due to rainfall events when stormwater runoff from the catchment flows into the lagoons. Sharp drops in lagoon water levels represent occasions when the entrance breaks open and water flows out until lagoon water levels reach equilibrium with ocean water levels. When the entrance is open, tidal periodicity can be seen in the water level records, although these patterns are difficult to discern at the 18- year scale the data is presented. Again, Terrigal Lagoon is highlighted as having quite different characteristics from the other lagoons, with management of the entrance having a more significant impact on water level fluctuations in this lagoon, although as discussed in **Section 4.3**, the rate of breakouts under natural conditions would likely be higher for this lagoon anyway.

As previously discussed, when the entrance is open, the ocean water levels will be the primary driver of lagoon water levels. Hydrodynamic and sediment transport investigations using the Delft3D model, with post 100-year ARI breakout bathymetry, were undertaken to establish the magnitude of tidal attenuation from the entrance channel from the ocean to the lagoons (Cardno, 2010; **Appendix F**). The model results showed that under the 100-year ARI entrance condition the tidal attenuated by about 60% and increases to 100% attenuation, (i.e. no tide in lagoons) as the entrance closes.

4.6.2 Water Balance

It is important to note that the water level analysis presented above is based on a data set compiled over the last 16 years, during which time the lagoon entrances have been actively managed. Therefore, the results reported do not necessarily reflect natural conditions (i.e. in the absence of no entrance management).

A water balance for the Gosford lagoons has been developed by considering each lagoon as a single water bucket with inflows from the catchment and outflows via the entrance opening events, evaporation from the water surface, seepage through the ground and during open periods tidal inflows into the lagoon. The change in volume, V (t), of a lagoon over time, t, may be represented by the water balance equation:

$$\frac{dV}{dt} = Q_{in} + Q_{rain} + Q_{evap} + Q_{ent} + Q_{seepage} \qquad (1)$$

where Q_{in} is the catchment inflow to the lagoons via creeks and stormwater drains, Q_{rain} is the inflow due to direct rainfall on the water surface, Q_{evap} is the water lost from the lagoon water surface by evaporation to the atmosphere, Q_{ent} is the water flow through the entrance including both flow from the lagoon (negative discharge) and to the lagoon (positive inflow of seawater) when the entrance is open and $Q_{seepage}$ is the water lost from the lagoon via groundwater seepage.

To apply this model to the lagoons requires measurements of each of the terms on the right side of equation (1). Available measurements include rainfall, evaporation and water levels in the lagoon and adjacent ocean. Time series of water levels may be transformed to lagoon water volume and surface area through application of the hypsographic curve for the lagoon (**Section 4.3**).

The water balance model assumes that the lagoon water level measurements represent a horizontal surface within the lagoon. The rainfall at Avoca Beach BoM station has been used to estimate the daily catchment inflow for the 16 years (1992 to 2008) of water level measurements. The contribution of direct rainfall on the lagoon water surface and evaporation from the water surface have been estimated from the surface area at each time multiplied by the rainfall at Avoca Beach and evaporation for the Narara BoM station (nearest available data set) respectively. The methods for estimating the various terms in equation 1 are summarised in **Table 4.9**.

Table 4.9: Summary of Methods Used to Estimate Various Terms of the Water Balance

Term in Eqn (1)	Method	Equation	Data Required
Change in volume dV/dt	Transform water level time series to volume time series.	V(t) = V(h(t))	Hypsographic table - V(h) Time series water level h(t)
Catchment inflow Q_{in}	Rainfall-runoff model of catchment MUSIC - see model description in **Appendix E.**	Q_{in} ~ R(t) A_c α	Rainfall - R(t) Catchment Area topography, soil type and runoff coefficient, etc
Rainfall Q_{rain}	Transform water level time sere is to surface are time	R(t) x A(t) A(t) = A(h(t))	Hypsographic table - A(h) Time series

Term in Eqn (1)	Method	Equation	Data Required
	series and multiply by rainfall.		water level h(t) Rainfall R(t)
Evaporation Q_{evap}	Transform water level time sere is to surface are time series and multiply by evaporation rate.	E(t) x A(t) A(t) = A(h(t))	Hypsographic table - A(h) Time series water level h(t) Evaporation E(t)
Entrance flow Q_{ent}	Rearrange Eqn (1) and apply at times when entrance open.	$Q_{ent} = \frac{dV}{dt} - Q_{in} - Q_{rain} - Q_{evap}$	
Seepage $Q_{seepage}$	Rearrange Eqn (1) and apply at times of high water level.	$Q_{seepage} = \frac{dV}{dt} - Q_{in} - Q_{rain} - Q_{eva} - Q_{ent}$	

The water balance is estimated for the following periods of interest:

- ***Breakout*** - the time from actual overtopping of the berm to the next lagoon water level minimum;
- ***Open*** - the time during which the entrance is open from the end of breakout to the cessation of tidal flows when the entrance closed to the sea; and
- ***Closed*** - the time from closure to the next breakout event.

The various terms in the water balance for each combination of breakout, open and closed event were calculated and the general statistics for the water balance are presented in **Tables 4.10 and 4.11**.

Table 4.10: Water Balance Summary - Breakout and Entrance Open Conditions

Lagoon	Breakout			Open				
	No. Events	Duration (hrs)	Change in Vol. (ML)	Duration (days)	$\sum V_{out}$ (ML)	$\sum V_{in}$ (ML)	Rain-Evaporation+ Catchment Inflow (ML)	Unaccounted Losses (ML)
Wamberal	24	8	960	11	1,112	1,005	633	-846
Terrigal	138	14	194	7	479	435	373	-372
Avoca	30	11	915	12	1,998	1,892	996	-1,206
Cockrone	27	8	608	9	593	510	410	-574

Table 4.11: Water Balance Summary – Entrance Closed Conditions

Lagoon	Closed					
	No. Events	Duration (days)	$\sum V_{out}$ (ML)	$\sum V_{in}$ (ML)	Rain-Evaporation+ Catchment Inflow (ML)	Unaccounted Losses (ML)
Wamberal	24	183	1,849	2,619	1,725	871
Terrigal	138	32	123	266	298	147
Avoca	30	173	1,892	2,663	2,687	1,880
Cockrone	27	196	1,196	1,692	1,961	1,436

The average breakout event change in volume is a significant fraction (>50%) of the lagoon volume just prior to breakout. The breakout events last about half a day on average, with Terrigal taking slightly longer to breakout because it commences with a lower head.

During the open entrance conditions that last 1-2 weeks there is significant tidal inflow and outflow that is typically about three times the lagoon volume at mean water level indicating significant inflow of saline marine waters. The sum of direct rainfall and catchment inflow less evaporation is also generally greater than the mean lagoon volume.

During periods of closure the water losses ($\sum V_{out}$) from the lagoons and water gains ($\sum V_{in}$) indicate significant loss by evaporation and/or seepage through the berm. When summed with the estimates of direct rainfall, evaporation and catchment inflow, the residual water is termed the unaccounted loss. The relatively large unaccounted losses may reflect an overestimate of catchment inflow.

4.6.3 Wave Climate

In closed systems, such as the four lagoons within the study area, the primary mechanisms for mixing and sediment transport are wind and wave driven processes. For shallower nearshore areas adjacent to the shoreline, the predominant forcing is that of waves. The lagoon wave climate is of interest to the geomorphic (**Section 4.9**) and ecological (**Section 6**) components of the study.

A detailed wave climate study was undertaken by Cardno (2010; **Appendix F**) to describe wave conditions within the lagoons and in order to assist in the assessment of shoreline stability, as well seabed and foreshore ecology. The assessment of wave climate was undertaken by wave hind-casting techniques incorporating historical wind data, as described in Cardno (2010). The nearshore wave transformation model SWAN was used to develop the wave ‘climate’ along lagoon foreshore locations by transforming historical wind conditions to wave conditions along the lagoon foreshores.

Results of the wave climate analyses undertaken in Cardno (2010) are presented for a range of recurrence intervals from 5-year and 100-year ARIs for each of the lagoons in **Figures 4.13 to 4.16**. These analyses were undertaken for entrance closed conditions. Wave propagation through the entrance has not been considered for this study.

Generally, the largest waves (in the order of 0.5m for the 100-year ARI) are found on the north-eastern and north-western foreshores where sufficient fetch exists, for the strong southerly (SE-SW) winds. Comparison between the wave conditions for 5-year and 100-year wind event ARIs shows relatively minor differences, suggesting that wave propagation and growth is limited by the fetch lengths across the lagoons.

4.6.4 Wave Forces on the Lagoon Bed

In addition to acting as an influence on shoreline circulation (wave breaking processes generate a longshore current) within a lagoon, waves also have impacts on the lagoon bed. The seabed shear forces caused by waves have significant impacts on the ecology of lagoon systems. Wave induced bed forces can have the ability to mobilise sediment and organic particulars that can directly or indirectly impact on biological function, for example, via the disturbance of seagrass areas.

The effect of wave induced bed forces depends on the bed material. Typically, sandy regions have bed forces described by the near-bed or depth averaged current speed, while muddy or silty areas are described by the bed shear stress. In both cases, the point is to describe the parameter value above which bed movement is initiated.

The SWAN model was used to prepare spatial maps of near-bed velocity and bed shear stress to identify regions where bed forces may be sufficient to initiate re suspension of bed (Cardno, 2010; **Appendix F**). On sandy beds this threshold occurs at a near bed wave orbital current of about 0.3m/s (van Rijn, 1993). On silty beds the bed shear stress needs to exceed about 0.2 to 0.5N/m^2, depending upon the degree of consolidation (van Rijn, 1993). Particulate organic matter, which is important from a water quality perspective, would be more readily suspended than silty material due to its lower specific gravity.

Figures 4.17 – 4.20 present the 1-year and 5-year ARI bed shear stress maps for the four lagoons. In both sets of figures, yellow regions identify locations where wave induced sediment re-suspension and transport is likely to occur, which is largely confined to the shallower margins of the lagoons. The affected areas would constitute habitats that are subject to what may be termed regular 'disturbance' events in an ecological sense. However, larger areas of the lagoon bed would likely be susceptible to re-suspension of particulate organic matter, which would have implications for water quality.

The 5-years ARI results generally show only a small increase over the 1-year ARI areas subject to re-suspension forces. This is likely due to the small size of the lagoon waterbodies and limited fetch. From a biological perspective, those conditions that occur more commonly (i.e. for a 1-year ARI) have a more significant influence on the ecology than conditions which occur less frequently (i.e. for a 5-years ARI), although extreme events may have catastrophic effects.

It is noted that this analysis does not take into account the presence of benthic aquatic plants such as seagrasses for which the root mass will increase the amount of shear stress required to mobilise sediments. Based on observations in Botany Bay, storm induced seagrass damage occurred at a near seabed velocity of about 1m/s (or a shear stress of 1N/m^2). The highest bed shear forces typically occur in parts of the lagoon subject to high water level variations and occasional bed exposure, whereas seagrasses are more likely to grow where they are submerged on a more permanent basis. Therefore, wind wave induced damage of seagrasses is unlikely to be an issue for the study lagoons. Damage to seagrasses and other benthic habitats is more likely to occur in the entrance channel due to scour during a breakout event.

4.7 Bank Erosion and Shoreline Condition

The *Gosford Coastal Lagoon Data Compilation Study* (Cardno, 2008a) identified a lack of assessments of bank stability and erosion within the lagoons. As such, a detailed assessment of bank erosion and shoreline conditions has been undertaken as part of this processes study. The assessment involved the following:

- Detailed field assessments to identify areas of erosion and categorise the shoreline condition (with regards to bank stability).
- Preparation of mapping to present the findings of the field assessments;
- Analysis of the risk areas associated with potential future erosion; and

- The preparation of a database that summarises findings of the bank conditions assessment, the hydraulic modelling (wave climate data) and the vegetation condition assessment. This database will assist Council in assessing development applications and maintenance.

4.7.1 Foreshore Condition Assessment

A detailed assessment of the foreshore of the lagoons was undertaken on 13 January 2009. The assessment was undertaken from the water by a coastal engineer and geomorphologist. The field work involved documentation of the entire foreshore using a GPS camera.

The data collected during the field work was analysed to identify the following:

- Regions of existing erosion; and
- Regions where shoreline protection works have been constructed, together with an assessment of their condition.

The information collected in the field was also used to determine the foreshore condition based on a foreshore stability index developed for this study. The foreshore stability index is described in **Table 4.12**.

Table 4.12: Foreshore Stability Index

Colour[1]	Index	Description
(yellow)	1	Bank Protection Works - Good Condition
(magenta)	2	Bank Protection Works - Poor Condition
(green)	3	No Bank Protection Works - Stable
(cyan)	4	No Bank Protection Works - Isolated Stability Issues
(orange)	5	No Bank Protection Works - Poor Stability

[1] Shown on Figures 4.21 to 4.24

The findings of the field work are presented on **Figures 4.21 to 4.24**. It can be seen that, in general, the lagoon foreshores are stable and there are only isolated areas of erosion.

It should be noted that an ecological disturbance assessment was also undertaken by the University of Newcastle as part of this processes study. The mapping resulting from this assessment is shown in **Appendix D**. The ecological disturbance assessment incorporated both an assessment of the vegetation condition and any foreshore protection works. These two condition assessments complement each other as both ecology and foreshore stability are linked but should not necessarily be assessed within this same index. The foreshore stability index and the ecological disturbance index have both been considered in the assessment of future erosion risk below.

4.7.2 Future Erosion Risk

The shoreline condition assessment outlined above demonstrated that there are very few locations of existing erosion. However, ongoing high intensity wave action or changes in foreshore vegetation could lead to a risk of erosion in the future.

The significant wave heights for various ARI storm events have been identified for the lagoon foreshores and are presented in Cardno (2010; **Appendix F**). A risk assessment has been undertaken to identify potential erosion risk areas around the lagoon foreshores.

The risk criteria described below in **Table 4.13** have been identified primarily based on those areas likely to be subject to higher intensity wave action. The future erosion risk areas are shown on **Figures 4.25 to 4.28**.

Table 4.13: Future Erosion Risk Areas

Index	Description	Comments
1	High Wave Intensity, No Bank Protection Works, Stable Banks, Good Vegetation Cover	It is likely that the existing vegetation in these areas is ensuring the ongoing resistance of the foreshore to the erosive forces of the wave energy. Care should be taken to ensure the vegetation remains in good condition.
2	High Wave Intensity, No Bank Protection Works, Stable Banks, Modified Vegetation	These areas are still stable; however, if the vegetation becomes further degraded or a large storm event occurs erosion may occur.
3	High Wave Intensity, No Bank Protection Works, Isolated Stability Issues, Good Vegetation Cover	Although the vegetation cover is good in these areas, the wave intensity is generally high than calculated in those areas noted as '1'. As such, some erosion is occurring; however, it is not significant at this stage. The existing vegetation should be protected. These areas should be monitored for further erosion.
4	High Wave Intensity, No Bank Protection Works, Isolated Stability Issues, Modified Vegetation	The modified vegetation in these areas may be attributing to the existing erosion. If further degradation occurs to the vegetation, the erosion may increase. These areas should be monitored for further erosion.
5	High Wave Intensity, No Bank Protection Works, Unstable, Good Vegetation Cover	Although the vegetation cover is good in these areas, it is not providing adequate stabilisation to the foreshore to withstand the erosive forces of the waves. These areas should be considered for future bank protection works.
6	High Wave Intensity, No Bank Protection Works, Unstable, Modified Vegetation	The vegetation is modified in these locations and there is insufficient bank stabilisation. These areas should be a high priority for future bank protection works.
7	High Wave Intensity, Unstable Bank Protection Works	The bank protection works in these areas have been degraded by the high wave intensity. This degradation will continue to occur (particularly during a storm event) if left unchecked.

4.7.3 Foreshore Database

To assist Council with assessing future development applications and proposed maintenance works around the lagoon foreshores, the foreshore assessment data has been compiled into a foreshore database. The database provides the following data for various zones around the foreshores:

- Foreshore condition (as shown in **Figures 4.21 to 4.24**); and
- Maximum 5 and 100-year ARI significant wave height (as shown in **Figures 4.13 to 4.16**).

The database and locations of the zones are provided in **Appendix G**.

4.8 Shoreline Recession

A number of locations representing natural shorelines have been selected for storm 'bite' analyses. Storm bite will typically occur over a period of hours. This response primarily involves the erosion of the normal sub-aerial beach face through offshore transport and deposition near the storm wave break point to form an offshore bar (which would be a small bar in the case of local sea for the study lagoons). On open sea coasts the beach face slowly rebuilds as sand in the bar is transported shoreward under swell wave conditions. However, the four lagoons that form the study area are not subject to swell and this re-building process does not occur. Therefore, what may normally be a short-term erosional process in many cases will translate into a long term recession of the shoreline. Local sea within the lagoons, however, has a reduced erosion potential when compared to the open coast and hence the resulting storm bite is much smaller in the lagoons.

An assessment of storm erosion was made for the selected locations (shown in **Figure 4.1**) using the SBEACH model (Cardno, 2010; **Appendix F**). Simulations within Wamberal, Avoca and Cockrone lagoons were undertaken at a water level of 2.0m AHD, and within Terrigal at water level of 1.0m AHD, over a period of three hours using the respective peak storm significant wave heights for the 5-year and 100-year ARI events. The results of the analyses are presented in **Table 4.14**. It is important to note that these values provide indications as to the magnitude of shoreline recession that may occur in relation to an individual event, which in the case of a 100-year ARI storm would be a very rare event. On a day to day basis wave heights are very low and, as discussed with reference to the bank condition assessment (**Section 4.7**), the banks are generally at equilibrium at the present time and not undergoing gradual erosion/recession.

In addition, it is important to note that the shoreline response to a storm event will depend upon the shoreline condition (as discussed in **Section 4.7**), such as whether the shoreline is currently armoured or whether there is healthy vegetation present that would aid in consolidating the bank sediments and reducing the extent of erosion. Bank condition is likely to be variable on relatively small scales.

Table 4.14: Storm Wave Shoreline Recession Water Line (m)

Profile	100-years ARI	5-years ARI	Profile	100-years ARI	5-years ARI
Avoca 1	0.24	0.1	Terrigal 4	2.63	1.69
Avoca 2	1.7	1.11	Terrigal 5	2.46	1.56
Avoca 3	0.97	0.49	Terrigal 6	0.84	0.57
Avoca 4	1.08	0.76	Terrigal 7	0.84	0.45
Avoca 5	0.21	0.08	Terrigal 8	3.25	2.05
Cockrone 1	2.14	1.43	Terrigal 9	1.12	0.59
Cockrone 2	1.32	1.07	Wamberal 1	0.39	0.29
Cockrone 3	0.53	0.37	Wamberal 2	0.69	0.49
Cockrone 4	0.21	0.15	Wamberal 3	2.04	1.34
Terrigal 1	1.73	1.00	Wamberal 4	0.76	0.49
Terrigal 2	1.75	1.08	Wamberal 5	0.24	0.10
Terrigal 3	3.48	2.15	Wamberal 6	0.81	0.6

However, it is noted that water levels in ICOLLs can be highly variable (**Section 4.6.1**) and therefore where storm waves occur coincident with lower lagoon water levels, less shoreline recession would occur. Although, in that case, the overall lower water depths would lead to lower wave heights and less shoreline recession. For those shoreline locations included in the analysis, recovery would occur slowly, or not at all, due to the short period nature of the waves at those sites.

4.9 Siltation Modelling

Detailed fine silt (cohesive sediment) modelling using the Delft3D model has been undertaken for each lagoon system where catchment sediment loads may potentially cause siltation during closed lagoon conditions (Cardno, 2010; **Appendix F**).

Catchment modelling has been undertaken to derive estimates of suspended sediment loads delivered to each of the four lagoons for representative average, dry and wet years, as outlined in **Section 3.9**. These sediment loads were applied to the Deltf3D model over a 2-week period to identify rates of siltation for each of the lagoons (Cardno, 2010). The 2 week sediment transport and deposition simulation undertaken in Delft3D has been applied to provide an estimation of 6-months of equivalent morphological change. The results are presented in **Table 4.15.**

Table 4.15: Annual Siltation Rates for Average, Wet and Dry Years

Lagoon	Annual Siltation Rate (mm/yr)			Per Decade (cm/10 years)
	Average Year	Dry Year	Wet Year	
Wamberal	0.222	0.016	1.088	0.338
Terrigal	0.353	0.019	1.34	0.467
Avoca	0.212	0.014	1.139	0.340
Cockrone	0.184	0.017	0.791	0.261

The average siltation rates calculated by WMA (1995) for the previous Estuary Processes Study are in the order of 1mm/yr for Avoca and Cockrone Lagoons and "somewhat less than" 2mm/yr for Terrigal Lagoon. These values are lower than those reported in **Table 4.15**, although whether this is due to changes in catchment land use since 1995 or the use of different methodology is difficult to ascertain.

The results presented in **Table 4.15** describe spatially averaged annual siltation rates for each lagoon. Siltation results for each lagoon have also been mapped on a seasonal basis as contours showing annual siltation depths for average conditions in **Figures 4.29 to 4.32**.

In all four lagoons there is considerable spatial variation in siltation patterns and depths, typically associated with tributary inlets:

- ***Wamberal Lagoon*** – The highest rates of siltation occur near the outlet of Forresters Creek;
- ***Terrigal Lagoon*** – The highest siltation rates occur in the western arm, followed by the northern arm;
- ***Avoca Lagoon*** – The highest siltation rates occur near the outlet of Saltwater Creek; and
- ***Cockrone Lagoon*** - The highest siltation rates occur near the outlet of Cockrone Creek, followed by Merchants Gully Creek.

As would be expected higher annual sedimentation rates occur in wetter years. On a seasonal basis, sedimentation rates are higher in winter.

It is important to note that sediment re-suspension was not considered in these investigations (Cardno, 2010). At some locations material in the lower sections of the tributary creeks during would be re-suspended under high flow conditions and this process is likely to reduce the net local siltation rate by transporting sediments away from the original deposition zone.

Generally, the modelled sedimentation rates for each of the lagoons are low and reflect the lower proportions of urban development in the catchments when compared to other lagoons (Cardno, 2010).

4.10 Influence of Climate Change on Physical Processes

4.10.1 Entrance Dynamics

To date there has been limited research conducted on the response of ICOLLs to climate change in the past, probably due to the relative rarity of ICOLLs on a global scale. Key literature published to date includes Haines and Thom (2007), which provides a conceptual assessment of climate change impacts on entrance processes for ICOLLs along the NSW coast.

An ICOLL's morphological response to climate change will be generally dependant on the berm behaviour, which in turn is influenced by the coastline response (littoral drift) to wave climate, SLR, storm frequency and intensity, fluvial sediment inputs and catchment inflows.

Where sufficient sediment supplies are available, the berm height may keep pace with SLR, thereby maintaining a similar height relative to mean sea level. In the event that sufficient sediment is not available, the berm will not be able to keep pace with SLR, resulting in an increase in the frequency and duration of entrance openings under natural conditions.

Haines and Thom (2007) considered likely ICOLL responses to SLR with respect to their location within the beach compartment (i.e. northern end, southern end or centre). The location of the ICOLL entrance within the beach compartment was considered important because of the role that longshore sediment transport (typically south to north direction) may have in slowing the rate of shoreline recession. Estuary berms located at the southern end of a beach compartment typically receive a more limited sediment supply compared to estuary berms located at the northern end of a beach compartment due to the northward longshore sediment transport. A summary of the findings of Haines and Thom (2007) as it relates to the likely response of ICOLLs to SLR is provided in **Table 4.16**.

Table 4.16: Summary of Climate Change Impacts on ICOLL Entrance Processes (after Haines and Thom, 2007)

Entrance Location	Mostly Open ICOLLs	Mostly Closed ICOLLs
Northern end / centre of beach	• Recession due to SLR. • Accretion due to south-to-north longshore sediment drift. • Increased intermittent entrance scour due to higher flood intensity. Result: May be more open or more closed depending upon the relativity between these factors.	• Recession due to SLR. • Accretion due to south-to-north longshore sediment drift. • Reduced intermittent entrance scour due to reduced average annual rainfall, and streamflow, and increased evaporation. Result: Likely to be increased accretion within the entrance, leading to increased periods of closure and reduced frequency of entrance breakouts.
Southern end of beach	• Recession due to SLR. • Erosion due to south-to-north longshore sediment drift. • Possible expansion of flood tide delta. • Increased intermittent entrance scour due to higher flood intensity. • Reduction in the influence of geomorphic entrance control. Result: Likely to be overall loss of sand from the entrance and increased potential for entrance to remain open.	• Recession due to SLR. • Erosion due to south-to-north longshore sediment drift. • Possible expansion of flood tide delta. • Reduced intermittent entrance scour due to reduced average annual rainfall and streamflow, and increased evaporation. Result: May be more open or more closed depending on the relativity between factors.

The locations of the Gosford Lagoon entrances are typically in the centre of the beach compartment, with the possible exception of Terrigal Lagoon which is located towards the southern end of the beach compartment and protected by the headland to the south. Wamberal, Avoca and Cockrone Lagoons would be considered mostly closed ICOLLs and hence fall into the Haines and Thom (2007) category that would likely be subject to (in the absence of entrance management) increased periods of closure and reduced frequency of breakouts. It is also considered that Gosford's beaches are embayed and are not subject to as high rates of net northerly longshore sediment transport as is commonly the case for long open beaches elsewhere on the NSW coastline. Whilst longshore sediment transport does occur along the Gosford Beaches, they're alignment is considered to be in equilibrium with the offshore wave climate, facing a general south-east direction, and hence the assumed net northerly sediment transport applied in Haines and Thom's (2007) model does not necessarily occur. As a result, the position of the estuary entrance along the beach (i.e. northern end or southern end of the beach) becomes less important in these embayed systems.

Rebuilding of the berm areas following breakout events is not solely a product of a net northerly longshore transport but rather from both northerly and southerly longshore transport over time as the beach responds to the offshore wave climate (particularly direction).

The key issue is whether there is sufficient sediment available within that particular beach compartment in which the ICOLL is located. Given that the plan alignment of the beach compartments at Gosford are considered to be formed by, and in equilibrium with, the offshore wave climate it is assumed that the sand volume within the beach compartments would be sufficient to supply the berm areas with adequate material in order to keep pace with SLR.

4.10.2 Modelling of Entrance Dynamics

The implications of SLR for berm response and physical processes of the lagoons has been considered by first assessing the entrance breakout process. Additional simulations were undertaken to describe the entrance breakout conditions under climate change conditions to the year 2050. This includes a 0.4m mean sea level rise (DECCW, 2009) and an assumed equivalent response in berm levels.

Council currently adopt a policy of controlled breakouts to minimise the risk of foreshore flooding around the lagoon entrances and this practice will be assumed to continue into the future, including under climate change scenarios. Therefore the same let-out level as is currently adopted (see **Table 3.4**) has been applied for these entrance breakout simulations. Initial water levels within the lagoon were set to the 1% exceedance level (existing) as the continuance of the mechanical breakouts will have little effect on this parameter. The breakout event was commenced at the start of the falling tide. The results of these entrance breakouts can be seen in **Figures 4.7-4.10** and are summarised in **Table 4.17**.

Table 4.17: 100-years ARI Entrance Breakout Dimensions under Sea Level Rise Conditions (2050)

Lagoon	Channel Width (m)	Invert Level (mAHD)	Entrance Scour (m^3)
Wamberal	70	-1.8	14,600
Terrigal	45	-0.7	6,550
Avoca	70	-0.6	19,300
Cockrone	65	-1.4	15,800

The results show that the breakout extents under climate change conditions differ slightly from that of the existing outcomes, with the resulting breakout channels having a reduced width. This is due of the reduced head at the beginning of the breakout event, that is, the difference between the peak lagoon water level and the offshore tide level. It is this difference that drives water through the entrance and the reduced head results in lower peak velocities and hence a reduced scour width.

Despite this reduction in channel width, the overall erosion scour volumes remain almost unchanged, with only slight reductions observed. Under climate change conditions, the berm is considered to have a greater volume of sand (increased crest level) and while the breakout channel is narrowed a similar invert level (the level to which the entrance channels scour down) remains. Hence a similar volume of scour is produced.

This outcome suggests that SLR will have little impact on the rate of closing following breakout events, assuming a similar offshore wave climate, and hence the duration of open entrance conditions is thought to remain relatively unchanged into the future. The period of closure is likely to decrease as the active lagoon volume will decrease due to the SLR.

4.10.3 Water Levels

The SLR of 0.4m to 2050 is likely to affect water levels and groundwater gradients around the lagoons by a similar level. It is therefore expected that the minimum lagoon water levels will likely increase by the full 0.4m. Given that current entrance management regime is expected to continue, the future maximum water levels would be tied to the present day flood mitigation levels and hence the range of water levels would decrease. This scenario assumes there is sufficient range in the lagoons currently to accommodate the reduction.

The breakout levels and ocean tidal planes for the current and SLR scenario are presented in **Table 4.18**.

Table 4.18: Comparison of Available Freeboard for the Present Day and Under SLR (2050)

Lagoon	Let Out Levels (m AHD)	Present Day (2010)		2050	
		Let Out Level – MHWS	Let Out Level - HAT	Let Out Level – MHWS	Let Out Level - HAT
Wamberal	2.40	1.72	1.22	1.32	0.82
Terrigal	1.23	0.55	0.05	0.15	-0.35
Avoca	2.09	1.69	0.91	1.01	0.51
Cockrone	2.53	1.85	1.35	1.45	0.95

These results indicate the freeboard above the MHWS is sufficient to accommodate SLR effects in Avoca, Wamberal and Cockrone Lagoons, but in Terrigal the 2050 scenario of 0.15m freeboard above MHWS would not be sufficient to allow flood release nor prevent ocean storm inundation.

The decrease in minimum water levels and hence operating range would lead to the three “mostly closed” lagoons transitioning towards more open conditions, i.e. more frequent breakouts and probably slightly longer open periods of tidal influence.

The current entrance management of Terrigal Lagoon, however, will need to be carefully considered in terms of the options available to mitigation potential flooding. The current strategy will not be appropriate as a flood mitigation action under the 2050 SLR scenario. The projected increase in intensity of rainfall events will lead to more rapid lagoon water level increases, possibly necessitating faster response to breakout events.

The projected decrease in water level range in Avoca, Wamberal and Cockrone Lagoons will also have implications for lagoon water and ecosystem response. This is discussed further in **Sections 5.5 and 6.6** respectively.

4.10.4 Ocean Storm Surge

Under climate change conditions an increase in sea levels has the potential to increase the risk of foreshore flooding as a result of large ocean wave and storm surge events. The developing nearshore slopes and entrance conditions may influence this outcome. As such modelling of the 100-year ARI storm surge event was undertaken with a 0.4m increase in ocean water levels. The 100-year ARI ocean storm surge profile (plus 0.4m sea level rise) and 100yr ARI wave conditions (Hs=10.6m, Tp=15.1s) were applied to the offshore model boundary of a coupled Delft3D flow/wave model. This allowed the simulation to include the influence of nearshore wave breaking on the water levels. The results of these storm surge simulations are summarised in **Table 4.19**.

Table 4.19: 100-year ARI Storm Surge Levels under SLR Conditions (2050)

Lagoon	100 yr ARI Ocean Inundation Water Level (mAHD)	
	2010	2050
Wamberal	2.66	3.12
Terrigal	2.10	2.49
Avoca	2.53	2.91
Cockrone	2.69	3.11

Generally the 2050 water levels increased from the 2010 levels by roughly the same amount as the imposed sea level rise (0.4m). There were, however, some differences between the lagoons in this regard. The water levels at Terrigal and Avoca increased by 0.39 and 0.38 respectively, meaning that not quite all of the storm surge propagated through the open entrance and into the lagoon. However at Wamberal and Cockrone, the water levels for the 2050 simulation increased by more than the imposed 0.4m (0.46 and 0.42m respectively) sea level rise.

The slight differences between the responses at the different lagoons is likely a result of the differences in nearshore wave setup at these beaches. Wave setup is a function of nearshore bed slopes which are steeper at Wamberal and Cockrone, suggesting that waves will generally break closer to the shore, resulting in more wave runup energy and hence larger wave setup at the lagoon entrance.

4.11 Summary of Key Processes and Management Implications

A summary of the key physical processes and management issues is provided below:

- ***Water Level Processes and Entrance Management:*** Based on the water level analysis shown in **Section 4.6.1**, it is apparent that management of the entrance for flood mitigation purposes has had a significant impact on lagoon hydraulics, with flow on effects for water quality, sediment transport and ecological processes. The let out (or breakout) levels in the entrance management policy are determined primarily by the desire to prevent inundation of surrounding property. Hence, development patterns and existing floor levels are the key determinants of entrance management practices. Development of low lying lands around the foreshores means that the adopted let out level for Terrigal Lagoon is quite low. Council is therefore required to break out the entrance on a regular (monthly) basis. This has likely resulted in significant modification of natural range of water levels, such that the variation in water levels is much more truncated than those observed for the other three lagoons. While current entrance management practices would also be having a similar effect on the hydraulics in the other lagoons, the magnitude of the impact is much greater for Terrigal.
- ***Rates of Berm Re-Building:*** It is noted that the entrance management policy includes specific processes for opening the lagoons aimed at minimising the depth

of scour and this would have implications for the rate of berm re-building. Under natural conditions the depth of scour and other entrance dimensions would show some degree of variability, such that the rate of berm re-building would also be variable. However, this range of variability would likely be truncated due to a tendency to more controlled breakouts under management intervention. The rate of berm re-building has implications for water quality and other estuarine processes, whereby quicker rates of berm re-building translate to shorter durations of open conditions and therefore less tidal exchange/flushing of the lagoon.

- ***Entrance Breakout Modelling:*** Modelling of the breakout process for a 100-years ARI flood, representing a very rare event, gives an indication of the possible maximum scour of the entrance channel that may occur. Should such a rare event occur, there would be a range of both direct and indirect impacts.
- ***Sediment Transport and Estuarine Ecology:*** One of the key mechanisms of sediment transport within the lagoons is the re-suspension of the fine benthic sediments due to bed shear stress. This naturally occurring process can result in a range of impacts including increases in turbidity, the re-introduction of nutrients (and any pollutants) into the water column, general sediment re-distribution and potentially smothering of benthic biota. The small size of the waterbodies means that the lagoons are fetch limited and therefore the areas in which sediment re-suspension would occur are likely to be limited. The impacts of scour during entrance breakout events would likely have a much more significant impact on lagoon ecology in those areas located near the entrance. This is also a naturally occurring process. Although the breakout frequency has likely increased under Council management, the lagoon ecosystems would have adjusted over time.
- ***Bank Stability and Shoreline Erosion:*** An assessment of the existing bank condition identified that the lagoon foreshores are relatively stable, with only isolated areas of erosion. The assessments of future erosion risk and shoreline recession indicate a potential for bank erosion to occur due to storm waves during very rare storm events. However, it is important to note that the level of risk will be highly dependent upon the bank condition in a specific location, with foreshore vegetation assisting in stabilising the shoreline and reducing the risk of erosion. This highlights the need for ongoing protection of foreshore vegetation and maintenance of any protection works. In the short term, shoreline erosion is more likely to occur in relation to human activities where, for example, people access the banks and/or waterways. Therefore, management of recreational usage of the lagoons is key ensuring the ongoing stability of the lagoon banks.
- ***Catchment Derived Sediments and Siltation:*** A total of around 1 million kg of sediments are being delivered to four lagoons from the catchment every year (**Section 3.9**). Whilst this is gradual infilling of the lagoons over geological time is a natural process, the rate is likely to be higher than would occur for an undeveloped catchment. Nonetheless, estimations of average annual siltation rates for the lagoons are quite low. However, it is noted that in fact this siltation will not be evenly distributed over the lagoon bed and will primarily be associated with delta formation around creek outlets. Some re-distribution of these sediments may then occur due to in-lagoon processes.
- ***Sediment Quality:*** Historic data suggests that the sediment quality of the lagoons has been impacted by activities in the catchment. This process is likely to be

ongoing as contaminants bound to catchment-derived sediments are delivered to the lagoons in stormwater runoff. Given that catchment land use is largely residential, heavy metals such as copper, lead and zinc are likely to be the types of contaminants that will continue to impact on estuarine sediment quality. However, it is noted that the intensity of land use in the catchment is relatively low with few industrial sites and therefore the total amount of sedimentary contamination is likely to be less than that observed for parts of the Brisbane Water Estuary (Cardno, 2008b).

- ***Acid Sulfate Soils:*** Both high and low risk ASS occur across large areas associated with the lagoons. The potential impacts on the lagoon water quality and ecology could be significant if exposure of these sediments occurs, therefore careful management of this risk will be required in the future.
- ***Catchment-based Controls:*** The ongoing implementation of catchment-based controls will be important in managing and mitigating the impacts of human activities in the catchment on sediment quality and siltation rates in the lagoons. This will likely require a range of measures including planning controls, compliance monitoring, community education and the implementation of WSUD features.

5 Water Quality Processes

5.1 Overview

Water quality is a very general term that is used loosely to describe concentrations of various constituents in a water body. Constituents are generally grouped into broad categories of variables to assist in simplifying discussion:

- Physico-chemical variables include temperature, dissolved oxygen, salinity, pH and turbidity;
- Nutrients include nitrogen in various forms, phosphorus in particulate and dissolved forms and silicate;
- Salt forming compounds including magnesium, sodium, potassium, calcium and chlorides;
- Microalgae populations measured as chlorophyll-a and algal cell counts;
- Heavy metals including iron, manganese, mercury, zinc and tin amongst others;
- Organic Compounds used in pesticides and herbicides; and
- Pathogens, viruses and thermotolerant coliforms.

Concentrations of these constituents within an ICOLL vary depending upon a range of physical and biogeochemical processes, and have important implications for higher life forms (or trophic levels), and for human recreation. Given the broad range of constituents and analytical costs associated with determining concentrations it is not surprising that only a few of these variables have previously been monitored in the Gosford lagoons.

Typically the key water quality variables in NSW coastal lagoons with rural and urban catchments include:

- Nutrients, as they can influence algal concentrations and cause potentially harmful blooms;
- Pathogens as they can have direct impact on human and ecological health;
- Physico-chemical variables, particularly salinity, that can influence mixing and geochemical processes, and has toxicity issues for various flora and fauna;
- Algal characteristics as they can indicate presence of harmful species, and
- Pesticides and herbicides that may influence ecosystem function.

ICOLL ecosystems are characterised by large changes in water quality due to the exposure to consistent freshwater inputs during extended periods of entrance closure and then, following entrance opening, periods of exposure to the marine inputs (as discussed in **Section 4.2**). Water quality in ICOLLS is typically controlled by the frequency and duration of the entrance opening and duration of the intervening periods of closure. The following discussion focuses on the water quality aspects during periods of closure and opening that are controlled by the balance between ocean wave driven beach accretion (berm re-building) and freshwater inflow erosion of the entrance berm. This balance and its influence on water quality are shown schematically in **Figures 5.1** and **5.2**.

There are variable timescales over which these water quality processes occur. When the entrances are closed, there is no tidal exchange and mixing of lagoon waters is determined by the wind energy inputs and atmosphere/water surface heating and cooling processes that control vertical water density stratification and mediate the metabolic rates of micro-organisms (**Figure 5.2**). During these periods the waters are generally fairly stagnant and a range of biogeochemical processes influence water quality, such as oxygen consumption and nutrient release from sediments that may lead to deteriorating water quality (refer to stage 4 on **Figure 5.2**). This gradual change in water quality occurs over long periods of time as the lagoon entrances can be closed for months at a time.

In contrast, rapid changes in water quality may occur during the breakout process due to the rapid outflow of water from the lagoon into the ocean. The rapid decrease in water levels increases water velocities, re-suspension of organic matter and other material from the lagoon beds that can stimulate biochemically mediated processes (e.g. algal die-off and decay). This is a short term process that generally occurs over a matter of hours (<24 hours). The nature of the shift in water quality is, however, dependent upon the water quality conditions immediately prior to the breakout event (e.g. was there a high biomass of macroalgae prior to breakout?).

Once the initial breakout has finished and the outflow of lagoon water has either ceased, or is controlled by the open entrance, a tidal exchange regime may occur until such time as the entrance berm re-builds (usually around two weeks). This process is illustrated in **Figure 5.1**. During this time there will be changes in lagoon water quality due to tidal flushing of the lagoons.

Water quality processes in the Gosford coastal lagoons are discussed below in terms of these three different phases: entrance closed conditions (**Section 5.2**), entrance breakout (**Section 5.3**) and entrance open conditions (**Section 5.4**). **Section 5.5** considers potential changes in water quality processes under the 2050 climate change scenario.

5.2 Entrance Closed Conditions

Overview of Available Data

Water quality sampling for various physico-chemical, nutrient, bacterial and algal water quality parameters is carried out by Council on a regular basis throughout the year. Data for the period 2006 to 2008 were provided by Council to assist with the analysis and interpretation of water quality processes.

It is understood that Council's water quality monitoring program is undertaken on a roughly 6 weekly basis throughout the year for compliance monitoring purposes. Samples may be taken in varying weather conditions and under different entrance conditions. The raw data set has been provided in **Appendix H**.

Water quality statistics have been calculated for each lagoon based on an analysis of the available data set. The statistics include the mean, median and 10th and 90th percentiles, with the summarised results presented in **Tables 5.3 to 5.6**.

The following sections describe the dynamics of the water quality variables within the lagoons and includes a comparison with the ANZECC (2000) guidelines for both the Protection of Aquatic Ecosystem Health and for Primary and Secondary Contact Recreation. These guidelines are presented in **Tables 5.1 and 5.2** respectively. The values provided in ANZECC (2000) have been converted to the same units as those in **Tables 5.3-5.6** for ease of comparison.

Table 5.1: Default Trigger Values for Physical and Chemical Stressors for South-East Australian Estuarine Ecosystems (after ANZECC, 2000)

Physical and Chemical Stressors	Trigger Values
Chlorophyll a	4 µg/L
Total Phosphorous (TP)	0.03 mg/L
Filterable Reactive Phosphorous (FRP) (Orthophosphate)	0.005 mg/L
Total Nitrogen (TN)	0.3 mg/L
Oxidised Nitrogen (NO_x)	0.015 mg/L
Ammonium (NH_4)	0.015 mg/L
Dissolved Oxygen (DO)	80% - 110% saturation (or >5mg/L)
pH	7.0 - 8.5
Turbidity	0.5 - 10 NTU

Table 5.2: Guidelines for Primary and Secondary Contact Recreation (after ANZECC, 2000)

	Primary Contact	Secondary Contact
Faecal Coliforms	150cfu/100mL	Median value of 1,000cfu/100mL
Enterococci	35cfu/100mL	Median value of 230cfu/100mL
Algal Species	Not to exceed 15,000-20,000 cells/L (dependent on algal species)	
pH	5-9	
Temperature	15-35℃	

The water quality sampling regime rarely captures the breakout event and open entrance conditions, and hence discussion of the available water quality data includes two components:

- Comparison with ANZECC guidelines (where relevant);
- Consideration of changes in water quality during entrance closed conditions.

Figure 5.3 shows a plot of lagoon water levels over the period corresponding to the available water quality data, identifying points corresponding to the beginning of lagoon breakouts (blue dots), end of the initial breakout and commencement of tidal exchange (red dots), and closure of the entrance and cessation of tidal exchange (red dots). The times at which water quality samples were collected are also indicated for each lagoon. Changes in entrance closed conditions have been assessed by comparing the available water quality data with days since entrance closure (refer to **Appendix H**).

Comments on Council's Monitoring Program

As noted in the discussion in **Sections 5.2.1-5.2.4**, it is difficult to develop an understanding of complex water quality processes based on an analysis of the existing data, noting that Council's water quality sampling program has been developed for compliance monitoring purposes rather than for describing water quality processes.

Compliance monitoring is important for managing risk to public health and safety. As identified in **Table 5.2**, the relevant water quality parameters for compliance monitoring are faecal coliforms, Enterococci, algal species, pH and temperature. Council may wish to consider limiting their program of compliance monitoring to these parameters (and any other parameters that may be measured on site using a water quality probe), and discontinuing those parameters (such as nutrients) that do not presently add significant value to the compliance monitoring program. This may result in a cost saving to Council.

Generally, the frequency of water quality sampling and parameters analysed do not correlate directly with key water quality processes as outlined in **Section 5.1**, hence the difficulty in analysing the data in to investigate these processes. Recommendations have been made where relevant as to additional sampling that might be conducted by Council in order to gain a greater appreciation of water quality processes that impact on aquatic ecosystem health.

5.2.1 Physico-Chemical Dynamics

Table 5.3 summarises the collected water quality data for physico-chemical parameters.

Comparison of observed turbidity values with the ANZECC (2000) guidelines shows that turbidity in Terrigal Lagoon tends to exceed the guideline value (5-10 NTU), but is generally within the guidelines for the other three lagoons.

Dissolved oxygen concentrations are measured in units of mg/L and hence difficult to compare with the ANZECC (2000) guidelines units in percent saturation. Generally the values appear to be above 5 mg DO/L in all lagoons – a value generally accepted as sufficient to support aquatic species such as fish.

Data on pH are within the ANZECC (2000) guidelines for aquatic ecosystem health for all lagoons except Cockrone Lagoon, which has values in excess of the upper limit of 8.5 regularly occurring (median pH=8.65, 90%ile pH=9.59). The cause of these elevated pH levels is unknown, but at these levels may be resulting in stress on aquatic organisms living in this lagoon.

Salinity values in the lagoons range from:

- ***Wamberal*** – range = 4-22 PSS, mean = 8.23 PSS;
- ***Terrigal*** – range = 8-22 PSS, mean = 15.43 PSS;
- ***Avoca*** – range = 8-33 PSS, mean = 18.79 PSS; and
- ***Cockrone*** – range = 11-36 PSS, mean = 20.94 PSS.

Cockrone and Avoca Lagoons appear to show the largest range and highest mean salinity values, noting that these salinity results are considered representative of a limited range of conditions in the lagoons. The exact location that salinity records are captured is unknown and also sampling is conducted on a regular basis irrespective of entrance conditions. In order to gain an understanding of the causes of variations in salinity in the lagoons it would be necessary to undertake higher frequency sampling. Vertical sampling may also be useful for understanding the effects of vertical stratification on water quality processes in the lagoon.

Salinity was found to consistently decrease with increasing time since closure for all four lagoons. This is due to the dilution of lagoon waters as a result of freshwater catchment inflows when the entrance is closed. Plots of salinity versus days since closure are presented in **Appendix H**.

5.2.2 Nutrient Dynamics

Nutrients, being species of nitrogen and phosphorus, are present in all lagoons in varying concentrations. **Table 5.4** summarises the water quality data for nutrient variables.

The lagoons all experience periods when nutrient concentrations are in exceedance of ANZECC (2000) aquatic ecosystem health guidelines, which suggests susceptibility to algal blooms. Concentrations of Ammonia, NO_x and TN generally exceed the guideline values for all four lagoons. Concentrations of TP are generally within the guideline values, indicating that phosphorous may be the limiting factor for algal growth.

In terms of changes in nutrient dynamics over time during the entrance closed conditions, no significant trends were observable across all four lagoons. For Terrigal Lagoon, nitrogen and phosphorus species generally tended to decrease in concentration with increased time since entrance closure. For Avoca and Cockrone lagoons, nutrients tended to increase in concentration with time, whilst nutrient parameters for Wamberal Lagoon tended to be variable.

Plots showing concentrations of nutrients against number of days since closure are presented in **Appendix H**.

The available data on nutrient concentrations is generally not sufficient to make particularly meaningful conclusions about water quality processes in the context of nutrient dynamics and algal bloom dynamics. Given that water quality issues tend to arise after the entrance has been closed for long periods of time (particularly when water levels are high) and immediately after breakout, it may be more useful to monitor nutrient concentrations focussing on these time periods in more detail. The sampling design should consider spatial and temporal variation in order to determine the number of samples to be collected.

5.2.3 Algal Dynamics

Algal blooms have been a significant issue for the study lagoons but the limited available water quality data on algae is not suitable for a quantitative assessment of this issue. Therefore, additional discussion has been provided on algal dynamics and modes of primary production.

Algal Dynamics and Modes of Primary Production

A number of microalgae and phytoplankton species occur in Gosford's coastal lagoons. The following taxa are known to occur (further discussion is provided in **Section 6.3.4**):

- Dinophyceae (Dinoflagellates);
- Bacillariophyceae (Diatoms);
- Chrysophyceae (Golden-Brown Algae); and
- Cyanophyta (Blue-Green Algae).

Phytoplankton and cyanobacteria are suspended in the water column and also grow on the surface of the lagoon bed as part of the microphytobenthos.

Despite its name, blue-green algae is classified as a bacteria (cyanobacteria) but has several commonalities with algae, such as requirements for light, carbon dioxide and nutrients. Blue-green algae can produce a range of cyanotoxins under certain conditions (Freewater and Gladstone, 2010) and cyanobacterial blooms may be triggered by high nutrient conditions, high sunlight/low turbidity and low circulation conditions. **Section 5.2.4** refers to bacterial pathogens that represent a health concern.

While visible blooms of planktonic species may occur, algal blooms have been discussed in this report with reference to macroalgal species. Two main species of macroalgae can be found in the lagoons, namely *Enteromorpha intestinalis* and *Cheatomorpha linum* (Freewater and Gladstone, 2010). Avoca and Cockrone Lagoons tend to support larger areas of macroalgae than either Wamberal or Terrigal Lagoons and are subject to spring outbreaks of these filamentous algae species that can have a range of impacts on ecological processes and lagoon amenity.

It is thought that there are shifts in modes of primary production during the period of entrance closure, whereby primary production is initially dominated by phytoplankton and benthic microalgae. During entrance closed conditions, water levels tend to gradually rise, inundating mudflats in the upper reaches of the lagoon and making available a greater surface area of the lagoon for both phytoplankton and benthic algae, which gradually increase in biomass. At some point water levels will increase to such a point that light penetration to the bed decreases to a level below which primary production by benthic algae decreases or ceases. In addition, as the water levels and nutrient concentrations continue to rise during entrance closed conditions, macroalgal species increase in biomass, floating on the surface and shading the water column, which leads to a further reduction in the biomass of microalgal species in the water column and on the lagoon bed. While sufficient nutrients are available to support algal growth natural mortality and decay of the macroalgae by oxygen consuming benthic detritivores leads to the accumulation of decaying organic matter on the lagoon bed that in turn leads to a decrease in DO concentrations in the overlying water column. These blooms may persist as long as there are sufficient nutrient loads available but will generally decline once the available nutrients have been consumed. Blooms of macroalgae occur in both Avoca and Cockrone Lagoons. The persistence of these blooms suggests nutrient loads in the water column and the sediments are sufficient for their existence.

The complex biogeochemical processes that influence the nutrient cycling within the lagoons are not well documented. An understanding of these processes would assist in understanding the extent to which the sediments act as a store of nutrients and contribute to algal bloom issues. Schematic diagrams of the key components of the nitrogen and phosphorus cycling processes in an estuary are coastal lagoon have been summarised by the Queensland EPA and are represented here in **Figures 5.4 and 5.5**.

As indicated in **Section 5.1**, it is thought that the water quality issues observed after an entrance breakout are dependent on the antecedent conditions prior to the breakout. In the case of Avoca and Cockrone Lagoons, it is thought that the persistence of elevated water levels for extended periods of time (e.g. 2-3 months) prior to a breakout event contribute significantly to increases in algal biomass and the water quality issues (e.g. fish kills and odours) that subsequently result. Council may wish to consider management of lagoon water levels for water quality purposes with a view to minimising the incidence of these water quality issues.

For example in Avoca Lagoon the large mudflat areas in the arms of the lagoon begin to be inundated at water levels of around 0.7m AHD (see hypsographic curve in **Figure 4.2**), thereby providing additional areas with high light conditions that can be colonised by the macroalgae. At water levels of around 1.1m AHD, there is likely sufficient shading of the bed such that the macroalgal growth begins to be limited by light in deeper areas. Where water levels persist for long periods of time above 1.1m AHD, the algal biomass is likely to increase. It is suggested that a trigger level to open the lagoon for water quality purposes could be developed that incorporates persistence of water levels in excess of 1.1m AHD for over 2 months and the biomass of algal mats. Opening the lagoon at a lower level could reduce the loads of macroalgae and organic matter before they reach the elevated levels that can lead to subsequent issues such as fish kills and odours after a break out event.

Analysis of Water Quality Data

Table 5.4 summarises the water quality data for algal parameters. In the context of the ANZECC (2000) guidelines for aquatic ecosystem health, there are some exceedences observed. The 90th percentile concentration of chlorophyll has exceeded the guideline values in all four lagoons, but the median and mean are within the guidelines.

Freewater and Gladstone (2010) state that chlorophyll-a concentrations are highly variable from year to year, and concentrations of chlorophyll-a show a marked seasonal trend in Avoca and Cockrone Lagoons, with maximums generally in spring and summer. This statement generally aligns with the analysed water quality data, although seasonal variability, particularly in Cockrone, is not all that evident.

Chlorophyll-a concentrations generally increased over time during entrance closed conditions for both Avoca and Wamberal lagoons. A decrease was noted in Terrigal Lagoon, whilst Cockrone remained fairly constant. The analysed chlorophyll-a concentrations generally relate to microalgae only, however the presence of macro-algae may affect the results.

In terms of the ANZECC (2000) guidelines for recreational usage, concentrations of blue-green algae can on occasion exceed the guideline values and at these times there may be a risk to public health and safety depending on the particular species present. As discussed in ANZECC (2000), toxicity is not necessarily directly related to cell count for blue-green algae and caution should be exercised in relation to problem species even when present at lower cell counts.

5.2.4 Bacterial Dynamics

Table 5.6 summarises the water quality data for bacterial parameters. A comparison of the observed water quality data with the ANZECC (2000) guideline values for recreational usage should be undertaken with reference to primary and secondary contact where bacteria are concerned because they may represent a threat to human health. The analysis shows that faecal streptococcal counts have on occasion exceeded the guideline values. This is likely in relation to stormwater inflows from the catchment or sewer overflows. Animal faeces can represent a source of faecal coliforms and may influence the sampling results.

Similarly, Enterococci counts have also recorded some exceedences. It is noted that Enterococci have a higher tolerance to saline waters than faecal coliforms and would therefore be a more reliable risk indicator at those times when lagoon waters are brackish or when the entrance is open.

In terms of changes in bacterial parameters during entrance closed conditions, no trends over time were found for any of the four lagoons. Faecal streptococcal concentrations were generally found to be variable over time during the closed phase. This is not surprising given the complex processes that can mediate the persistence of bacteria, including predation and competition, and mortality due to exposure to UV light. Plots according to time since last entrance breakout are presented in **Appendix H**.

Table 5.3: Physico-Chemical Analysis

Physico-Chemical Parameters		Wamberal						Terrigal					
Parameter	**Units**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**
Depth	m	6	0	0.10	0.10	0.10	0.10	7	0	0.10	0.10	0.10	0.10
Tide Mark	m	6	0	1.88	2.15	2.50	0.98	0	0	NS	NS	NS	NS
Temperature	℃	6	0	21.02	19.75	27.40	15.90	12	0	19.47	19.15	24.81	13.60
Conductivity	mS/cm	6	0	14.05	9.46	24.30	8.39	12	0	25.40	24.95	35.01	17.82
Salinity	PSS	6	0	8.23	5.25	14.80	4.65	12	0	15.43	15.00	21.94	10.47
Turbidity	NTU	24	0	11.33	7.65	30.06	0.79	30	0	12.69	10.60	23.47	2.98
pH	-	6	0	7.95	8.00	8.25	7.60	12	0	7.82	7.75	8.19	7.51
Dissolved Oxygen	mg/L	24	0	7.23	7.15	8.84	5.44	30	0	6.98	6.85	9.54	4.80
BOD (5-Day)	mg/L	6	6	1.00	1.00	1.00	1.00	12	12	1.00	1.00	1.00	1.00
Suspended Solids (Total @105℃)	mg/L	6	0	6.83	4.50	13.50	2.50	12	0	12.64	11.55	21.09	8.00

		Avoca						Cockrone					
Parameter	**Units**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**
Depth	m	7	0	0.10	0.10	0.10	0.10	7	0	0.10	0.10	0.10	0.10
Tide Mark	m	0	0	NS	NS	NS	NS	7	0	1.31	1.70	1.84	0.64
Temperature	℃	12	0	19.63	20.25	24.20	12.84	12	0	19.40	19.45	23.97	13.44
Conductivity	mS/cm	12	0	30.32	25.80	49.54	15.49	12	0	33.45	28.40	49.53	21.65
Salinity	PSS	12	0	18.79	15.70	31.79	8.96	12	0	20.94	17.35	31.87	12.94
Turbidity	NTU	30	0	7.24	3.90	19.00	0.99	30	0	8.72	2.40	30.32	0.09
pH	-	12	0	8.03	8.00	8.30	7.80	12	0	8.68	8.65	9.59	7.72
Dissolved Oxygen	mg/L	30	0	6.90	6.80	8.71	4.69	30	0	7.48	7.95	9.32	5.18
BOD (5-Day)	mg/L	12	12	1.00	1.00	1.00	1.00	12	11	1.25	1.00	1.00	1.00
Suspended Solids (Total @105℃)	mg/L	12	0	5.33	4.00	7.80	2.00	12	0	5.00	4.00	8.80	2.00

INSUFF >50% of samples for the parameter were non-detect samples
NS No samples were taken for the parameter (parameter left in for completeness)

Table 5.4: Nutrient Analysis

Nutrient Parameters		Wamberal						Terrigal					
Parameter	**Units**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**
Ammonia Nitrogen as N	mg/L	24	5	0.07	0.04	0.18	0.01	30	4	0.04	0.04	0.08	0.01
NOx	mg/L	24	8	0.03	0.01	0.05	0.01	30	5	0.05	0.03	0.07	0.01
Ortho-Phosphate (as P)	mg/L	24	20	INSUFF	INSUFF	INSUFF	INSUFF	30	16	INSUFF	INSUFF	INSUFF	INSUFF
Total Nitrogen as N (TKN + NOx)	mg/L	24	0	0.68	0.60	1.10	0.50	30	6	0.35	0.35	0.61	0.05
Total Phosphorus	mg/L	24	9	0.02	0.02	0.05	0.01	30	11	0.03	0.03	0.04	0.01
Total Kjeldahl Nitrogen	mg/L	6	0	0.72	0.65	1.00	0.50	12	0	0.33	0.35	0.49	0.11

		Avoca						Cockrone					
Parameter	**Units**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**	**Number of Samples**	**Number of Non-Detect Samples**	**Mean**	**Median**	**90th Percentile**	**10th Percentile**
Ammonia Nitrogen as N	mg/L	30	0	0.15	0.09	0.34	0.04	30	4	0.21	0.03	0.71	0.01
NOx	mg/L	30	9	0.37	0.03	0.10	0.01	30	13	0.03	0.01	0.07	0.01
Ortho-Phosphate (as P)	mg/L	30	24	INSUFF	INSUFF	INSUFF	INSUFF	30	27	INSUFF	INSUFF	INSUFF	INSUFF
Total Nitrogen as N (TKN + NOx)	mg/L	30	0	0.67	0.60	1.20	0.20	30	0	0.80	0.70	1.21	0.30
Total Phosphorus	mg/L	30	11	0.03	0.02	0.06	0.01	30	15	INSUFF	INSUFF	INSUFF	INSUFF
Total Kjeldahl Nitrogen	mg/L	12	1	0.48	0.45	0.80	0.11	12	0	0.57	0.55	0.88	0.30

INSUFF — >50% of samples for the parameter were non-detect samples
NS — No samples were taken for the parameter (parameter left in for completeness)

Table 5.5: Algal Analysis

Algal Parameters

		Wamberal						Terrigal					
Parameter	Units	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile
Chlorophyll a	µg/L	24	5	2.63	2.00	7.00	0.50	30	11	2.52	1.00	4.10	0.50
Total Blue Green Algae	cells/mL	0	0	NS	NS	NS	NS	6	0	23316.67	40.00	69910.00	0.00

		Avoca						Cockrone					
Parameter	Units	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile
Chlorophyll a	µg/L	30	8	3.97	1.50	9.70	0.50	30	18	INSUFF	INSUFF	INSUFF	INSUFF
Total Blue Green Algae	cells/mL	0	0	NS	NS	NS	NS	6	0	180.00	80.00	460.00	0.00

INSUFF >50% of samples for the parameter were non-detect samples
NS No samples were taken for the parameter (parameter left in for completeness)

Table 5.6: Bacterial Analysis

Bacterial Parameters

		Wamberal						Terrigal					
Parameter	Units	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile
Faecal Streptococci	CFU/100mL	6	1	218.17	68.00	579.50	7.00	6	1	75.17	60.50	149.00	16.00
Thermotolerant Coliforms	CFU/100mL	0	0	NS	NS	NS	NS	6	1	18.33	9.00	42.00	4.00
Enterococci	CFU/100mL	0	0	NS	NS	NS	NS	6	2	26.50	11.50	67.00	1.00

		Avoca						Cockrone					
Parameter	Units	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile	Number of Samples	Number of Non-Detect Samples	Mean	Median	90th Percentile	10th Percentile
Faecal Streptococci	CFU/100mL	6	3	17.67	7.00	41.00	5.00	6	2	82.83	58.50	185.00	5.00
Thermotolerant Coliforms	CFU/100mL	6	3	8.00	5.00	17.50	1.50	6	4	3.17	1.50	7.00	1.00
Enterococci	CFU/100mL	6	0	42.33	30.50	89.50	7.00	6	0	62.83	50.00	132.00	6.50

INSUFF >50% of samples for the parameter were non-detect samples
NS No samples were taken for the parameter (parameter left in for completeness)

5.2.5 Mixing Processes

As previously discussed, during periods when the entrance is closed, the water quality of a lagoon is influenced by catchment inflows, evaporative and groundwater losses, accumulation (settling) and recycling processes in the sediments, as well as primary production. Modelling investigations have been undertaken to describe the fate of pollutants introduced to the lagoons from the catchment tributary inflows (Cardno, 2010; **Appendix F**). Discharge, sediment and nutrient loads hydrographs were developed from the catchment modelling described in **Section 3.9**.

Diffusion and Dispersal of Catchment Inflows

The transport and dispersion of catchment-derived nutrient loads was investigated using the Delft3D models established for each of the lagoons. The models were operated in the 3-dimensional (3D) mode using five equal thickness water column layers to facilitate resolution of stratification effects. The buoyancy of creek flows was included by specifying the fresh water (0 ppt salinity) inflows into brackish/saline lagoon waters. The lagoon waters were simulated for a dry period when the observed salinities are typically around 32 ppt prior to rainfall events.

The modelling was divided into a series of climatically variable (wet, average or dry) years, and hence the temporal variation in pollutant loads and freshwater plume transport, were described for these conditions. Initial and model boundary concentrations for TN and TP were derived from data held in Council's water quality database discussed in (**Section 5.2**). The nutrient data (surface water samples) at each available sampling point within the lagoons were assumed to represent the concentration over the total depth (i.e. no vertical stratification). Spatial interpolation of the typically 5 data samples was then applied to form initial distributions of TN and TP to specify the initial nutrient concentrations over the model domain.

The average duration of entrance closure under the three different climatic conditions (i.e. rainfall scenarios) was calculated for each lagoon and used as model simulation period (i.e. no entrance opening during the simulation). Using Wamberal Lagoon as an example, the average duration of entrance closure during wet years was estimated at 79 days (**Table 4.2**). Therefore, a representative 79-day period leading up to an entrance breakout during a wet year was chosen for simulation. MUSIC catchment model time-series outputs were then applied at the tributary inflow locations in the Delft3D lagoon models. This provided a typical seasonal case for each lagoon under closed entrance conditions.

As discussed in **Section 4.1**, following an entrance breakout event, a period of diminishing tidal exchange ensues until the berm re-builds, cutting off the tidal connection to the ocean. During this period of tidal exchange mixing of nutrient-poor ocean waters and the lagoons waters leads to a decrease in lagoonal nutrient concentrations to levels similar to the offshore ocean concentrations. The effectiveness of this process depends on the duration of the entrance opening and hence the total volume of seawater introduced by tidal exchange. The nutrient concentrations likely to occur under these conditions, as represented by the average of the lower 10^{th} percentile nutrient concentration for each lagoon, were applied as an initial concentration within the lagoon.

By contrast, the introduction of high salinity ocean water increases the lagoon salinities as long as tidal flushing continues, and hence an initial value of 30ppt under entrance closed conditions was applied to the model in line with typical observations following cessation of tidal exchange.

Further details regarding the modelling methodology are provided in Cardno (2010; **Appendix F**).

Findings

The results of these simulations have been presented in Cardno (2010) as time series plots for each lagoon showing TN and TP concentrations. They provide a basis for describing the likely ambient concentrations of those contaminants for different annual rainfall scenarios and seasonal conditions when the entrance remains closed.

Rainfall runoff events induce sharp rises in the lagoon water levels and corresponding decreases in salinity due to the diluting effect of the freshwater inflow. By contrast the simulations show nutrient concentrations increase sharply following rainfall events then gradually decrease due to mixing and dispersion. As would be expected, there is a general accumulation of nutrients within the lagoon and concentrations can reach up to 4 to 5 times the initial concentration just prior to lagoon opening. Although there are relatively large increases in nutrient concentrations, these values fall within observed ranges of measured water quality parameters. It is noted that the model only simulates the physical dispersion of nutrients and does not include the more complex biogeochemical cycling processes that also influence the nutrient concentrations.

The model results indicate some spatial variability with nutrient concentrations in the upper reaches of the lagoons (i.e. closer to the tributary outlets) tending to spike during rainfall events prior to being dispersed and mixing across the entire lagoon (Cardno, 2010; **Appendix F**). The model outputs also indicated rapid mixing, and while vertical stratification occurs, it did not persist for any prolonged period presumably because of the shallow nature of the lagoons. It is noted, however that the model did not include the atmospheric heat fluxes that could lead to thermal stratification (although no physico-chemical data was available to assess whether stratification is an issue).

Generally speaking, the results for the average rainfall year had the highest nutrient concentrations. This may be a result of the volume of catchment inflows whereby, for example, during a wet year the nutrient loads entering the lagoon are reduced due to the nature of rainfall/run-off patterns. That is, the nutrient load from a catchment can be somewhat exhausted following a series of high flow events.

Table 5.7 provides a summary of the water quality outcomes, just prior to breakout, for the four estuaries over an average period of entrance closure. As previously discussed, the average duration of entrance closed conditions is different for each lagoon and for each rainfall scenario, and has been calculated based on analysis of the lagoon log book.

Table 5.7: Modelled Water Quality Parameters - Concentrations at Conclusion of the Simulation

Lagoon	Dry Year			Wet Year			Average Year		
	TN (mg/L)	TP (mg/L)	Sal. (ppt)	TN (mg/L)	TP (mg/L)	Sal. (ppt)	TN (mg/L)	TP (mg/L)	Sal. (ppt)
Wamberal	1.63	0.22	11.1	1.83	0.25	8.5	1.06	0.12	8.2
Terrigal	0.68	0.03	28.6	1.17	0.12	20.9	1.13	0.11	21.3
Avoca	1.32	0.17	11.4	0.95	0.11	15.0	0.76	0.09	15.1
Cockrone	1.12	0.13	8.3	1.09	0.12	5.0	1.01	0.10	6.2

Comparisons between the modelled water quality parameters and the historical data shows that the MUSIC model nutrient loads provide a reasonable representation of the observed variability. Therefore, the model system could be used to assess potential changes to these loads that might arise from any changes in land use (e.g. proposed developments) in the catchment.

5.3 Entrance Breakout

As discussed in **Section 5.1**, rapid changes in water quality can occur during a breakout event and with the subsequent initiation of tidal exchange with the ocean.

There is no data available tracking the changes in water quality parameters that occurs during a breakout event, but these are likely to include:

- Increases in salinity,
- Changes in water temperature,
- Changes in pH,
- Temporary increases in turbidity (due to scour), and
- Decreases in nutrient concentrations.

In addition, water levels rapidly decrease and portions of the lagoon bed may become mobilised (particularly towards the entrance) and scour out of the lagoon. These rapid changes in water quality will have flow on effects on lagoon biota and water quality issues can arise at these times.

The macroalgae *E. instestinalis* and *C lignum* have relatively low salinity tolerances, and where these macroalgal species are present in the lagoon at the time of the breakout, they will suffer die-back due to both the increase in salinity and drop in water levels when the lagoon volumes typically decrease by 50%. At the same, any fine organic matter that has accumulated on the bottom during the period of closure is particularly susceptible to re-suspension (due to its low specific gravity), thereby increasing turbidity and increasing concentrations of dissolved nutrients in the water column. These turbid, nutrient rich waters then become ‘concentrated’ in deeper parts of the lagoons as the lagoon volume diminishes.

Fish kills have been observed in Cockrone Lagoon on several occasions, and one such incident was captured in a photolog (**Appendix A**). While these fish kills can be a natural occurrence (**Section 6.4.4**), it is thought that eutrophication and the high macroalgal biomass in the lagoons is a contributing factor to this issue. Wilson and Evans (2002a and b) and Gale (2007) report fish kills occurring after some period after an entrance opening event. While there is no data of sufficient resolution prior to, during and following the event to identify the exact mechanism, resulting rapid dissolved oxygen depletion is provided as a plausible explanation of the phenomenon. This rapid decrease in oxygen levels is likely due to the increase in Biochemical Oxygen Demand associated with the re-suspension of organic matter and decay of the macroalgae that drains to the deeper lagoon areas during breakout.

5.4 Entrance Open Conditions – Tidal Flushing

5.4.1 Berm Recovery and Closure

After the breakout period ends, the berm remains open to the sea and tidal exchange with the ocean occurs. As discussed in **Section 4.2**, the entrance berm gradually re-builds over a period of typically 1-2 weeks. The process of re-building the berm serves to increasingly attenuate the lower end of the tidal prism. In addition to tidal inflows and outflows, during the time the entrance is open there may also be some additional outflow of lagoon waters in the event that there is ongoing rainfall in the catchment (as illustrated in **Figure 5.1**). At these times, the introduction of any additional nutrients via catchment inflows or in-lagoon processes is mediated by these tidal processes and nutrients tend to decrease in concentration and salinity increase.

5.4.2 Tidal Flushing

The concept of estuarine flushing refers to the rate at which water is exchanged between the lagoon and the Tasman Sea due to the ebbing and flooding tidal flows (i.e. under entrance open conditions). Quantitative investigations into flushing can be used to describe the likely character of water quality responses of an estuarine system although the concept is less applicable to ICOLLs with prolonged periods of entrance closure. For example, flushing rates can be used to assess the time it takes for a particular pollutant to disperse in different sections of a lagoon. By considering flushing times, nutrient loads and biological response rates for a particular lagoon, an assessment of the possible water quality outcomes can then be investigated.

The flushing of ICOLLs occurs following an entrance breakout event, after which the lagoon becomes tidal for a period of days to weeks. During this period the lagoon is connected to the ocean via a narrow, shallow channel. Hence, attenuation of the tide occurs as it propagates into the lagoon, mainly due to frictional energy losses through the entrance channel (as discussed in **Section 5.4.1**). As the berm re-establishes tidal exchange diminishes resulting in reduced water exchange and flushing times with flow-on effects on lagoon water quality. The condition of the open entrance is therefore critical to the estimation of tidal flushing.

Simulations using the Delft3D models were undertaken for each lagoon with an initial uniform tracer concentration of 100 dispersed over the entire lagoon waterbody (Cardno, 2010; **Appendix F**). The initial tracer concentration in the ocean offshore the entrance was set to zero. The initial entrance bathymetry condition was extracted from the 100 year-ARI entrance breakout simulations and fixed for the run duration (discussed in **Section 4.5.2**). Water level boundaries were prescribed for the ocean boundary based on regional tidal constants. The model simulations were undertaken for up to two consecutive spring-neap tidal cycles (28-days). No catchment flows were supplied to the models; that is, the tidal flushing times determined by these analyses represented maximum flushing rates because catchment inflows reduce flushing times by causing a net transport through (i.e. out of) the lagoon.

The results of the flushing simulations are illustrated in **Figures 5.6 to 5.9**. **Table 5.8** summarises the e-folding (flushing) times derived from the models for each lagoon and the average duration of opening based on previous analyses of the entrance condition data by WMA (1995) and Gale *et al.* (2007). Average durations of tidal exchange (for entrance open) derived from an analysis of available water level data are provided in the final column of **Table 5.8**.

Table 5.8: Estimated Flushing Times

Lagoon	Model Results		Avg. Duration of Tidal Exchange (days)	
	Avg. e-Fold Time (days)	Max. e-Fold Time (days)	After WMA (1995) & Gale *et al.* (2007)	Historic Water Level Data (Cardno)
Wamberal	4.4	29.9	10	11
Terrigal	2.4	4.5	8	7
Avoca	7.4	35.1	21	12
Cockrone	7.4	40.2	9	9

The data provided in **Table 5.8** indicate that, since the average e-folding time is less than the average duration of opening for all four lagoons, the majority of the lagoon waterbody would undergo complete tidal exchange during a single (average) entrance opening. The flushing time calculated for Wamberal Lagoon concurs with an estimate of 4 days presented in Gale *et al.* (2007), comparing favourably with the average e-folding calculated from modelling (4.4 days). Terrigal Lagoon exhibits the most efficient tidal flushing and would most likely undergo complete tidal exchange during a single entrance opening. This is due to its smaller storage capacity compared to the other estuaries (WMA, 1995). The rapid flushing is confirmed by the increase in salinity from the pre-open values to around the ocean values several days after the entrance opening. For the other lagoons, complete tidal exchange of the lagoon waterbody would only happen when the entrance stays open for prolonged periods of time (i.e. in the order of 30-40 days). This is most likely to occur for Avoca Lagoon, for which the average duration of entrance open conditions is higher (12 days).

It is noted that the modelled flushing times are likely to overestimate actual flushing times for an ‘average’ breakout event. The models have assumed the extreme condition of largest conveyance of entrance channel following breakout of a large inflow event. For smaller events the degree of entrance scour during the breakout process is likely to be smaller than for this high-flow event and hence the berm recovery and duration of entrance opening will be shorter. Under smaller inflow event breakouts it is likely that the tidal exchange will only partially replace the lagoon waters prior to the entrance closure. In addition, an open entrance was maintained for the full simulation period and the channel conveyance reduction due to berm re-building was neglected.

5.5 Climate Change and Water Quality Processes

Tidal flushing in terms of e-folding times was assessed under sea level rise conditions within the four lagoons using the same methodology as for the existing scenario. The model offshore water level boundary was increased by 0.4m to simulate predicted sea level rise to 2050. Model simulations were undertaken for up to two consecutive spring-neap tidal cycles (28-days). As for the existing conditions, no catchment flows were supplied to the models; meaning that the resulting e-folding times are conservative as they omit any freshwater flows through the estuary. The results of these flushing simulations are presented in **Figures 5.6-5.9** and summarised in **Table 5.9**.

Table 5.9: Estimated Flushing Times under Sea Level Rise Conditions

Estuary	Average e-Fold Time (days)	Maximum e-Fold Time (days)
Wamberal	2.5	31.1
Terrigal	1.3	2.7
Avoca	1.5	2.9
Cockrone	2.6	32.1

Comparing the e-folding times for the current conditions (**Table 5.8**) with the projected 2050 SLR results (**Table 5.9**) indicates each lagoon experiences a reduced e-folding time under sea level rise conditions, that is, an increase in tidal flushing. This is the result of the increase in mean sea level and, therefore, an increase in the tidal prism within the lagoons during open entrance conditions. As mean sea levels rise, a greater volume of water is transported in and out of the lagoon by the tides enhancing tidal flushing.

Wamberal lagoon experienced a significant reduction in e-fold time under the sea level rise scenario. The existing high tide extent does not extend far into the lagoon, however under climate change conditions the high tide extent covers the majority of the lagoon area, reducing flushing times. The most northerly extents of the lagoon experience an e-folding time of approximately one month under both existing and SLR scenarios.

Due to its low lying nature, Terrigal lagoon experiences the shortest e-folding times. The e-folding times generally seem to be reduced by a day or two by sea level rise with the average 2050 e-folding time just 1.3 days (down from 2.5 in 2010).

Avoca lagoon experienced the most significant reduction in e-folding time as a result of sea level rise, with the average e-folding time reduced by 80%. While the areas in the centre of the lagoon did not differ much, the northern, western and southern arms of the lagoon showed greatly reduced e-folding times. In these places, e-folding times of up to a month in 2010 were reduced to just over 2 days in 2050. This can be explained by the bathymetry of the lagoon, as the outer extents of the lagoon sit at a higher elevation and are thus most impacted by increased tidal inundation.

Cockrone lagoon experienced a significant increase in the high tide extent under the 0.4m sea level rise scenario. As a result the average e-folding time was reduced to around one-third of the value observed under existing conditions, with the greatest reduction occurring in the northern and western extents. Despite this, areas of the lagoon in the far north western area (near the creek entrance) remained high, with e-fold times of around four weeks observed.

These outcomes suggest that a greater amount of flushing will occur during periods of open entrance conditions under future climate change.

5.6 Summary of Key Processes and Management Implications

The key findings of the assessment are:

- ***Day to Day Water Quality:*** Based on an assessment of the available water quality data, the water quality in the lagoons is generally quite good. Exceedences of the relevant ANZECC (2000) guidelines for recreational usage and aquatic ecosystem health seldom occur and typically occur in relation to nutrients. Nutrient loads from the catchment might have increased over background levels due changes in land use patterns over time. However, on the other hand, the entrance management practices are likely to have resulted in a higher frequency of entrance breakouts and therefore a higher net rate of flushing. When the entrance is open, the water quality condition would be expected to fall within the guideline values.
- ***Short-Term Water Quality Issues:*** In general, the day to day water quality of the lagoons probably closely resembles its natural condition. However, there are periods when sharp deteriorations in water quality can occur. Very rapid changes in water level will naturally lead to odour issues and potentially short-lived period of poor water quality. These rapid changes in water level occur during entrance breakout events.
- ***Algal Blooms:*** it is thought that the water quality issues observed after an entrance breakout are dependent on the antecedent conditions prior to the breakout. In the case of Avoca and Cockrone Lagoons, it is thought that the persistence of elevated water levels for extended periods of time (e.g. 2-3 months) prior to a breakout event contribute significantly to increases in algal biomass and the water quality issues (e.g. fish kills and odours) that subsequently result following breakout. Council may wish to consider management of lagoon water levels and algal build up with a view to minimising the incidence of these water quality issues following breakout.
- ***Tidal Flushing and Climate Change:*** The average e-folding time is less than the average duration of opening for all four lagoons, suggesting the majority of the lagoon volume would undergo complete tidal exchange during a single (average) entrance opening. Terrigal Lagoon exhibits the most efficient tidal flushing (shortest e-folding times) and would most likely undergo complete tidal exchange during a single entrance opening. For the other lagoons, complete tidal exchange of the lagoon waterbody would only happen when the entrance stays open for prolonged periods of time (i.e. in the order of 30-40 days). Comparing the e-folding times for the current conditions (**Table 5.8**) with the projected 2050 SLR results (**Table 5.9**) indicates each lagoon experiences a reduced e-folding time under sea level rise conditions, that is, an increase in tidal flushing. This likely results from an increase in the tidal prism within the lagoons during open entrance conditions under the 2050 scenario.

6 Ecological Processes

6.1 Overview

The lagoons represent an interface between a range of different environments: marine and freshwater, terrestrial and aquatic. Within these broad categories are a number of different habitats ranging from terrestrial habitats, to intertidal habitats and aquatic habitats. Although the study area has been extensively modified by urban development of the catchment, the four ICOLLs that are the subject of this study remain areas of considerable biodiversity.

A number of ecological studies were undertaken by the University of Newcastle as part of this study (see Freewater and Gladstone, 2010; **Appendix D**). This section provides details of the ecology of the lagoons and includes a synopsis of these studies.

6.2 Overview of ICOLL Ecology

A considerable amount of literature exists on the ecology and hydrology of ICOLLs in NSW. However, there have been few studies that consider the relationship between the frequency of lagoon opening and the lagoon ecology. It is reasonable to assume that the range of physical processes driving estuarine ecology will differ when comparing estuaries that are closed most of the time, with estuaries that are predominantly open. A number of studies have shown that estuaries that remain isolated from the sea for protracted periods experience large fluctuations in physio-chemical conditions (e.g. Millet and Guelorget, 1994).

While some estuarine species may be adapted to a wide range of physical variables, others are not, and rapid changes in estuarine assemblages may occur in response to an entrance breakout event. The smallest of the multicellular invertebrates are the meiofauna (sized between 50 µm and 500 µm), which are represented by almost all invertebrate phyla and are present in large abundances. Together with the macrobenthos (>500 µm in size), meiofauna perform a range of important ecological functions (Coull, 1999), including:

- Mineralisation of organic matter and nutrient cycling,
- Bioturbation of benthic sediments,
- Stimulation of bacterial production, and
- Acting as a food source for organisms at higher trophic levels.

Freewater and Gladstone (2010) include a review of the literature in relation to the use of benthic macroinvertebrate communities as indicators of ecological health or environmental change.

It has been demonstrated that the abundance and diversity of meiofauna are lower under highly variable conditions, such as those found in ICOLLs (Dye and Barros, 2005a). Others have demonstrated that macrofauna are also impacted by disturbance events similar to those that occur in relation to an entrance breakout event (e.g. Dernie *et al.,* 2003).

However, it is important to emphasise that, despite their importance in estuarine food webs, nutrient cycling and so on, changes in the structure of macroinvertebrate and meiofaunal assemblages do not necessarily translate into changes in ecological function at the system level – unless their abundances are significantly reduced (McArthur *et al*., 2000). As a result, significant, detectable impacts on assemblages of higher trophic groups such as fish and crustaceans are unlikely. It is considered much more likely that direct impacts on the physical and water quality processes in the lagoons will be the key drivers of change with respect to higher estuarine fauna.

One such direct impact is the physical isolation of ICOLLs, where an open connection to the sea is erratic. This can have significant implications for recruitment, with recruitment depending upon the appropriate timing and duration of opening. An open connection with the sea facilitates the exchange of propagules, larvae and adult fauna (and flora in the case of mangrove and saltmarsh propagules) between estuaries and the sea. If a lagoon breaks open at a time coincident with the presence of larval or juvenile fish or prawns, significant recruitment events can occur, and this has been observed on a number of locations for Avoca Lagoon (M. Kilp – T. Mackenzie, Cardno, pers. comm). This exchange supports lagoon biodiversity by maintaining populations of species, some of which may be marine-dependent for some portion of their life cycle (Millet and Guelorget, 1994). In addition, this process of exchange between estuaries facilitates the recovery or recolonisation of any communities or species that may have been subject to local impacts. In systems such as these, biodiversity is low as only a limited number of highly adapted species are able to tolerate such fluctuations in environmental conditions (Teske and Wooldridge, 2001; Dye and Barros, 2005a and b). This concept of isolation from the sea will be one of the key factors in structuring aquatic ecology as a direct result of activities such as entrance management.

6.3 Flora

6.3.1 Fringing Wetlands and Riparian Habitats

This section provides discussion on those vegetation communities that may be found on the land or in the intertidal zone, but that are more tightly linked with estuarine processes. Discussion on terrestrial vegetation communities located in the catchment is provided in relation to catchment processes in **Section 3.5**, which includes consideration of endangered ecological communities and changes in catchment vegetation over time.

The University of Newcastle (**Appendix D**) undertook vegetation surveys of the vegetation communities located around the lagoon foreshores. Several types of fringing wetlands have been identified as occurring around the lagoons:

- Alluvial Paperbark Sedge Forest,
- Coastal Sand Swamp Forest,
- Estuarine Paperbark Scrub Forest,
- Estuarine Swamp Oak Forest,
- Swamp Mahogany – Paperbark Forest,
- *Phragmites* Rushland, and
- *Baumea* Sedgeland.

Wetlands play important roles in providing breeding areas for fish and habitat for migratory birds and other waders and for trapping nutrients that would otherwise flow into the lagoons. All wetlands in NSW are considered endangered habitats. Notwithstanding this, the extensive areas of wetland that exist in the Gosford lagoons (except Terrigal) are considered to be in excellent condition.

Riparian vegetation, while not strictly estuarine, is important for stabilizing the banks of creeks and controlling sediment supply thereby directly affecting water quality. It is also important as a habitat for native animals and for providing wildlife corridors. Fluctuations in water levels are necessary for maintaining soil and water quality. In this context it is important to note that dry periods are just as important to wetlands as periods of inundation. It is possible that the entrance management regime implemented by Council has resulted in some changes to the patterns of naturally occurring water level fluctuations, particularly for Terrigal Lagoon, which has the lowest let out level.

In general, the vegetation communities found at all four lagoons are quite similar. The fringing vegetation of Wamberal Lagoon was described as being in very good condition, although some weeds were observed (Bitou Bush), mostly along the western shore. Avoca Lagoon was found to have significant wetland habitats around its shorelines and on Bareena Island (Freewater and Gladstone, 2010; **Appendix D**). Weeds are also affecting habitat quality, with infestations of Bitou Bush having been recorded. Cockrone Lagoon was said to have similar wetland communities to those observed at the other lagoons (Freewater and Gladstone, 2010).

In contrast to the other three lagoons, urban development has significantly impacted parts of the Terrigal Lagoon foreshore. Development has occurred on low lying lands very close to the shoreline, and it is understood that Council may open the entrance up to 12 times a year in order to prevent flooding of private property and Council assets. This is thought to have resulted in significant impacts on the lagoon ecology. Mangroves have not previously been recorded for the lagoons. However, on the day of the field survey two species of mangroves were recorded (*Avicennia marina* and *Aegicerus corniculatum*), thought to be present in Terrigal due to the frequent entrance opening of the lagoon (Freewater and Gladstone, 2010; **Appendix D**). Some of the fringing vegetation present is in poor condition and is currently being impacted by weeds (Asparagus Fern and Lantana). The foreshore has also been modified in places due to the presence of seawalls or other protection works (Freewater and Gladstone, 2010; **Appendix D**).

A search of National Herbarium of NSW's PlantNet database indicated that there exist records for 47 different introduced species within the general study area. None of these species are gazetted weeds. The full list of introduced species is included in **Appendix G**.

Weed species observed by Freewater and Gladstone (2010) as being present in the foreshore vegetation included:

- Bitou Bush (*Chrysanthemoides monilifera*)*;
- Asparagus Fern (*Asparagus spp.*)*;
- Morning Glory (*Ipomoea spp.*); and
- Lantana (*Lantana camara*)*.

A search of the Protected Matters Search for Matters of National Environmental Significance under the EPBC Act was undertaken (on 25/01/2010) for a 10km^2 search area centred on the study area. This search recorded 10 terrestrial weed species "known to occur" or are "likely to occur" in the study area. Those identified as Weeds of National Significance that were also observed by Freewater and Gladstone (2010) have been identified with an asterix (*) in the list above.

6.3.2 Seagrass and Macroalgae

Aquatic habitat surveys were undertaken by the University of Newcastle (Freewater and Gladstone, 2010) over the summer of 2009-2010. The habitats surveyed were classified as follows: *Ruppia megacarpa*, *Zostera capricorni* seagrass, macroalgae, rock or bare substratum. Figures 1.22-1.24 of Freewater and Gladstone (2010; **Appendix D**) show the distribution of these various habitats for each the lagoons. The results have been summarised in **Table 6.1**.

Table 6.1: Vegetated Aquatic Habitats 2009/2010 (after: Freewater and Gladstone, 2010)

Lagoon	*Ruppia megacarpa*	*Zostera capricorni*	Macroalgae
Wamberal	27.67ha	0.46ha	3.69ha
Terrigal	-	-	-
Avoca	8.14ha	0.68ha	44.09ha
Cockrone	6.85ha	-	23.95ha

The aquatic survey showed that there is considerable variation among the lagoons in the composition of their seagrass and algal habitats (**Appendix D**). While Terrigal has no vegetated sediment, extensive areas of seagrass (*R. megacarpa*) dominate Wamberal, with smaller areas of *Z. capricorni*. Small areas of macroalgae also occur. Avoca has large areas of macroalgae and some seagrass (*R. megacarpa* and *Z. capricorni*). The dominant habitat in Cockrone was macroalgae with some seagrass (*R. megacarpa*). Macroalgal communities in the lagoons generally consisted of *Enteromorpha intestinalis* and *Chaetomorpha linum.*

Avoca and Cockrone are prone to outbreaks of the filamentous macroalgae. While blooms of these algae can occur naturally, there is some suggestion that there has been an increase in the incidence of macroalgae blooms due to eutrophication. In addition to impacting on the aesthetic appeal of the lagoons, these algal blooms can have significant impacts on the lagoon ecology. As discussed in **Section 5.2.3**, shifts in modes of primary production can occur, with seagrasses, benthic and planktonic algae contributing to the dominant mode of primary production at times, and macroalgae dominating at others. While small amounts of macroalgae may stimulate productivity, when blooms occur the negative impacts on lagoon ecology typically result. When macroalgae increase in biomass, they begin to shade the water column, thereby reducing primary productivity by phytoplankton, benthic microalgae and seagrasses. They may also reduce wind-induced circulation at the surface. In addition, when the macroalgae begins to decay it impacts other aquatic algae/plants directly by smothering and indirectly through by altering the chemistry of the water column (i.e. depleting dissolved oxygen). A study by Cummins *et al.* (2004) conducted in Tuggerah Lakes focussing on the effects of these blooms on seagrasses found that the presence of macroalgal mats led to both lethal and sub-lethal effects on seagrasses, as well changes in faunal assemblages in seagrass beds (either through mortality or migration). It was suggested that this process may have considerable implications for productivity in these systems (Cummins *et al.,* 2004).

With reference to blooms of these filamentous macroalgae, Freewater and Gladstone (2010) reference anecdotal evidence that the incidence of blooms has decreased in recent years. However, no data on the occurrence and coverage of these blooms was identified. A data set of this nature is likely to be difficult to acquire. Analysis of aerial photographs would be useful but the cost of capturing this data would be prohibitive. Council may wish to consider the use of alternative methods for monitoring the extent of these algal mats.

High levels of nutrients and sediment loads may also impact on other vegetated habitats. Other issues identified in Freewater and Gladstone (2010) include the impact of disturbance by waterway users, primarily through disturbance but also by stirring up sediments.

A search of the Protected Matters Search for Matters of National Environmental Significance under the EPBC Act was undertaken (on 25/01/2010) for a 10km^2 search area centred on the study area. This search recorded two aquatic weed species as being "known to occur" or "likely to occur" in the study area: Alligator Weed (*Alternanthera philoxeroides*) and Salvinia (*Salvinia molesta*). However, no direct observations of these introduced species have been recorded for the study lagoons.

6.3.3 Changes in Seagrass and Macroalgae Over Time

The University of Newcastle (Freewater and Gladstone, 2010; **Appendix D**) provide a review of historic surveys of aquatic flora in the Gosford coastal lagoons. Aquatic flora previously recorded in the lagoons includes:

- The seagrasses
  - *Ruppia spiralis*,
  - *Ruppia megacarpa*, and
  - *Zostera capricorni*; and
- Macroalgae.

The literature review highlighted the large variation in data and apparent discrepancies between the methodologies applied in the various reports (**Appendix D**).

As previously discussed, the results of surveys of the extent of aquatic vegetation carried out for this study suggest significant loss compared with earlier studies, although this could be partly due to differences in methodology. For example, Williams *et al*. (2006) reported 94% cover of *R. megacarpa* in Wamberal and 84% in Cockrone, compared to 60% and 20% (respectively) in the present study. Similarly, in the 1980's, Avoca supported large areas of *R. spiralis* and a fringe of *Z. capricorni*, but by 1991 there was no *Ruppia*, virtually no macroalgae and a small remnant fringe of *Zostera,* and by 2006 there were no seagrasses in this lagoon. It is estimated that *Ruppia* currently covers 8% of the lagoon.

6.3.4 Phytoplankton

Phytoplankton consists of microscopic algae and bacteria that float in the water column. While most spend their entire life cycle floating (holoplankton), some form resting spores which settle on submerged vegetation and sediment and are responsible for forming dense blooms at certain times of the year (given the right environmental conditions). While the abundance of phytoplankton can be determined by counting the individual cells, it is more commonly estimated by measuring the concentration of chlorophyll a, the green pigment that plant cells use for photosynthesis.

There is not a great deal of information available on the phytoplankton ecology of the study lagoons. This is not considered to be a significant issue and the implementation of a program of monitoring of plankton and/or chlorophyll a concentrations is unlikely to add significant value in terms of estuary management.

The University of Newcastle (Freewater and Gladstone, 2010; **Appendix D**) include a review of available phytoplankton data. Phytoplankton species previously recorded in the lagoons are listed in **Table 6.2.**

Table 6.2: Phytolankton of Gosford's Coastal Lagoons (after: Freewater and Gladstone, 2010)

Phytoplankton Species	Wamberal	Terrigal	Avoca	Cockrone
Dinophyceae (Dinoflagellates)				
Ceratium	√	√	√	√
Gymnodinium	√	√	√	√
Peredinium	√	√	√	√
Bacillariophyceae (Diatoms)				
Cyclotella	√	√	√	√
Navicula	√	√	√	
Synedra	√			
Surirella	√		√	√
Coconeis		√		
Gyrosigma	√			
Chrysophyceae (Golden-Brown)				
Cryptomonas	√	√	√	√
Cyamnophya (Blue-Green Algae)				
Oscillatoria				√
Anabaena	√			√

In addition, Freewater and Gladstone (2010) also report an analysis of chlorophyll a concentrations from water samples collected from the lagoons is compared with historical data. Surveys of the Gosford lagoons indicate that chlorophyll a concentrations are highly variable from year to year. Concentrations of chlorophyll a showed a marked seasonal trend in Avoca and Cockrone Lagoons, with the maximum in spring and summer (Freewater and Gladstone, 2010). While not statistically significant, the data suggest an increase in Terrigal and Wamberal in recent years, possibly related to increased development (assumed to translate to nutrient inputs), while there appears to have been a decrease in Avoca and Cockrone.

Analysis of diatoms in sediment cores collected from Lake Illawarra found that significant changes in the phytoplankton community had occurred over the last 60 years, thought to be due to eutrophication and increasing salinity (Liu, 2008). These findings suggest that the coincident processes catchment development (and associated impacts on nutrient inputs) and entrance management by Council would likely have had a significant impact on the phytoplankton ecology of the study lagoons.

Blue-green algae are actually bacteria, not phytoplankton. Both types of cyanobacteria recorded in Wamberal and Cockrone Lagoons produce a range of cyanotoxins and have the potential to represent a risk to public health under certain conditions (Freewater and

Gladstone, 2010). Cyanobacterial blooms can be triggered by high nutrient conditions, high sunlight/low turbidity and low circulation conditions. In addition, some species (such as Anabaena) have heterocysts that can are nitrogen fixing and when under stress, a normal blue-green algal cell can convert into this form.

6.3.5 Protected Flora Species

This section provides an overview of protected flora species found in the study area.

Terrestrial Flora Species

A search of the National Parks and Wildlife Service (NPWS; part of DECCW) Atlas of NSW Wildlife database for threatened flora species (under the *Threatened Species Conservation* (TSC) *Act 1995*) was conducted on 16 April 2010 for the entire Gosford LGA. The reported results were further analysed to identify threatened species records for the study area, returning a total of five threatened flora species records, including three endangered and two vulnerable species, as listed in **Table 6.3**.

A search of the Protected Matters Search for Matters of National Environmental Significance under the EPBC Act was undertaken (on 25/01/2010) for a $10km^2$ search area centred on the study area. This search reported five vulnerable plant species that are “known to occur” or are “likely to occur” in the study area. Two endangered plant species were recorded that “may occur” in the study area. These records are also listed in **Table 6.3**.

Table 6.3: Listings of Threatened Flora Species

Common Name	Scientific Name	TSC Act Listing*	EPBC Act Listing*
Biconvex Paperbark	*Melaleuca biconvexa*	V	V
Magenta Lilly Pilly	*Syzygium paniculatum*	E1	V
Sand Spurge	*Chamaesyce psammogeton*	E1	
Coast Grounsel	*Senecio spathulatus*	E1	
Heart-leaved Stringybark	*Eucalyptus camfieldii*	*V*	V
Bynoe's Wattle, Tiny Wattle	*Acacia bynoeana*		V
	Apatophyllum constablei		E
Thick-lipped Spider-orchid	*Caladenia tessellata*		V
Leafless Tongue-orchid	*Cryptostylis hunteriana*		V
Eastern Underground Orchid	*Rhizanthella slateri*		E

*V=Vulnerable, E/E1=Endangered.

An overview of EECs protected under the TSC Act, SEPP 14 wetlands and other vegetation conservation measures are discussed in **Section 3.5.1** and mapped in **Figure 3.9**.

Aquatic Flora Species

Aquatic vegetation may be protected under the NSW *Fisheries Management (FM) Act 1994* and/or the EPBC Act. A search of the relevant online databases did not reveal and listings of protected aquatic flora species for the study area.

However, mangroves and seagrasses are protected under the FM Act and a permit is required in order to undertake any activity that may result in harm to these habitats.

6.3.6 Ecological Assessment of the Lagoon Foreshores

The report by Freewater and Gladstone (2010) presents an assessment of the disturbance to natural shorelines and provides an overview of the general condition of foreshore vegetation around the four Gosford coastal lagoons: Avoca, Terrigal, Cockrone and Wamberal. The full report is provided in **Appendix D**.

The foreshores of Avoca, Terrigal, Cockrone and Wamberal Lagoons are the interface between the terrestrial and aquatic environments and include the lagoon beaches, saltmarshes and wetlands, public reserves and privately owned land. It is where the community's interaction with the lagoon begins and their perceptions about the “health” of the lagoon are developed.

Wamberal Lagoon is the least developed with only 16% of the foreshore developed and extensive native forest. Two thirds of the foreshore of Terrigal has been developed with the remainder supporting native riparian vegetation. However, all of the catchments behind the foreshore have been developed and this is likely to be impacting on this habitat. Avoca and Cockrone are less developed than Terrigal, with 28% and 22% of the foreshore developed, respectively. The remainder supports native riparian vegetation with undeveloped catchments.

The assessment of shoreline vegetation was conducted by surveying aerial photographs from 2005 and 2007 and validated by ground-truthing (foreshore survey conducted via kayak). A Disturbance Index was applied to sections of the shoreline and is presented in **Table 6.4**.

Table 6.4 Disturbance Index Used to Assess Each Section of the Gosford Lagoon Foreshores (After: Sainty and Roberts, 2007)

Index	Description
1	**Highly disturbed/modified foreshore**. Includes seawalls with limited ecological niches e.g. vertical concrete or stone. Includes buildings in close proximity to the seawall, often with jetties and stormwater inlets. Catchment* substantially developed.
2	**Disturbed/modified foreshore**. Seawall with limited ecological niches. Includes foreshore with *Phragmites* or other native vegetation limited to narrow discontinuous strip. Catchment substantially developed.
3	**Modified foreshore**. Seawall absent. Includes irregular strip of fringing vegetation or natural rock platform associated with a variable width forest, contiguous to water's edge. Catchment partly/variably developed.
4	**Modified catchment**. *Phragmites*, *Baumea* or other native forest type on water's edge. Catchment partially or wholly developed, weeds, trampling or other disturbance.
5	**Native forest and foreshore**. *Phragmites*, *Baumea*, or other native forest type on water's edge. Catchment with no development. Few if any weeds or other signs of disturbance.

* Catchment refers to adjacent sub-catchment draining to particular section of shoreline.

The foreshores of the four Gosford lagoons extend in length as follows:

- Wamberal: 4.88km,
- Terrigal: 5.68km,
- Avoca: 11km, and
- Cockrone: 5km.

Tables 6.5 to 6.8 show the number of locations, percentage of total foreshore lands and kilometres represented by each Disturbance Index for Wamberal, Terrigal, Avoca and

Cockrone Lagoon respectively. Figures 1.18 to 1.21 of the Freewater and Gladstone (2010) report show the locations of each Disturbance Index for the foreshore assessment.

Table 6.5: Summary by Disturbance Index for Wamberal Lagoon (after: Freewater and Gladstone, 2010)

Disturbance Index	No. Discrete Locations	% of Total Foreshore Length	Total kms
1	1	0	0.01
2	0	0	0
3	3	16	0.78
4	4	30	1.45
5	2	54	2.65
TOTAL	**10**	**100**	**4.88**

Table 6.6: Summary by Disturbance Index for Terrigal Lagoon (after: Freewater and Gladstone, 2010)

Disturbance Index	No. Discrete Locations	% of Total Foreshore Length	Total kms
1	2	6.84	0.39
2	1	0.67	0.04
3	6	60.60	3.43
4	3	31.89	1.81
5	0	0	0
TOTAL	**12**	**100**	**5.66**

Table 6.7: Summary by Disturbance Index for Avoca Lagoon (after: Freewater and Gladstone, 2010)

Disturbance Index	No. Discrete Locations	% of Total Foreshore Length	Total kms
1	2	0.46	0.05
2	0	0	0
3	6	27.65	3.03
4	7	51.17	5.61
5	2	20.72	2.27
TOTAL	**17**	**100**	**10.97**

Table 6.8: Summary by Disturbance Index for Cockrone Lagoon (after: Freewater and Gladstone, 2010)

Disturbance Index	No. Discrete Locations	% of Total Foreshore Length	Total kms
1	0	0	0
2	1	4.13	0.21
3	3	18.13	0.90
4	3	46.86	2.34
5	1	30.87	1.54
TOTAL	**8**	**100**	**4.99**

A total of 47 different sections of foreshore were identified using aerial photography and ground-truthing across the four Gosford Lagoons (Freewater and Gladstone, 2010). The shorelines range from an unmodified tidal interface with a catchment that has little or negligible development, to an extensively modified foreshore and catchment.

It is noted that the Disturbance Index developed for this assessment focuses on the ecological value of the foreshore, assessing such factors as whether the shoreline is natural or artificial (i.e. a seawall), or whether healthy native vegetation is present.

6.4 Fauna

This section focuses on fauna that are in some way directly dependent on lagoon processes, be it for food resources or as their primary habitat. No detailed discussion of terrestrial fauna is provided, however, a full list of threatened and protected fauna, including terrestrial fauna, is provided in **Appendix I** and Freewater and Gladstone (2010; **Appendix D**).

6.4.1 Mammals

This section focuses primarily on marine mammals. A number of species of marine mammals have been observed transiting the general study area, although it is noted that there are no records of marine mammals inhabiting the lagoons.

Records of marine mammals sighted offshore of the coastline are provided in **Table 6.9**, including their status under the TSC Act and EPBC Act, as well as the number of recorded sightings (where available). It is noted that none of these species would be resident in the Gosford LGA coastal zone, but would transit the area from time to time (e.g. Humpback Whale). Additionally, some of these records represent very unusual occurrences where a species is outside of its normal range (e.g. the Dugong). The number of sightings has been included to provide context. It is unlikely that estuary management activities would impact on any of these species.

Table 6.9: Records of Marine Mammals for the Larger Study Area

Common Name	Scientific Name	No. of Sightings	TSC Act Listing*	EPBC Act Listing*
Dugong	*Dugong dugon*	2	E1	
New Zealand Fur-Seal	*Arctocephalus forsteri*	4	V	L
Australian Fur-Seal	*Arctocephalus pusillus doriferus*	1	V	L
Southern Right Whale	*Eubalaena australis*	8	V	E, M
Humpback Whale	*Megaptera novaeangliae*	11	V	V, M
Sperm Whale	*Physeter macrocephalus*	4	V	
Blue Whale	*Balaenoptera musculus*	P		E, M
Bryde's Whale	*Balaenoptera edeni*	P		M
Pygmy Right Whale	*Caperea marginate*	P		M
Dusky Dolphin	*Lagenorhynchus obscurus*	P		M
Killer Whale, Orca	*Orcinus orca*	P		M

*V=Vulnerable, E/E1=Endangered, M=Migratory Marine, L=Listed Marine, P= may occur in the study area.

There are also records for a number of introduced mammals in the general study area, as identified via the Protected Matters Search Tool under the EPBC Act. These include:

- Goat (*Capra hircus*);
- Cat* (*Felis catus*);
- Rabbit* (*Oryctolagus cuniculus*);
- Pig (*Sus scrofa*); and
- Fox* (*Vulpes vulpes*).

Those with known to occur in the study area, or considered likely to occur in the study area, are marked with an asterix (*). It is understood that breeding deer are also present and have been observed around Avoca Lagoon.

While these species may impact on native terrestrial fauna through a range of mechanisms (such as competition for resources and predation), impacts on estuarine fauna or estuarine processes are unlikely. The exception is the Rabbit, which may impact on bank stability if they burrow in foreshore areas. However, there are no known instances of this issue occurring.

6.4.2 Avifauna

Despite their proximity to a major city (Sydney) and the regional centre of Gosford, the Gosford coastal lagoons provide a diverse array of habitats suitable for birds. There are a number of databases with records of species observations (e.g. Birds Australia), however apart from this information, their bird assemblages are poorly studied. Birds are an important part of the overall biodiversity of estuaries and lagoons and may also be valued for their functional role in ecological processes such as nutrient cycling, seed dispersal and population regulation (including both predation and herbivory).

The study area is on the route of the East Asian-Australasian Flyway which is used by shorebirds to move between Australia / New Zealand, East Asia and the Arctic region of the northern hemisphere. Migratory birds are protected primarily by the China-Australia Migratory Bird Agreement (CAMBA), the Japan-Australia Migratory Bird Agreement (JAMBA) and/or the Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA). The four Gosford lagoons are a stopping-off point for birds travelling between wetlands.

According to a search of the Birds Australia database (conducted on 7/12/2009), there are records for 207 bird species in the general study area and this includes:

- 15 species protected under the TSC Act,
- 65 species listed marine species under the EPBC Act,
- 17 species protected under JAMBA,
- 17 species protected under CAMBA, and
- 12 species protected under ROKAMBA.

Due to the large size of the list, it has not been reproduced in this report. However, **Table 6.10** identifies threatened species listed under the TSC Act, as well as those species listed under the JAMBA, CAMBA and ROKAMBA agreements. The full list of Birds Australia records is provided in **Appendix I**.

Table 6.10: Protected Birds (Source: Birds Australia, 2010)

Common Name	Scientific Name	TSC Act Listing	Migratory Bird Agreements
White-throated Needletail	*Hirundapus caudacutus*		J, C, R
Wedge-tailed Shearwater	*Ardenna pacifica*		J
Sooty Shearwater	*Ardenna grisea*		J, C
Short-tailed Shearwater	*Ardenna tenuirostris*		J, R
Eastern Great Egret	*Ardea modesta*		J, C
Cattle Egret	*Ardea ibis*		J, C
Eastern Reef Egret	*Egretta sacra*		C
White-bellied Sea-Eagle	*Haliaeetus leucogaster*		C
Pacific Golden Plover	*Pluvialis fulva*		J, C, R
Latham's Snipe	*Gallinago hardwickii*		J, C, R
Bar-tailed Godwit	*Limosa lapponica*		J, C, R
Red Knot	*Calidris canutus*		J, C, R

Common Name	Scientific Name	TSC Act Listing	Migratory Bird Agreements
Red-necked Stint	*Calidris ruficollis*		J, C, R
Sharp-tailed Sandpiper	*Calidris acuminata*		J, C, R
Curlew Sandpiper	*Calidris ferruginea*		J, C, R
Ruff	*Philomachus pugnax*		J, C, R
Little Tern	*Sternula albifrons*	E	J, C, R
Caspian Tern	*Hydroprogne caspia*		C
Common Tern	*Sterna hirundo*		J, C, R
Crested Tern	*Thalasseus bergii*		J
Bush Stone-curlew	*Burhinus grallarius*	E	
Swift Parrot	*Lathamus discolor*	E	
Black-browed Albatross	*Thalassarche melanophris*	V	
Australasian Bittern	*Ixobrychus flavicollis*	V	
Eastern Osprey	*Pandion cristatus*	V	
Square-tailed Kite	*Lophoictinia isura*	V	
Australian Pied Oystercatcher	*Haematopus longirostris*	V	
Sooty Oystercatcher	*Haematopus fuliginosus*	V	
Glossy Black Cockatoo	*Calyptorhynchus lathami*	V	
Gang-gang Cockatoo	*Callocephalon fimbriatum*	V	
Powerful Owl	*Ninox strenua*	V	
Barking Owl	*Ninox connivens*	V	
Sooty Owl	*Tyto tenebricosa*	V	
Masked Owl	*Tyto novaehollandiae*	V	

*V=Vulnerable, E=Endangered.

Habitat availability is likely to play a part in the occurrence of threatened and migratory avifauna within the study area. Maintenance of estuarine processes can play an important role in ensuring these habitats remain viable. The importance of water level variations for wetland vegetation was discussed in **Section 6.3.1**. Birds such as the Red-necked Stint feed on intertidal mudflats and regular exposure of these areas is required to ensure a food source, although it is understood that the mudflats areas are perceived as being unattractive and as emitting foul odours. In the case of the Osprey, this species feeds on fish and so maintenance of water quality is important for hunting success, whilst maintenance of fish habitats is important for ensuring ongoing availability of a food source. Other management issues for permanent and transient bird species may include disturbances (by dogs or via noise pollution) and habitat degradation or loss. Predation, particularly by introduced species such as feral cats and foxes, is also an issue.

It is unclear if algal blooms are having an impact on avifauna diversity and abundance. On the one hand, these blooms can attract a large number of birds which feed on the macroalgae. However, the blooms may have a negative impact on other bird species. This process would bear further investigation.

6.4.3 Amphibians and Reptiles

Records of amphibians and reptiles sighted in the general study area are provided in **Table 6.11**, including their status under the TSC Act and EPBC Act. It is noted that some of these species would be resident in the Gosford LGA coastal zone, with others travelling through the area from time to time (i.e. the turtles).

Table 6.11: Records of Amphibians and Reptiles for the Larger Study Area

Common Name	Scientific Name	TSC Act Listing*	EPBC Act Listing*
Wallum Froglet	*Crinia tinnula*	V	
Giant Burrowing Frog	*Heleioporus australiacus*	V	V
Stuttering Frog	*Mixophyes balbus*	E1	V
Giant Barred Frog	*Mixophyes iteratus*	E1	E
Red-crowned Toadlet	*Pseudophryne australis*	V	
Green and Golden Bell Frog	*Litoria aurea*	E1	V
Green-thighed Frog	*Litoria brevipalmata*	V	
Littlejohn's Tree Frog	*Litoria littlejohni*		V
Green Turtle	*Chelonia mydas*	V	V, M, L
Leathery Turtle	*Dermochelys coriacea*	V	E, M, L
Rosenberg's Goanna	*Varanus rosenbergi*	V	
Broad-headed Snake	*Hoplocephalus bungaroides*	E1	V
Stephens' Banded Snake	*Hoplocephalus stephensii*	V	

*V=Vulnerable, E/E1=Endangered, M=Migratory Marine, L=Listed Marine, P= may occur in the study area.

One species for which there is good information available is the Green and Golden Bell Frog, for which there is a resident population of about 100 adults (as at 2006) at North Avoca in Bareena Wetland. A Plan of Management has been prepared for this species (Biosphere Environmental Consultants, 2006). Key species requirements/tolerances include:

- Breeds in spring/summer in shallow (<1m deep) slowing moving or still waterbodies that are unshaded, free of fish and have an area of open water, with low salinity (<8ppt) and warm water (>20°C).
- Responsive to certain types of habitat disturbance that trigger movement and breeding, such as changes in water level, salinity or aquatic vegetation.
- Forages on the ground or on low vegetation in areas of low vegetation cover or sparse tree cover.
- Refuge is sought underwater, under low vegetation, rocks, fallen timber or other debris. During colder weather they seek more permanent shelter under rocks, timber or other ground cover items.

Key threats include (in order of relative importance):

- Habitat loss,
- Increased salinity,
- Predation by introduced fish (Gambusia, which is said to be present at Avoca Lagoon),
- Chytrid fungal disease,
- Predation by foxes, and
- Deposition of dog faeces.

The mechanical opening of the lagoon may have significant impact (with potential to eliminate a cohort of tadpoles) depending upon the timing of opening and relative change in water levels (Biosphere Environmental Consultants, 2006). DECCW also identify changes to drainage patterns and stormwater runoff, and herbicides and other weed control measures as threats.

Biosphere Environmental Consultants (2006) provide a number of recommendations to maintain and enhance the Green and Golden Bell Frog population at Avoca, focussing on the top three threats listed above. Monitoring of the Avoca population should form an important part of any program of adaptive management. Other documents providing advice include best practice guidelines for habitat management by DEC (2005) and a Recovery Plan prepared by DECC (2008).

The entrance management policy (GCC, 2006) currently includes a recommendation relating to management of impacts on Green and Golden Bell Frogs that notification of an impending mechanical breakout should be provided to Council's City Services Directorate and what is now DECCW to ascertain breeding status and implement salvage strategies. However, this is likely to be difficult to implement due to the time pressure to open the lagoon and it is unknown how successful these strategies have been in the past. The Management Study and Plan should consider this issue further and suggest any modifications to the entrance management policy as required.

6.4.4 Fish, Prawns and Crustaceans

There is a wide diversity of fish species that inhabit coastal lagoons. The resident species spend their entire lives in the lagoon and dominate many of these systems. Marine-estuarine dependent species utilize estuaries as juveniles and during part of their adult stages, but the adults migrate out to sea to spawn. When the entrances to lagoons are closed, many species shelter in surf zones until it is possible to enter and so nearby surf zones play an important role in the dynamics of fish populations utilising lagoons.

The University of Newcastle (**Appendix D**) undertook a study of the estuarine fish communities which includes a comparison with historic data provided by NSW Fisheries (DII) for the purposes of the this study, a literature review, and additional field sampling undertaken in 2009-2010. The sampling aimed to assess the process of recruitment of fish to the lagoons and describe changes in fish assemblages over time.

NSW Fisheries (DII) Data

NSW Fisheries has previously surveyed fish and prawns over the period 1986 to 2008. A summary of that data provided in Freewater and Gladstone (2010) has been reproduced below:

- A total of 72 species of fish were collected over the sampling period.
- There was a general trend towards lower diversity and abundance of species through time until 2002 and then the trend reverses.
- Terrigal had the highest diversity of species, attributed by the authors to the frequency of lagoon openings (permitting biological exchange) rather than habitat availability or water quality.
- Species recorded in particularly high abundances include Glassfish (*Ambassis jacksoniensis*), Small Mouth Hardyhead (*Atherinosoma microstoma*) and *Philypnodon* spp. (especially Flathead Gudgeon *Philypnodon grandiceps*). The most abundant fish were normally the smallest.
- In terms of larger fish, relatively abundant species included Bream (*Acanthopagrus australis*), Sand Grey Mullet (*Myxus elongatus*), Flat-tail Mullet (*Liza argentea*),

Flathead Mullet (*Mugil cephalus*), Eastern River Garfish (*Hyporhamphus regularis ardelio)* and Sand Whiting (*Sillago ciliata*).

- Few prawns or other crustaceans were recorded. Those recorded include a Sergestid shrimp (*Acetes sibogae australis*), School Prawns (*Metapenaeus macleayi*) and *Palaemon* spp.

Shellfish are relatively rare in the Gosford lagoons with Pipis (*Donax deltoides*) being most abundant at Avoca, but only one sample with a single individual was found at Wamberal and none in the other lagoons. Shellfish inhabiting hard substrata, such as rock or mangrove roots and trunks, are rare as these habitats are not well represented in the lagoons.

Fish Sampling

Freewater and Gladstone (2010; **Appendix D**) report on the findings of a study of fish assemblages sampled using a variety of gear types from each of the four lagoons on several occasions in the months of February, April, July, September and November of 2009. The fish fauna of the surf zone of the adjacent beaches was also surveyed in late 2009-early 2010, however issues with the sampling technique meant that a representative sample could not be collected at that time. For this reason, historical data on surf zone fishes from earlier work by University of Newcastle (Edwards and Gladstone, 2009) was used to inform the analysis.

The data were then analysed using a range of multivariate statistical techniques. It is understood that the data presented are part of an ongoing sampling regime being undertaken as part of PhD studies by a student at University of Newcastle until 2011 and it is hoped that this additional data will assist in assessing the impacts of entrance opening on fish assemblages.

The study showed that Terrigal Lagoon had the greatest diversity of fish (23 species), followed by Avoca (15 species), Wamberal (13 species) and Cockrone (12 species). A total of 16 fish species from 14 families were sampled from the surf zones. Of these, six families of fish occurred in both the lagoons and the surf zone sites, three families of fish recorded from the lagoons were absent from the surf zone, and eight families recorded from the surf zone were absent from the lagoons (Freewater and Gladstone, 2010).

A comparison between fish assemblages of the lagoons (12 species, 3,308 individuals) and the surf zone (16 species, 598 individuals) showed that the diversity of fish in the lagoons was lower but abundances were higher (Edwards and Gladstone, 2009). This is likely a function of both habitat availability and the large size and more dynamic nature of the surf zone. The most abundant fish species from the lagoons was the Flathead Gudgeon (*Philypnodon grandiceps*), while the Sandy Sprat (*Hyperlophus vittatus*) was the most abundant species occurring in the surf zone.

Comparing the lagoons, Wamberal had the highest abundance of fish and Terrigal the lowest (Edwards and Gladstone, 2009), likely due to the low habitat diversity of this lagoon. While there were substantial changes in the abundance and diversity of larval and juvenile fish in all the lagoons over time, there was no evidence that these changes were associated with lagoon openings. In contrast, Freewater and Gladstone (2010; **Appendix**

D) found that both the diversity and abundance of fish in Wamberal, Avoca and Cockrone Lagoons (which opened at approximately the same time) decreased after entrance openings. However, it was considered that the study may have been limited due to the fact that there was no control lagoon (i.e. one that remained closed over that period) for comparative sampling. It is hoped that the additional sampling being undertaken by University of Newcastle (until 2011) will provide additional data to further our understanding of the impacts of lagoon breakouts on fish assemblages.

Fish assemblages in Terrigal Lagoon did show slight differences in fish assemblages when compared to the other three lagoons. This is discussed further in Freewater and Gladstone (2010; **Appendix D**) who state that this is indicative of the resilience of fish to the effects of opening, which include changes in water level, water quality and access to habitat. While there is certainly a lack of habitat diversity in Terrigal Lagoon, water levels records show less variability than the other three lagoons, as discussed in **Section 4.6.1**.

Freewater and Gladstone (2010) provide a review of the literature on the dynamics of larval and juvenile fish in surf zones. Peak abundances of estuarine-dependent species are said to generally occur during the spring and summer periods, with potential for a second peak during the winter months. Other potential contributing factors to variation in surf zone fish assemblages include:

- Wind,
- Coastal currents,
- Protection from swell,
- Larval swimming ability, and
- Recruitment cues.

For the data reported by Freewater and Gladstone (2010), there were no significant temporal patterns in the total abundance of larval and juvenile fish except at Terrigal Beach, where two abundance peaks occurred during winter (June and July) due to the presence of large numbers of the dominant species *Hyperlophus vittatus*. Apart from this particular species, the abundance of surf zone fish was relatively depauperate.

The highest abundance of surf zone fishes was recorded from Terrigal Beach and the lowest abundance from Copacabana Beach (near Cockrone Lagoon). In surf zones, the likelihood of change in fish assemblages over time was unrelated to the status of the lagoon entrances (Edwards and Gladstone, 2009).

A comparison of fish assemblages from the lagoons and the adjacent surf zones showed distinct differences (Freewater and Gladstone, 2010). The lagoons generally had lower species diversity with a higher abundance of some dominant species. Surf zones had higher species diversity but lower abundances of individual species. Both Edwards and Gladstone (2009) and Freewater and Gladstone (2010) found that there was no evidence of migration of surf zone fishes into lagoons (or vice versa). The results indicated that recruitment of fish from surf zones into the lagoons during periods when the entrance is open was not an important process (Freewater and Gladstone, 2010), possibly due to the dominance of estuarine species. The four lagoons were dominated by estuarine species, while the surf zones were dominated by estuarine-marine species, the most abundant of which were not found in the lagoons. While some species were common to both lagoons and surf zones, the sample size captured was so small that it was not possible to draw any firm conclusions.

While these University of Newcastle studies did not find any significant indicators of recruitment to lagoons after breakout, anecdotal evidence suggests that this process does occur, on occasion resulting in very large increases in abundances of fish or prawns, dependent upon the timing of the lagoon breakout (M. Kilp – T. Mackenzie, Cardno, 22/05/10, pers. comm). This can attract large numbers of birds and recreational fisherman to the lagoons.

Fish Kills

A fish kill is defined by NSW Fisheries as "any sudden and unexpected mass mortality of wild or cultured fish" (DPI, 2000). As fish kills are very visible events, particularly in waterbodies such as the Gosford lagoons, they often cause considerable interest and concern to the public and the media because they are often perceived to be the result of pollution or contamination of waters (DPI, 2000). In reality there are many and varied causes of fish kills, and a large proportion are due to natural events and are often related to water quality, with low dissolved oxygen (DO) levels being the primary reported cause.

DPI (2000) report that relatively more fish kills occur in the summer months of January and February, although fish kills are likely to happen at any time of the year. The main contributing factor appears to be higher water temperatures in the summer (which can cause stratification of lagoon waters) and consequently lower DO levels.

According to DPI (2000), many fish kills are simply a natural phenomenon, caused by natural events through normal environmental cycles and there is little that can be done to prevent them. The three main factors that play a role in fish kills, according to DPI (2000) are, toxicants/pollutants, environmental factors (e.g. salinity, temperature, acidity levels, DO levels) and disease pathogens. In lagoon environments, the most common factors that lead to fish kills are rain and excessive plant growth or nutrients within a lagoon, which deoxygenates the waters, and salinity and acid waters.

A number of fish kills have occurred in the Gosford lagoons that are the subject of this study. Investigations into fish kills in Cockrone Lagoon were carried out by Wilson and Evans (2002). Their report examines water quality records to explain the fish kill that occurred on 16 February 2002, following a large rain event and a subsequent mechanical breaching of the berm to prevent flooding of low-lying properties. The beach berm closed naturally after four days, by which time lagoon water levels were approximately 70cm lower than prior to the breakout event. The fish kill occurred four days after the closing of the lagoon.

Wilson and Evans (2002) concluded that the fish kill in February 2002 was primarily due to the rapidly declining and persistent low dissolved oxygen levels following the death of a significant amount of algae around the previously unexposed shoreline (decomposition of this organic matter would have consumed most of the oxygen from the water), compounded by rapid changes in salinity, pH and temperature. Whilst this process may be a significant contributor to fish kills in Cockrone Lagoon, it is noted that water levels decrease significantly after a break out event and large expanses of the lagoon (if not the entire waterbody) drain to dry. This is likely a contributing factor as the availability of refugia for fish is very limited.

GCC also conducted preliminary water quality testing in Cockrone Lagoon following a fish kill in June of 2009. Photographs of this event have been provided in **Appendix A**. Again, very low DO levels (below 1mg/L) were recorded, which are too low for fish to survive. The main response by fish to lack of oxygen is gasping at the surface (DPI, 2000) and this was observed in Cockrone Lagoon during the March 2009 fish kill (pers. comms.). Interestingly, the photographs captured 4 June 2009 (**Appendix A**) also show a number of birds that appear to be feeding on the exposed algae and dead fish.

6.4.5 Macrobenthic Invertebrates

A benthic community is the assemblage of bottom dwelling species occurring in a particular location at a particular time. Infaunal benthic invertebrates are divided into groups based on their size: being micro- (<0.04mm), meio- (0.04-0.1mm), macro- (0.5-2.0mm) or megafauna (>2.0mm). These can be very diverse communities representing a range of different phyla of animals.

Freewater and Gladstone (2010; **Appendix D**) provide a literature review on the use of macroinvertebrates as indicators of disturbance to marine and estuarine ecosystems. Community structure, biomass and relative abundance of trophic groups and indicator species have developed and used for this purpose. There has likely been sufficient data collected by Freewater and Gladstone (2010) and Gladstone (2004) to establish baseline conditions for any future comparison.

Patterns of Distribution and Abundance

Freewater and Gladstone (2010; **Appendix D**) undertook field surveys of the four coastal lagoons in an effort to describe patterns of distribution and abundance of benthic macroinvertebrates. Sampling was undertaken on 30 July 2008 in the entrance berm, central (deep) basin and creek deltas (two sites each) in each of the four lagoons. At each site, seven cores were collected. Five cores were sieved and the captured invertebrates identified. Two cores were retained for analysis of organic carbon content, percentage fine sediments and chlorophyll a (surficial sediments only). Other environmental variables analysed at each site included depth, distance from the entrance, fetch, condition of the foreshore habitat and water quality (TN, TP, chlorophyll a, temperature, DO, pH and salinity).

Water level records obtained for this project only go until 30 June 2008 and so it is not known if the entrance had broken open in the month preceding sampling. However, for those records that are available, the most recent breakout events for each lagoon were:

- ***Wamberal*** – broke open 21 April, fully closed 29 April;
- ***Terrigal*** – broke open 4 June, fully closed by 18 June;
- ***Avoca*** – broke open 9 June, fully closed by 30 June; and
- ***Cockrone*** – broke open 20 June, fully closed by 26 June.

A total of 412 individuals were collected from four phyla, including 7 families of molluscs, five families of polychaetes, six families of crustaceans and three families of insects recorded by Freewater and Gladstone (2010). Diversity and abundances of macrobenthic invertebrates were greatest in the central mud basin of the lagoons and least in the beach berm regions. This is likely due to lower rates of disturbance in these deeper parts of the lagoons.

The berm regions differed significantly from other regions sampled within each lagoon (Freewater and Gladstone, 2010). Species abundance and diversity was greatest in the central basin regions, likely due to the more stable nature of these environments. During a breakout event, creek delta areas may become exposed and the sand comprising the berm is washed out to sea. In contrast, deeper basin areas will likely remain inundated even after a breakout event and therefore these areas are subject to lower rates of disturbance. Arthropods of the family Paracalliopiidae were the main cause of differences between central basins and berm where they were most abundant. The capitellid polychaetes and exoedicerotid crustaceans were the cause of differences between the basin and creeks where they were most abundant.

Macrobenthic assemblages in each of the lagoons were different. Those in the central basin in Wamberal differed significantly from those in Terrigal, Avoca and Cockrone (Freewater and Gladstone, 2010). Capitellid polychaetes and exoedicerotid crustaceans accounted for the differences between Wamberal and the other lagoons, while capitellids differentiated Terrigal, where they were most abundant, from Cockrone. There were, however no statistically significant differences between Terrigal and Avoca or between Avoca and Cockrone.

Macrobenthos are influenced by a large number of physical and chemical variables. These include distance from the berm, sediment characteristics, salinity, turbidity, oxygen, pH, nutrients and organic carbon. Statistical analyses undertaken by Freewater and Gladstone (2010) indicated that species richness and diversity do not appear to be strongly related to variables related to water quality and nutrients. The strongest correlations were with organic carbon, percent fine material and distance from the berm.

Effect of Entrance Opening on Macrofaunal Communities in the Entrance Berm

A study was previously conducted by Gladstone (2004), focussing on the impact of breakout events on macroinvertebrates inhabiting the berm by comparing assemblages in the entrance barriers of the lagoons before artificial opening and after the berm had become re-established.

No significant difference in assemblage structure was found for any of the lagoons when comparing assemblages before lagoon breakout to when the lagoon has re-established. These results indicate that the effects of artificial opening are short-lived and that the benthos recovers rapidly in the entrance barrier (Gladstone *et al*. 2006). This is most likely due to re-colonization by physical dispersal from adjacent areas of sediment. More subtle, cumulative effects on the benthos cannot be ruled out, however, as there were a relatively large number of cores devoid of macrobenthos.

These findings are similar to those from large-scale studies of macrobenthos in ICOLLs in NSW by Dye (2005, 2006) who found little difference between macrobenthic assemblages in the mouth and middle reaches of artificially opened vs. natural lagoons, although there were consistent differences for assemblages in the inner reaches. It seems that the macrobenthos are resilient to the disturbances caused by opening and can recover rapidly. A similar result was found for macrobenthos in dredged vs. undredged locations in the entrance to Tuggerah Lakes (CEL, 2009).

6.4.6 Zooplankton

Zooplankton comprises single-celled and more complex organisms. The term zooplankton describes both holoplankton, which spend their entire life cycle in the plankton, and meroplankton, which spend only part of their life cycle in the plankton (e.g. larvae).

There have been few studies of zooplankton ecology in the four coastal lagoons.

Surveys of zooplankton in the Gosford coastal lagoons in 1996, 1997 and 1999 (Laxton, 1997 and 1999) indicated the presence of large numbers of copepod crustaceans and gastropods, as well as the eggs, larvae and juveniles of fish in Wamberal. In Terrigal and Avoca, copepods and amphipods were the most numerous animals in seagrass beds (present in Terrigal at that time), but fish, molluscs and polycheates were also common. In Cockrone, large numbers of small gastropods were caught over *Ruppia* beds and high densities of copepods were caught in open water. Fish and crustacean larvae were also caught in Cockrone.

6.4.7 Threatened and Protected Species

Records of threatened and protected mammal, amphibian, reptile and bird species have been provided in **Sections 6.4.1, 6.4.2 and 6.4.3**. Therefore, the discussion in this section has focussed on aquatic estuarine/marine species including fish, crustaceans and molluscs. Aquatic species may be protected under the *Fisheries Management Act 1994*, TSC Act 1995 or the EPBC Act 1999.

Searches of the BioNet database and EPBC Protected Matters Search Tool for the Gosford LGA were undertaken on 23 April 2010 and 25 January 2010 respectively. Species records for the Gosford LGA have been listed in **Table 6.12**, however it is noted that only the Grey Nurse Shark, Macquarie Perch and Australian Grayling have been confirmed sightings within the LGA, although not for the study area. All other species are identified as having the potential to occur in the Gosford LGA. Furthermore, for several of these species, there are not suitable habitat or food resources available.

Table 6.12: Records of Threatened and Protected Aquatic Species

Common Name	Scientific Name	FM Act Listing*	EPBC Act Listing*
Grey Nurse Shark	*Carcharias taurus*	E	CE
Great White Shark	*Carcharodon carcharias*		V, M
School Shark	*Galeorhinus galeus*		CD
Green Sawfish	*Pristis zijsron*		V
Whale Shark	*Rhincodon typus*		V, M
Macquarie Perch	*Macquaria australasica*		E
Australian Grayling	*Prototroctes maraena*		V
Hairy Pygmy Pipehorse	*Acentronura tentaculata*		L
Girdled Pipefish	*Festucalex cinctus*		L
Tiger Pipefish	*Filicampus tigris*		L
Upside-down Pipefish	*Heraldia nocturna*		L

Common Name	Scientific Name	FM Act Listing*	EPBC Act Listing*
Beady Pipefish, Steep-nosed Pipefish	*Hippichthys penicillus*		L
Eastern Potbelly Seahorse, New Zealand Potbelly, Seahorse, Bigbelly Seahorse	*Hippocampus abdominalis*		L
White's Seahorse, Crowned Seahorse, Sydney Seahorse	*Hippocampus whitei*		L
Briggs' Crested Pipefish, Briggs' Pipefish	*Histiogamphelus briggsii*		L
Javelin Pipefish	*Lissocampus runa*		L
Sawtooth Pipefish	*Maroubra perserrata*		L
Red Pipefish	*Notiocampus ruber*		L
Weedy Seadragon, Common Seadragon	*Phyllopteryx taeniolatus*		L
Spiny Pipehorse, Australian Spiny Pipehorse	*Solegnathus spinosissimus*		L
Blue-finned Ghost Pipefish, Robust Ghost Pipefish	*Solenostomus cyanopterus*		L
Harlequin Ghost Pipefish, Ornate Ghost Pipefish	*Solenostomus paradoxus*		L
Spotted Pipefish	*Stigmatopora argus*		L
Wide-bodied Pipefish, Black Pipefish	*Stigmatopora nigra*		L
Double-ended Pipehorse, Alligator Pipefish	*Syngnathoides biaculeatus*		L
Bend Stick Pipefish, Short-tailed Pipefish	*Trachyrhamphus bicoarctatus*		L
Hairy Pipefish	*Urocampus carinirostris*		L
Mother-of-pearl Pipefish	*Vanacampus margaritifer*		L

*V=Vulnerable, E/E1=Endangered, CD=Conservation Dependent, M=Migratory Marine, L=Listed Marine, P= may occur in the study area.

6.5 Threats to Lagoon Biodiversity

Key issues identified by Freewater and Gladstone (2010; **Appendix D**) as impacting on lagoon biodiversity include:

- Introduced species (weeds and pest fauna);
- Declines in water quality associated with stormwater runoff (primarily in relation to nutrients);
- Removal of snags and partial or full obstruction of fish passage;
- Changes in hydrology (via changes in patterns of land use and stormwater runoff, channelisation of watercourses, etc.);
- Encroachment of development leading to loss and fragmentation of habitat;
- Changes to vegetation structure (such as underscrubbing) to permit access;
- Disturbance; and
- Inappropriate fire regimes.

As noted by Freewater and Gladstone (2010), there have been several flora and fauna surveys targeting specific sites or species, however there is not readily available a data set available for a systematic survey of changes in lagoon flora and fauna. The data collected for the purposes of this study should significantly aid this process in establishing a baseline condition for the present day.

Some of these issues have been discussed in further detail below.

Weeds

Weeds are a common issue for all the lagoons and represent an ongoing issue for management. Weed species may be transmitted to an area via a range of processes including, natural and artificial watercourses, deliberate planting by members of the community or other individuals, illegal dumping of vegetative material, or transport of seeds via animals. Many of these processes are difficult to manage and public education would be the main technique. Currently weeds are managed through Bushcare activities, which are facilitated by Council but are largely volunteer organisations. These Bushcare groups perform an important function in revegetating disturbed areas and removing weeds and it is recommended that Council continue to provide the necessary resources for continuation of this program.

Introduced animal species are discussed in **Section 6.4.1**.

Changes in Hydrology

Wetland and floodplain vegetation habitats are dependent upon periods of both wetting and drying. In addition, the periodic exposure of areas of mudflat are important for providing foraging opportunities for a number of bird species.

Changes in hydrology may result through alterations to land in the catchment and resultant impacts on the timing and delivery of stormwater flows, and through manipulation of lagoon water levels for flood mitigation purposes. In relation to the first point, it is expected that stormwater runoff is delivered to the lagoons more quickly and in higher volumes, resulting in some increase in net water balance due to development of the catchment.

In relation to the second point, the impact of entrance management of lagoon water levels is more complex. AWACS (1994) provide estimate maximum berm heights based on surveys of back beach areas undertaken by Public Works:

- ***Wamberal and Avoca Lagoons*** - berm levels of 3.0m AHD are common, with a level 3.5m AHD achievable over time;
- ***Terrigal Lagoon*** – berm levels of 2.5m AHD could be expected, with a level of 3.0m AHD achievable over time; and
- ***Cockrone Lagoon*** – berm level of 3.5m AHD likely and a level of 4.0m AHD is possible.

These values would represent the likely upper limit of possible lagoon water levels under natural conditions, noting that sufficient catchment inflows would be required to fill the additional volume and also that high rates of percolation through the berm would be observed under these conditions, and that therefore the extreme water levels would only be achieved infrequently. Even when this is taken into consideration, comparison of these values with the analysis of historical water level data (**Figure 4.11**) indicates that the entrance management regime has significantly impacted on the range of water levels that may be achieved naturally within the lagoons. This would have resulted in a higher range of fluctuations in water levels and patterns of wetting and drying along foreshore areas. It is likely that vegetation dependent upon even infrequent inundation would have been lost over time as a result. There is concern that frequent opening of the lagoons is causing a reduction in the extent of floodplain forests where few new seedlings have appeared and older trees are not being replaced (Freewater and Gladstone, 2010). The loss of those wetland areas would have resulted in a contraction in the available habitat for a variety of species, including for example the Green and Golden Bell Frog and a number of bird species.

However, management of lagoon water levels has been undertaken for around 40 years and no historic data is available on changes to vegetation. In addition, this practice is unlikely to be relaxed in the future due to the risk to life and property.

Physical Disturbance

Fringing vegetation may also be lost or degraded in relation to the activities of adjacent landowners and recreational use of the lagoons. In the past, reclamation works have also resulted in the loss of wetland areas.

As identified in **Section 8**, the lagoon foreshores have been developed for recreational access and amenity. This has involved the replacement of native vegetation with grassed open space in some locations. Vegetation has also been lost or otherwise impacted in order to provide recreational facilities in some locations. Uncontrolled access, be it due to a lack of formal paths or by people deviating from the designated pathway, has also resulted in damage to vegetation.

Other impacts can result from vegetation management techniques. This can include 'over-mowing' of grassed areas, where mowing extends beyond boundary of the grassed area and infringes on native vegetation. In addition, as noted in **Section 8**, it is understood that there have been instances of deliberate removal of native vegetation by residents in order to enhance views and/or provide access.

Management should target public education, as well as proper planning for and control of recreational use of the lagoons.

Disturbance in the form of loud noises or the presence of dogs may also impact directly on wildlife, birds in particular. In the case of feeding or roosting birds, the presence of a dog in the area may deter birds, and dogs may actively chase and scare off birds at some times. Ongoing enforcement of regulations governing dog walking is very important.

Modification of Fish Habitat

Creeks flowing into the lagoons have also been significantly affected by urbanisation. Construction of roads and buildings, channelisation, removal of snags, erosion and high nutrient loads leading to proliferation of weeds have combined to reduce habitat extent and quality. This impacts upon many invertebrate taxa and fish.

Future Management

Despite urban and rural residential development, the lagoon catchments still maintain high biodiversity values. The lagoon catchments not only provide specialised terrestrial and aquatic habitat but also provide an important corridor for a variety of fauna species that frequently move between the four lagoon catchments (CEN, 2007a). An important habitat link is also provided between the Cockrone Lagoon catchment and Bouddi National Park (CEN, 2007b).

The Wamberal Lagoon and foreshores represents a Nature Reserve under the NP&W Act. The vegetation on the Wamberal Lagoon sand dunes is an excellent example of a successive vegetation assemblage where zones of vegetation reflect different environmental factors along an environmental gradient (NPWS, 1993). The Wamberal Nature Reserve Plan of Management (NPWS, 1993) provides a management framework for the reserve and outlines policies for the sustainable management of the reserve. The reserve is utilised for education and research purposes as well as low-impact recreation. Appropriate and managed research is encouraged within the reserve. Over time, research findings may help to increase understanding of the lagoons and the ecological processes that take place within them.

Freewater and Gladstone (2010; **Appendix D**) provide a range of management recommendations in relation to biodiversity management.

6.6 Potential Influence of Climate Change on Lagoon Biodiversity

As discussed in **Sections 4.10 and 5.5**, the lagoons are likely to exhibit the following responses to climate change:

- Higher average water levels;
- Less variation in water levels than is currently the case;
- An increase in the frequency of breakouts; and
- Increasing marine influence.

While estuarine biota are generally well adapted to the range of environmental conditions experienced in these environments (see **Section 6.2**), variation in species-specific requirements with respect to physio-chemical parameters (e.g. patterns of inundation and salinity), along with inter-specific competition, results in the establishment of characteristic assemblages. This can be observed in the zonation of estuarine vegetation. Therefore, it is reasonable to expect a shift in patterns of diversity and abundance within estuarine assemblages under a climate change scenario. This section provides a brief discussion of the potential response of estuarine biodiversity to climate change.

One of the readily observable changes in estuarine processes that will likely occur under climate change is an increase in the average standing water levels of the lagoons. This will lead to inundation of parts of the foreshore that are currently not inundation, or only on an infrequent basis. The way in which the existing assemblages of estuarine vegetation will respond is dependent on their species-specific tolerances to inundation by saline water. The few studies of estuarine species that have been undertaken suggest that tolerance to waterlogging, and waterlogging with saline water, varies dependent upon both the species and the stage of growth of the plant (e.g. Barrett-Lennard, 2003; Clarke and Hannon, 1970). While mature vegetation may not suffer mortality, sub-lethal effects may result and seed germination and propagation may decline. In terms of vertical migration by foreshore vegetation, this will be limited in some locations by the presence of infrastructure, resulting in a net loss of fringing vegetation. Vertical migration of aquatic vegetation may also be required due to an increase in water levels and resultant decrease in light penetration to locations where aquatic plants (e.g. Ruppia or seagrasses) currently occur.

The macroalgae presently observed in the lagoons may become less prevalent due to low tolerance of saline waters. In combination with the increased frequency of breakout events, this would likely lead to a decrease in the incidence of blooms by those macroalgal species that are currently problematic in the lagoons. Assuming, however, that eutrophic conditions persist then there may simply be a shift to another bloom forming algal species that is more tolerant of a wider range of salinity.

As indicated in **Section 6.2**, biological exchange between the lagoon and the ocean is an important ecological process and "boom and bust" cycles where a breakout event coincides with a mass spawning or recruitment event have been observed on many occasions for Avoca Lagoon (M. Kilp – T. Mackenzie, Cardno, pers. comm). The timing of breakout event is very important in this regard and an increase in the frequency of breakout events would likely translate to an increase in the likelihood of coincidence of breakout with recruitment opportunities, although it is noted that this may include recruitment of pest species.

Further discussion on potential changes in lagoon biodiversity has not been provided due to high levels of uncertainty as to the direction and magnitude of change in physical and water quality processes. It may be that the range in environmental variables observed under climate change conditions is not significantly different to that which occurs in the present day, in which case lagoon biodiversity may not undergo much change, particularly with reference to aquatic species. It is also important to consider the timescales over which these changes may occur and the high rate of natural variability that is inherent to these systems. Ongoing monitoring of lagoon ecology will become increasingly important in identifying any impacts of climate change and in facilitating a management response (where required).

This discussion of the potential implications of climate change for estuarine biodiversity assumes that management will continue as it does at present. This may not be the case, particularly in the context of Terrigal, for which the current entrance management strategy has been identified as being unsustainable.

6.7 Summary of Key Processes and Management Implications

The key processes and management issues identified in relation to lagoon ecology are as follows:

- ***ICOLL Ecology:*** ICOLLs are a subset of estuaries that, under natural conditions, experience long periods of isolation from the sea punctuated by periodic breakouts. Such systems are subject to large and often rapid changes in several physical factors including water level, salinity, oxygen, temperature, turbidity and nutrients. The fringing vegetation and wetlands in these lagoons are adapted to periods of constant inundation interspersed by periods of tidal inundation and exposure.

Aquatic fauna, particularly invertebrates, is also adapted to long periods of gradually declining salinity and it is not surprising therefore that the composition of invertebrate assemblages in ICOLLs is different to those in permanently open estuaries. ICOLLs that are opened frequently differ from natural intermittent lagoons primarily in that they experience a greatly reduced range of variability in many of the key physical variables, such as water level and salinity. This may result in reductions in the area of wetland and associated biodiversity since the higher levels of the shore are rarely inundated, but, on the other hand, they may also support a larger number of marine species, such as fish and invertebrates that are not estuarine residents, but periodically migrate to the ocean. More frequent opening also tends to flush out nutrients, but can cause die back of algal mats with decay-driven depletion of oxygen on subsequent tidal inundation resulting in fish kills.

- ***Entrance Management and Lagoon Ecology:*** The University of Newcastle ecological study (**Appendix D**) discusses at length the significant impact that mechanical opening of the lagoon entrances has had on lagoon ecology. Whilst this viewpoint is likely to have some weight, it is noted that active intervention in terms of managing the lagoon entrances has been undertaken since the late 1960's representing a period of around 40 years. Therefore, it is likely that any long term impacts on lagoon ecology resulting from these activities would have occurred by the present day. In addition, it is unlikely that Council or the State Government would now cease these management practices due to the risk to life and property. For these reasons, it is considered that a pragmatic management approach be adopted that seeks to maintain and enhance the lagoon ecology within the parameters of the pre-existing framework.
- ***Introduced Species:*** A number of introduced species are present within the study area, both terrestrial and aquatic. At present, terrestrial weeds are the key issue, however, possible increases in breakout frequency under climate change may create additional opportunities for aquatic introduced or pest species to become established in the lagoons.
- ***Ongoing Monitoring:*** There is limited data available on biodiversity and, perhaps more importantly, ecological function of the lagoons. Given the large amount of variation in ecological and physical processes, ongoing monitoring of key indicators should be considered, particularly in the context of climate change. At present there is no active, adaptive management of the lagoon ecology, apart from some management of terrestrial vegetation.
- ***Conflicts in Usage:*** There are presently some uses of the lagoons that have implications for biodiversity and ecological processes. Management of the lagoon entrance has been discussed above, but it is important to also consider the impacts of recreational usage and catchment management on the lagoon ecology. These impacts are primarily felt along the foreshore, where trampling of habitat and general disturbance of animals occurs. The key impact on aquatic habitats is likely eutrophication, which contributes to the incidence of algal blooms.

7 Cultural Heritage

7.1 Overview

A desktop and database survey was undertaken to identify cultural items and identify how they are integrated within the estuarine processes. Cultural heritage assessment included consideration of both Aboriginal and non-Aboriginal (European) heritage.

Investigations with respect to Aboriginal heritage included relevant consultation with the interested Aboriginal communities, formation of a general history of the area including environmental development, and identification of sites listed in the Aboriginal Heritage Information Management System (AHIMS) database. This assessment indentifies a number of issues which will need to be considered when managing Aboriginal heritage of the area.

The occurrence of non-Aboriginal heritage within the study area is considered in **Section 7.3**. This section includes a general history since European settlement and identifies protected heritage sites listed on a series of government registers. It also discusses some of the issues likely to be faced when considering management of the heritage of the area.

Where cultural heritage items are identified, discussion is provided as to the potential opportunities and constraints (both in terms of cultural heritage and other estuary processes) that are posed by the features. General management issues surrounding heritage items in association with estuary process and climate change are also reviewed.

7.2 Indigenous Heritage

The Greater Sydney Basin has been inhabited by the Aboriginal people for at least 20,000 years according to available radiocarbon dates. The earliest known site in the Gosford region is the Loggers Shelter at Mangrove Creek dating to 11,050 BP (Before Present). Given this length of history the location (and function) of many Aboriginal heritage items within the study area can vary significantly (i.e. Aboriginal sites identified may have been utilised when sea level was about 120 metres below present day value). The preservation of the Aboriginal story, through both time and geography, is a key management focus that needs to be established.

The Gosford area has traditionally been inhabited by the Kuringai and Darkinjung people. The arrival of Europeans within these communities from 1788 is known to be associated with rapid declines in Aboriginal populations through disease (e.g. small pox) and fighting over land settlement (HLA Envirosciences, 2005). Land grants provided to settlers limited access to resources by local Aboriginal communities. By 1841 only 16 Aborigines were recorded as living within the Gosford region (HLA Envirosciences, 2005). This rapid decline in population thus resulted in a lack of knowledge regarding Aboriginal practices in the area and highlights the need to adopt a temporal/geographical approach to Aboriginal conservation; identifying and preserving the story associated with the items which have been identified.

Aboriginal Items

The geology of the catchment areas for each of the coastal lagoons is typically composed of sandstone and shales. These large areas of relatively soft sandstone are susceptible to rapid erosion, leading to the formation of numerous rock shelters along the coast. Such shelters are recognised as being highly utilised by the local Aboriginal communities, and are commonly associated with findings of Aboriginal items (middens, rock engravings, tools). This erodible nature of the geological substrates is fundamental to the Aboriginal utilisation of the region. However, these erodible properties make many existing heritage items particularly susceptible to degradation and decay through natural processes which may require active management.

A search of AHIMS provided information relating to Aboriginal sites in the area as summarised below:

- 30 known sites/items have been identified in the Gosford Coastal Lagoons Catchment. Within the catchment of Brisbane Water to the south of the study area some 274 items have been identified (Cardno, 2008b).
- The majority of these 30 sites are rock engravings, middens or shelters with middens indicating the dominant activities of the Aboriginal people at that location in the past.
- A number of highly sensitive burial sites are also found in the region;
- 25 of the items are located along beachfront, at the mouths of lagoons, or along the related tributaries. To protect these items, site locations are not provided in this report.
- Avoca Lagoon Catchment was observed to have the highest density of sites, with a similar number within the Wamberal Catchment.
- Given the high level of development immediately surrounding many of the lower reaches of the estuaries, the probability of discovering previously unresolved Aboriginal items in these areas is lower than in the upper reaches of the estuary, where there is a high probability of discovering further Aboriginal items.

All Aboriginal sites are protected under the *National Parks and Wildlife Act 1974* and therefore any management considerations that impact upon Aboriginal sites must include this in their design. Known Aboriginal sites should be left undisturbed if possible, however if a management option requires their destruction, a Section 90 “Consent to Destroy” permit must be sought from DECCW. Normally a Section 87 Preliminary Research Permit is required as a precursor to a Section 90. This can be a long process that should be factored into management plans. Under the *National Parks and Wildlife Act 1974* it is a requirement that any developments show “due diligence” with regard to Aboriginal heritage in the area.

Based on distribution of known items and existing development, a predictive modelling exercise was undertaken by the study team to identify areas which are known or considered likely to contain Aboriginal items within the Coastal Lagoon catchments, as illustrated in **Figure 7.1**. Further ground truthing of these areas and riparian corridors is required to effectively manage Aboriginal heritage. In particular, the close association of Aboriginal items and waterbodies should be considered when developing management actions. Erosion of sandstone or buried items can result in damage or even loss of items. This is of social concern to aboriginal communities, particularly in regards to burial sites (e.g. burial site skeletal remains either becoming exposed, or washed away). Management initiatives should consider the potential for capping, relocation or restoration where appropriate and involve regular monitoring works and surveys.

The known high utilisation of the general study area by Aboriginal communities in the past means that any development or works will need to seriously consider the likelihood of Aboriginal heritage on the site in question, and develop a budget and timeframe that incorporates this consideration. It is recommended that consultation be initiated with the local Aboriginal community early in the project in order to ensure due consideration of these factors.

Declared Aboriginal Places

Places within Australia have different levels of cultural significance to the different Aboriginal communities, reflecting the diversity in how Aboriginal people view their cultural heritage. Under the NPW Act 1974 such places can be gazetted to be Declared Aboriginal Places. Such places typically carry a relationship between one person and another, and between people and their environment. These places are critical in maintaining the Aboriginal story within a region.

Under Section 90 of the NPW Act 1974 it is an offence to damage, deface or destroy an Aboriginal place without consent. The potential impacts of the development on an Aboriginal place must be assessed if the development will be in the vicinity of an Aboriginal place.

No Declared Aboriginal Places currently occur within the study area. However, such areas may be declared in the future. This may constrain management opportunities in regards to estuary processes.

Land Claims

A number of Native Title Land Claims have been made under the Native Title Act 1993 within the Gosford LGA and by the Darkinjung community. Currently, none of these land claims occur on areas where Native Title is present. The designation of any future native title lands will impact upon management procedures in the area.

Consultation

The local indigenous people are the Darkinjung. Darkinjung country is comprised of mainly the Gosford and Wyong LGAs. Debra Swan from the Darkinjung Local Aboriginal Land Council (LALC) was contacted as representative of the wider community. Ms Swan provided useful information regarding current management efforts in regard to preservation of Aboriginal items (**Section 2.2**).

7.3 Non-Indigenous Heritage

The greater Gosford area was not significantly settled by Europeans until 1823. Use of the Central Coast first developed after the establishment of a penal colony in Newcastle in 1804. However, it was not until James Webb established a property in Brisbane Water in 1823 and the distribution of land grants that development within the region established itself (predominantly agricultural in nature).

In comparison with Aboriginal heritage issues there is a much stronger connection between the heritage items in question and the current society in place. This provides for both a large number of items of heritage significance and the ability to discriminate between those that are of representative value and those that are not. Management of non-Aboriginal heritage needs to take into consideration both the costs associated with conservation and the value of the specific item in question.

7.3.1 Terrestrial Heritage

A series of online databases were searched to identify historic heritage relating to the study area, including:

- State Heritage Register (NSW Heritage Office);
- State Heritage Inventory (NSW Heritage Office);
- Gosford Local Environment Plan (GCC);
- Register of National Estate (Australian Heritage Commission); and
- National or Commonwealth Heritage List (DEWHA).

At the time of writing a total of some 187 historic sites were listed in the Gosford LGA. Of these, just seven are located within the four lagoon catchments. These seven Heritage listed sites (and the catchment in which they occur) are recorded in **Table 7.1**. All items have local heritage significance, except the Wamberal Lagoon Nature Reserve, which has National heritage significance.

Table 7.1: Listed Heritage Items in or near the Study Area

Item Name	Catchment	Address	Suburb	Description	Listing
Wamberal Cemetery	Wamberal	Ulamba Avenue	Wamberal	Cemetery	GPSO (2007) State Heritage Register
Allen MacMaster’s Gravestone	Cockrone	Corribeg Reserve, Tudibaring Parade	Macmasters Beach	Gravestone	GPSO (2007) State Heritage Register
“The Gunyah”	Terrigal	Lot B, DP347541, 168 Terrigal Drive	Terrigal	House	GPSO (2007)
“Seville”	Terrigal	Lot 1, DP348393, 374 Terrigal Drive	Terrigal	House	GPSO (2007)
Former Uniting Church	Terrigal	Lot 5, DP959078, 600 The Entrance Road	Wamberal	Church	GPSO (2007)
Erina Heights Public School	Terrigal	The Entrance Road	Erina Heights	School	GPSO (2007)
Wamberal Lagoon Nature Reserve*	Wamberal	Ocean View Drive	Wamberal	Natural Reserve	Register of the National Estate

The location of these heritage items is displayed in **Figure 7.2**. Of the listed heritage items, the majority are located within highly urbanised areas. The only items in close proximity to the estuarine foreshore were:

- ***The Gunyah*** – A historical cottage built 100 years ago by James Stewart. "Gunyah" is the local aboriginal word for "shelter". The cottage is within 30m of Terrigal Lagoon, separated only by Terrigal Drive, and immediately upstream of the Ocean View Drive bridge.
- ***Wamberal Cemetery*** – The cemetery is located immediately adjacent to Wamberal Lagoon Nature Reserve. It was first dedicated in 1881 and is closely associated with the early development of the Wamberal region.
- ***Wamberal Lagoon and Nature Reserve*** – Wamberal Lagoon Nature Reserve consists of a coastal lagoon and an associated holocene sand barrier vegetated with a wide range of remnant habitat. The reserve is bounded by the ocean for 1.5km on its eastern margin and elsewhere by built up areas which are also largely associated with the relatively recent phase of rapid siltation of the lagoon. As identified in **Section 3.5** of this report, the vegetation contained within the reserve is unique and contains a number of endangered species and communities. As this site is listed on the Register of the National Estate it is protected by Commonwealth Legislation.

All heritage items within the catchments should be managed appropriately and taken into consideration during and development or management action. In particular, any works that may physically or visually impact on these areas should be sympathetic to nature of the heritage items. In terms of estuary management this will be pertinent for the two identified heritage items in close proximity to the estuaries. In particular, the ecological and hydrological processes and management of Wamberal Lagoon must give due consideration to its protected status. Any management actions should seek to sustain and improve the estuarine processes contributing to the unique characters of the Lagoon.

7.3.2 Maritime Heritage

Two online databases were searched to identify shipwrecks in Brisbane Water and its surrounding tributaries:

- National Shipwreck Database (DEWHA).
- Maritime Heritage Online (NSW Heritage Office).

These databases indicated the occurrence of 19 wrecks along the coastline covered by the four lagoon catchments (and up to three miles offshore). The wrecks are recorded in **Table 7.2**.

Table 7.2: Shipwrecks in Brisbane Water Estuary and Surrounding Waters (after: HLA Envirosciences, 2005)

Ship Name	Type	Date Lost	Location
Sir Robert Peel	Ship	1847	Avoca Bay
Union	Ketch	1848	Avoca Bay
Barangaroo	Hulk	1933	Off Terrigal
Commonwealth	Screw Steamer	1916	Foggy Reef, Terrigal
Fifeshire	Screw Steamer	1886	Moores Beach, Terrigal
Friend	Cutter	1860	Terrigal Head

Ship Name	Type	Date Lost	Location
Galava	Screw Steamer	1927	3 miles off Terrigal
Gitana	Ketch	1857	Terrigal
Kathleen	Barquentine	1867	Between Terrigal and Norah Head
Lord Ashley	Screw Steamer	1877	Terrigal Reef
Maud Weston	Screw Steamer	1904	Terrigal Head
Pompey	Schooner	1852	Terrigal
Rainbow	Ketch	1857	Terrigal
Rose	Schooner	1852	Terrigal Beach
Tamar	Paddle Steamer	1873	Terrigal
The Pathfinder	Motor vessel	1934	Terrigal (1.5 miles east)
Wave	Brig	1868	North of Terrigal
William and Alexander	Ketch	1892	Terrigal Beach
Queen Bee	Steamer	1922	Broken Bay 2 miles NE

The precise location and nature of these wrecks, as well as their current condition, is poorly known. The majority of wrecks are considered likely to have occurred offshore as vessels travelled between Sydney and Newcastle. However, some vessels may have either run aground on the foreshore, or even potentially within the estuaries (most likely Terrigal or Avoca Lagoons).

All shipwrecks are protected under Commonwealth and State legislation, including the *Historic Shipwreck Act 1976* and the *Heritage Act 1977*.

It is considered unlikely that the presence of shipwrecks would significantly impact upon existing estuarine processes or provide management constraints or opportunities. However, given the number of wrecks recorded in the area, the potential for occurrence should be considered for all estuarine and shoreline works.

7.4 Climate Change and Cultural Heritage

The potential impacts of climate change on estuarine processes are discussed in **Sections 3.10 and 4.10**.

Both the Aboriginal and non-Aboriginal Heritage items in the area have the potential to be influenced by these changes; particularly those items either within (i.e. Maritime Heritage) or in close proximity to the estuarine regions. Negative outcomes on heritage items from climate change impacts may include:

- Increased rate of decay through temperature/salinity changes (increase maintenance costs);
- Submergence of heritage items;
- Erosion of substrate (leading to partial or entire loss of items); and
- Restriction on public access to heritage items.

Any management plans to address cultural heritage within the estuary regions would need to include measures in response to these issues.

7.5 Summary of Key Processes and Management Implications

The key processes associated with, and impacting upon cultural heritage within the vicinity of the four lagoons are summarised below:

- ***Aboriginal Heritage:*** The natural resources found in the estuary and catchment made the Gosford Coastal Lagoons an attractive place for Aboriginal groups. Subsequently, a large number of Aboriginal places and items have been found within the area. In particular, the Avoca Lagoon and Wamberal Lagoon catchments have the greatest number of known aboriginal items. Some work has recently been undertaken by the CMA in association with the Darkinjung LALC on methods to manage the impacts of coastal processes on heritage sites (e.g. relocation of sites or capping of middens). Any proposals regarding the management of or impacting upon Aboriginal heritage items should be developed in consultation with local Aboriginal people.
- ***Aboriginal Heritage – Unidentified Sites:*** With respect to the Aboriginal heritage of the Gosford Coastal Lagoons, there is a high probability that further Aboriginal items exist and may be discovered. The need to identify and protect items, particularly those likely to be influenced by estuarine processes and/or management actions, is of high importance.
- ***Non-Aboriginal Heritage:*** There are seven items of European heritage significance located within the estuary catchments, two of which are in close proximity to the estuary foreshores. These sites are particularly sensitive. Any future management plans need to consider potential impacts on these items.
- ***Maritime Heritage:*** A number of ships have been wrecked within the general Gosford Coastal Lagoons region. Most of these would have occurred off the coast. The exact location of these wrecks is largely unknown. There is potential for wrecks to have occurred near to or at the entrance of the lagoons, but the likelihood of these wrecks being uncovered is low.
- ***Climate Change:*** The implications of global climate change and sea level rise should be considered in the ongoing management and conservation of historic sites and artefacts, both Aboriginal and European. Significant information is now available in regards to potential hazards posed by climate change. This information should be used to inform the management of heritage items, particularly for those items which are located in foreshore areas, or partially submerged.

8 Recreational Usage

8.1 Overview

Wamberal, Terrigal, Avoca and Cockrone lagoons provide a significant recreational resource for the local community and regional visitors to the area. This is primarily due to the aesthetic and ecological values of the lagoons, combined with their proximity to populated areas.

In part due to differing foreshore land ownership (**Section 8.2.1**), recreational usage of the waterways and foreshores varies for each lagoon. Avoca and Terrigal Lagoons, for example, are utilised more frequently by individuals with hired paddle craft, due to the availability of such vessels on these lagoons (**Section 8.2.3**).

8.2 Recreational Amenity

According to a survey conducted by the Central Coast Community Environment Network (CCCEN), approximately 92% of respondents thought that Avoca Lagoon and its catchment have recreational and aesthetic appeal and cultural significance (CEN, 2007c). In a similar survey, 98% of respondents thought that Cockrone Lagoon and its catchment have recreational and aesthetic appeal and cultural significance (CEN, 2007d).

The surveys for Avoca and Cockrone Lagoon (CEN, 2007a and b) also asked residents to rank known environmental issues in order of importance. Highly ranked environmental issues included:

- Water quality,
- Lagoon opening,
- Siltation,
- Littering and dumping of rubbish, and
- Exotic plants.

These results may have implications for the management of the lagoons in terms of recreation. The survey results indicate which features of the lagoons attract (or deter) visitors, as well as highlighting which activities or processes the public are concerned about from an ecological perspective.

The similarities between the ranked issues for Avoca and Cockrone Lagoons may suggest that these issues would rank highly for all four lagoons. Data for the Terrigal survey was not available and no survey was undertaken for Wamberal Lagoon.

It is understood that Council intends to gain feedback on management issues from the community via the use of a community feedback form that will be distributed at the community information session undertaken in May 2010. This will likely provide useful further information that may inform recreational planning for the lagoons.

8.2.1 Publicly Accessible Foreshores

All four lagoons incorporate varying degrees of access to the lagoon foreshores. Foreshore land ownership varies with each lagoon, but generally consists of a combination of Crown land, Council-owned community land, nature reserve and private land. Foreshore land use and land tenure is discussed in more detail in **Section 3.3**.

In assessing the mapping of land tenure as shown in **Figure 3.4**, it is apparent that the amount of foreshore lands in public ownership is greatest at Wamberal Lagoon. This is due to the presence of the Nature Reserve (**Section 8.3.1**), which extends across the lagoon waterbody and all the foreshores. However, it is noted that accessibility is still largely limited to the southern foreshore along Remembrance Drive due to dense natural vegetation covering a large proportion of the remaining foreshore.

Mapping for Terrigal and Avoca Lagoons shows that the extent of Crown lands and community land does not cover the entire lagoon foreshores and direct public access to the waterway can be limited. However, while more of the Terrigal Lagoon foreshore is abutted by private property, most of the areas that are accessible to the public are highly modified and managed for passive recreation, and are therefore easily accessible. As a result, Terrigal Lagoon is more readily accessible to the general public than any of the other lagoons.

For Cockrone Lagoon, Crown lands are confined to the coast and do not include any lagoon foreshores, however there are some stretches of community land along the foreshores of the lagoon. Additionally, a number of informal access points exist around the foreshores of the lagoons, including informal craft launching points.

It is noted that in some locations illegal clearing of foreshore vegetation has occurred to provide access from private properties to the lagoon foreshores and to enhance views. This type of activity can have significant implications for lagoon ecology and bank stability.

The distinction between *publicly owned land* and *direct access* to the foreshores is important in the management of recreational activities, e.g. foreshore land that is publicly owned and theoretically accessible to the public may not actually be accessible due to a lack of direct access points or routes such as walking tracks. This is the case for Wamberal Lagoon, which, being a Nature Reserve, has only a few access points. However, for this location, imposing some restrictions on access is consistent with maintaining this natural resource as a nature reserve.

At the entrances to all of the lagoons, direct public access to the lagoon foreshores is generally good. Land-based access tends to diminish with increased distance from the entrance. Privately owned lands dominate much of Terrigal Lagoon, with access points generally confined to near the entrance and near the Willoughby Road Bridge. Avoca Lagoon is similar, with access points at the Scouts Hall and near the recreational area at the entrance. Cockrone Lagoon has some access points at the entrance, however fencing (such as the permanent fencing observed on a site inspection to the area) limits public access to the western reaches of the lagoon.

8.2.2 Land-Based Recreational Facilities

Picnic areas, picnic tables and seating, barbeques, playgrounds, toilets and car parking facilities are provided at various locations around each of the lagoons, and these facilities are likely to be frequently utilised by various recreational users. These features compliment the water-based facilities and recreational users may utilise them before or after participating in water-based or land-based recreational activities.

For some foreshore areas, land-based access to the lagoons is very limited, e.g. the western side of Cockrone Lagoon (**Section** 8.2.1). Walking tracks are not prevalent in many areas of the lagoon foreshores. No formal cycleways exist along the foreshores of the lagoons, and as such, cycling as a recreational activity is likely to be carried out on roads and footpaths in the vicinity of the lagoons.

8.2.3 Water-Based Recreational Facilities

There has been a long history of recreational boating in two of the lagoons. Avoca Lagoon has one commercial operator, Aquamuse, who hires out small paddle-craft such as canoes, kayaks and paddle-boats. They have been operating on Avoca Lagoon for approximately 30 years, however, there are suggestions that various recreational watercraft hire businesses have been present at Avoca Lagoon for as long as 50 years. Terrigal Lagoon has two commercial operators, Terrigal Paddle Boats (which has been operational since at least 1970), which hires out craft such as paddle-boats and kayaks, and Terrigal Water Sports which hires out sailboards.

Hire facilities located on the foreshores are shown in **Figure 8.1**. All these water craft hire operators have obtained a Hire and Drive licence from NSW Maritime (**Table 2.1**). The Hire and Drive licensing system was implemented by NSW Maritime to ensure that safety standards are strictly adhered to by operators of small and human powered hire and drive vessels (NSW Maritime, 2010). A licence must be obtained by the operators of any powered or unpowered vessels including canoes, kayaks and pedal craft.

According to the UBD street directory (2009), there are no formal boat ramps located in any of the lagoons. However, during site visits, informal watercraft launch points were observed in several lagoon foreshore locations.

8.3 Recreational Usage

The following recreational activities are known to be carried out on the lagoons or lagoon foreshores:

- Swimming,
- Fishing,
- Kayaking,
- Paddle-boating,
- Sail-boarding,
- Wind-surfing,
- Rowing,
- Model boats sailing,
- Walking,
- Running,
- Cycling,
- Dog-exercising, and
- Picnicking.

According to the GCC (1995), Terrigal and Avoca Lagoons are likely to be more suited to active or passive recreation with formal recreation facilities, whilst Wamberal and Cockrone Lagoons are more suited to minimal, informal water-based activities (GCC, 1995).

Good water quality is important in maintaining the coastal lagoons for various recreational uses. Water quality is discussed in detail in **Section 5**.

8.3.1 Permissible Activities

Lagoons and Lagoon Foreshores

The recreational activities listed in **Section 8.3** are all permissible in certain areas within the lagoons or lagoon foreshores. Some restrictions apply to the type or location of recreational activities and when they can be carried out. The following applies to recreational activities in the four lagoons (GCC, 1995):

- Motorised boating is not permitted;
- Dog-exercising is only permissible in the designated areas shown in **Figure 8.1**;
- Foreshore picnicking is encouraged only in the locations shown in **Figure 8.1**; and
- Fishing for commercial purposes is not permitted (recreational fishing is permitted).

The majority of the permissible activities undertaken in and around the lagoons are generally compatible with each other, and with the natural values of the lagoons, however conflicts may occasionally occur between different recreational users. Regulations and exclusion areas exist to provide suitable sites within the lagoons and foreshores as a measure to ensure public safety and reduce conflict between different activities. The erection of signage to advise that motorised boating is not permitted in the lagoons, for example, facilitates awareness and decreases the risk to public safety. Similarly, swimming, canoeing and sail boarding are discouraged from areas of high current flow and from sensitive seagrass beds and wetland areas within the lagoons.

Nature Reserves

The Wamberal Lagoon Nature Reserve was dedicated in 1981 for its environmental education value. The frontal dune carries an example of dune vegetation succession that is not found elsewhere near Sydney (GCC, 1995). In accordance with the Wamberal Nature Reserve Plan of Management (NPWS, 1993), use of the reserve is promoted as being primarily for primary, secondary and tertiary education purposes. Research opportunities are also encouraged. Minimal impact and passive recreational activities are permitted within the reserve provided that no damage is caused to the natural condition of the reserve (NPWS, 1993). Water-based and land-based recreational activities of this type are permissible.

8.4 Recreational Fishing

Recreational fishing is a popular activity in the study area. Recreational fishing in the four lagoons is permitted, however some restrictions apply. For all four lagoons, fishing by any method involving the use of a holift net, a hand-hauled prawn net, a push or scissors net (prawns), a crab trap, or a lobster trap is not permitted. Normal bag and catch size restrictions also apply.

A number of species of fish can be caught in the lagoon waters, e.g. mulloway, bream, mullet, flathead and estuary perch. Mulloway season is said to be from November to the end of May, whilst other species are more common in the winter months (Marinews, 1999). Recreational fishers may utilise the entrance and beach environments as well as the lagoons when partaking in a recreational fishing session. The lagoon entrances are particularly popular locations, especially when the entrance has been recently opened, as fish are washed out of the lagoon through the narrow entrance channel. Additionally, Avoca Lagoon is reported to be a popular location for catching live bait.

Further details on fish assemblages in the lagoons is provided in **Section 6.4.4**.

8.5 Tourism

There are approximately 3 million international, domestic overnight and domestic day travellers to the Gosford LGA each year. Whilst no data exists as to how many of these tourists actually visit the lagoons themselves, around 77% of international, 45% of domestic overnight and 25% of domestic day travellers do visit the beaches in Gosford. Swimming and paddling is confined largely to the entrance areas of the lagoons.

Walking is another popular activity enjoyed by tourists, and the foreshore areas offer visitors a chance to appreciate the natural and aesthetic values of the lagoons to those who like to partake in land-based recreational activities.

Avoca and Terrigal Lagoons are both important recreational areas, in part due to the presence of tourist operators that offer activities such as paddle boating, canoeing and sailboarding to visitors (**Section 8.2.3**). Other activities that can be enjoyed by visitors to the lagoons include those listed in **Section 8.3**.

The Central Coast Marine Discovery Centre has recently been established at Terrigal Rotary Park, Terrigal Drive, Terrigal. The Centre brings together a range of stakeholders with diverse interests including environment and conservation, education, tourism, economic development, scientific research and development, natural resource management, business and industry. Their vision is to promote the sustainable use and enjoyment of the coasts and oceans through the use of educational displays, special events, education programs and fun activities for the community. The Centre is open on weekends and during the school holidays.

8.6 Conflicts in Usage

There is potential for conflict to occur between recreational users, or between recreational activities and the ecological values of the lagoons.

Examples of recreational activities that may conflict with other recreational activities are as follows (KBR, 2005):

- Paddle boating, through potential conflict with other boating users, not complying with relevant boating rules and car parking;
- Fishing, through potential conflict with other waterway and foreshore users, not complying with fishing regulations and car parking; and

- Dog-exercising, through odour/visual impact of uncollected dog faeces, water quality impacts where animal faeces are not properly disposed of and potential for aggression between dogs or directed at other users.

Recreational activities that may impact on the natural and environmental values of the lagoons include the following (Freewater and Gladstone, 2010):

- Trampling of foreshore habitats;
- Littering;
- Development of foreshore infrastructure to support visitor amenity and resultant loss/fragmentation of habitat;
- Noise and other disturbances may impact fauna (e.g. birds);
- Increased turbidity; and
- Recreational fishing, through overfishing, erosion of foreshores and increased bank instability due to trampling, seabed disturbance and decreased water quality from boats and collection of bait.

These issues highlight the need for active management of recreational usage of the lagoons.

8.7 Future Recreational Opportunities

Additional future recreational opportunities are likely to be fairly limited due to a number of environmental and land use constraints. It is reasonable to expect that existing recreational amenity and facilities will need to be maintained and enhanced to a small degree in the future in the context of low-impact recreational activities. Future changes to land uses in the lagoon and foreshore areas is unlikely, and high impact recreational activities are not likely to be suitable for the lagoon and lagoon foreshore areas. It is considered that opportunities such as fish stocking are not likely to be viable due to the conditions that are associated with the lagoons (e.g. periodic mechanical opening of the entrances, water quality issues and fish kills).

8.8 Summary of Key Processes and Management Implications

The key processes associated with and impacting upon recreational usage of the four lagoons are summarised below:

- ***Public Access:*** The distinction between *publicly owned land* and *direct access* to the foreshores is important in the management of recreational activities. It is important to actively manage access to the foreshores with consideration of both ecological processes and bank stability. This is likely to require public education, particularly with respect to definition of property boundaries, illegal removal of vegetation and general principles of vegetation management.
- ***Bank Stability:*** Bank conditions vary with each lagoon, both in terms of the area currently experiencing bank instability and erosion and those areas that are vulnerable to erosion which could experience future erosion risk. This has implications for current and future management, especially with regard to recreational and environmental management. This issue should be addressed in the Management Study and Plan. **Section 4** provides further detail on the bank conditions of the lagoons.

- ***Land Ownership:*** Ownership of foreshore lands is important in terms of managing the lagoon banks, maintaining healthy vegetation and providing ecological connectivity. It is recommended that Council and the LPMA capitalise on any opportunities to acquire additional foreshore lands, bringing them into public ownership as they arise in order to maximise opportunities to improve and enhance public access and foreshore ecological values of the lagoons.
- ***Recreational Usage:*** Ongoing active management of recreational activities though the application of tools such as zoning (e.g. designation of off-leash dog walking areas) is recommended in order to manage and minimise conflicts between (and amongst) recreational users and the environment values of the lagoons. As identified in **Section 5**, water quality can periodically deteriorate. Ongoing monitoring of water quality for primary and secondary contact recreation should continue in order to manage the risk to public health.
- ***Lagoon Breakouts:*** Public safety is an issue during mechanical lagoon entrance openings. Direct impacts on public safety may arise through people using the outflow of water in inappropriate ways (e.g. surfing) or bank instability around the entrance, whilst indirect impacts on public safety may arise due to water quality issues associated with the lagoon breakout. Reference is made to photos provided in **Appendix A** for illustration of some of these issues. Active risk reduction is important, particularly with respect to restriction of public access during the actual breakout event.
- ***Climate Change:*** Due to active management of the lagoon water levels for flood mitigation, sea level rise is unlikely to result in inundation of the lagoon foreshores. However, landward migration of the entrance berm may occur and this may impact on public and/or private lands.

9 Discussion

The previous sections of this report have focussed on consideration the broad processes that operate in each of the four coastal lagoons. This section seeks to consider how these different estuarine processes interact with each other and how relates to ongoing management of the lagoons by Council.

9.1 The Management Context

Estuaries are complex environments that sit at the interface between the freshwater and marine environments. Because of their intermittent connection to the ocean, ICOLLs in particular are highly dynamic systems that may experience large fluctuations in environmental variables range from being driven solely by freshwater inputs during periods of closure to marine inputs during periods of ocean flushing. The processes that determine ecosystem status at any given time scales from hours (e.g. breakout) to years (e.g. wet dry and El Niño cycles). As discussed in **Sections 3 and 4**, the two key drivers of the systems are catchment conditions (e.g. catchment inflows and patterns of development) and entrance conditions (flushing and the exchange of marine water). Human activities are currently exerting considerable control on the entrance for flood mitigation purposes, as is described in **Section 4.5**.

This presents a significant challenge to management, with considered decision making a key requirement for the sustainable ongoing management of these systems. The NSW Government (1990) advocates in the *Estuary Management Manual* a holistic and integrated approach to management. This type of approach is described by Haines (2006) as a 'systems-based' approach, taking under consideration the interactions between the various processes, including all physical, chemical and biological processes. This may be directly related to the principles of Ecologically Sustainable Development. Haines (2006) provides a review of the literature in relation to the key concepts.

9.2 Key Interactions

As outlined in **Section 1.2**, the next step of the Estuary Management Process is to prepare a Management Study and Plan. This process will need to be informed by an understanding of the key interactions occurring within the lagoons in order to inform decision making.

Conceptual models are a useful tool for illustrating the complexities of processes operating in a lagoon. An effort has been made to capture the key interactions identified in this Estuary Processes Study in a conceptual process model, as shown in **Figure 9.1**. The model incorporates the following key interactions:

- Catchment Inflows – Water Quality,
- Lagoon Water Quality,
- Sewer Overflows,
- Lagoon Water Levels,
- Lagoon Flushing,
- Riparian Vegetation Condition,
- Seagrass Condition,

Environmental

- Catchment Development,
- Foreshore Flooding,

Social

- Recreational Amenity, and
- Cost of Implementation (capital and ongoing).

} ***Economic***

The conceptual model endeavours to illustrate the linkages between these different processes such that both the direct and indirect impacts of potential management options may be considered in an holistic sense. It effectively permits a triple bottom line approach, assessing the potential environmental, social and economic impacts of a particular management intervention (or combination thereof). This model may be applied to any of the four study lagoons to aid in decision making and may be informed by the data compiled in the undertaking of this study. However, it will be important to consider context in relation to the specific issues and processes occurring in each individual lagoon.

An effort has been made to provide some indication of issues that will require further consideration as part of the Management Study and Plan. More specific recommendations for moving forward with management of the Gosford coastal lagoons are:

- Despite the significance of some ecological features of the lagoons, current management is primarily for social drivers, being mitigation of flood risk, odour minimisation and for recreational usage. There is a need to seek community input on the ecological values of the lagoons perceived as being important and to articulate these as part of the Management Study and Plan. This would allow the current management regime to be modified to enhance any identified environmental values and move towards a more holistic approach.
- More detailed assessment of the link between sea level rise, entrance berm management and flooding is required. As part of that process, there is a need to identify locations in surrounding areas that may be under threat due to sea level rise and devise appropriate management responses. This is particularly important for Terrigal Lagoon.
- In terms of water quality, more strategic monitoring is required to resolve water quality processes prior to, during and after breakout events to assist in developing an effective water quality management response.

10 Conclusions

The overall aim of the study was to document the key physical, chemical and ecological processes that characterise each of the lagoons, as well as those processes relating to human usage and interaction with the four study lagoons: Wamberal, Terrigal, Avoca and Cockrone.

The four lagoons are classed as ICOLLs, being intermittently closed and open. These patterns of opening and closing are mediated on the one hand by catchment processes, with flood flows from the catchment raising water levels sufficient to initiate an entrance breakout event, and on the other hand by coastal processes, with coastal waves and currents re-building the berm resulting in closure of the entrance after a breakout event. Any change in these parameters will result in a change in the entrance behaviour, and therefore impact on the range of processes such as water quality and ecological function.

For this reason, human activities in the catchment, coupled with active management of the lagoon entrances for flood mitigation purposes, has likely resulted in changes in lagoon condition over time. An absence of detailed process orientated data, however, makes it difficult to gain an appreciation of the direction and magnitude of these changes. In any case, it is expected that these activities will continue to be undertaken into the future and therefore continue to exert an influence on lagoon processes.

The study has been undertaken as required under the NSW Rivers and Estuaries Policy and in accordance with the Estuary Management Process outlined by the NSW Government (1990). It is intended that the information detailed in this report will aid Council in providing a basis for moving forward with the development of the Gosford Coastal Lagoons Management Study and Plan.

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Figures

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Gosford Coastal Lagoons Processes Study

FIGURE 1.1
STUDY AREA

LJ2713/R2472/V2
July 2010

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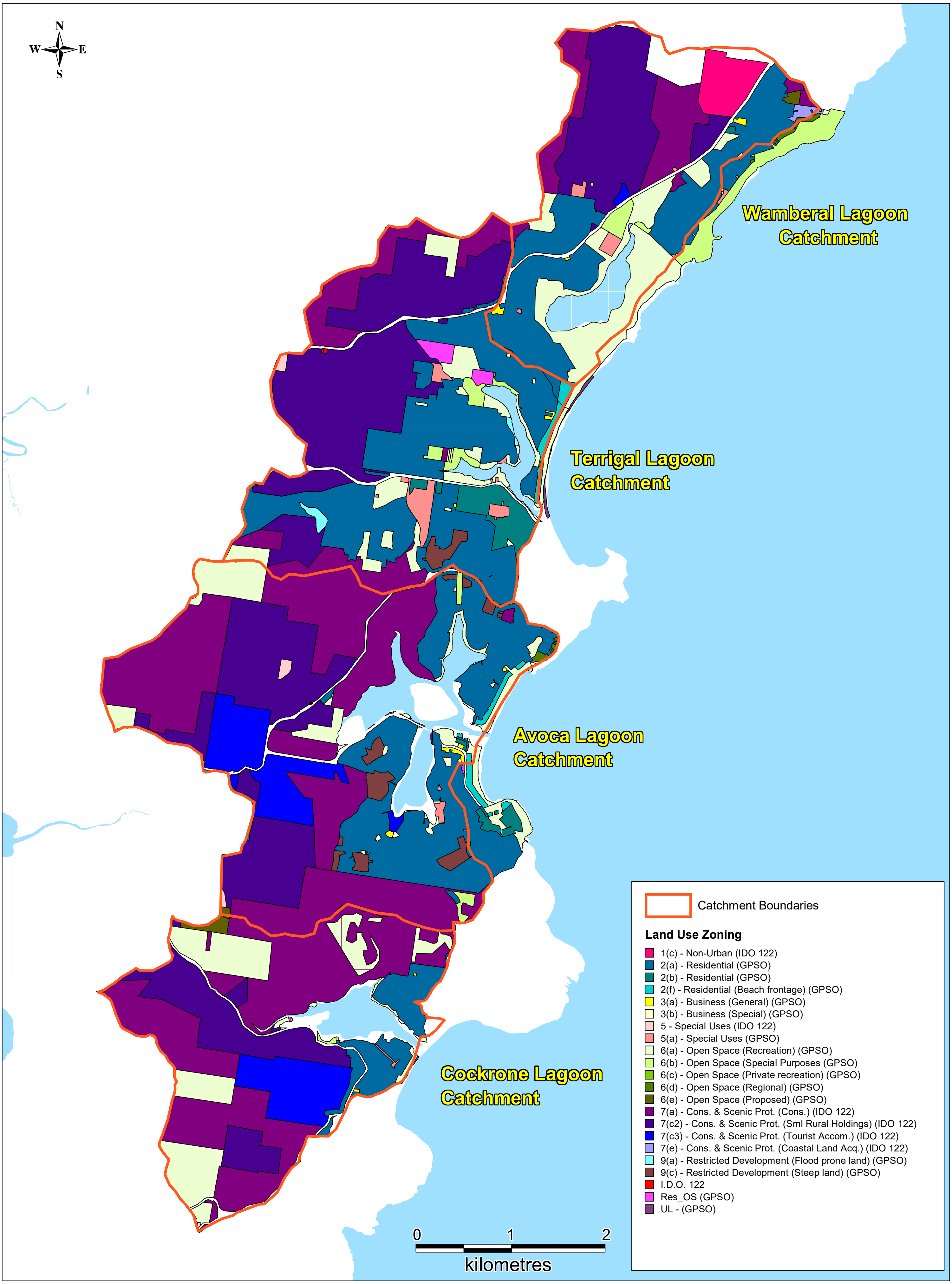
FIGURE 3.1
TRIBUTARY CREEKS



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Gosford Coastal Lagoons
Processes Study

FIGURE 3.2
LAND USE ZONING

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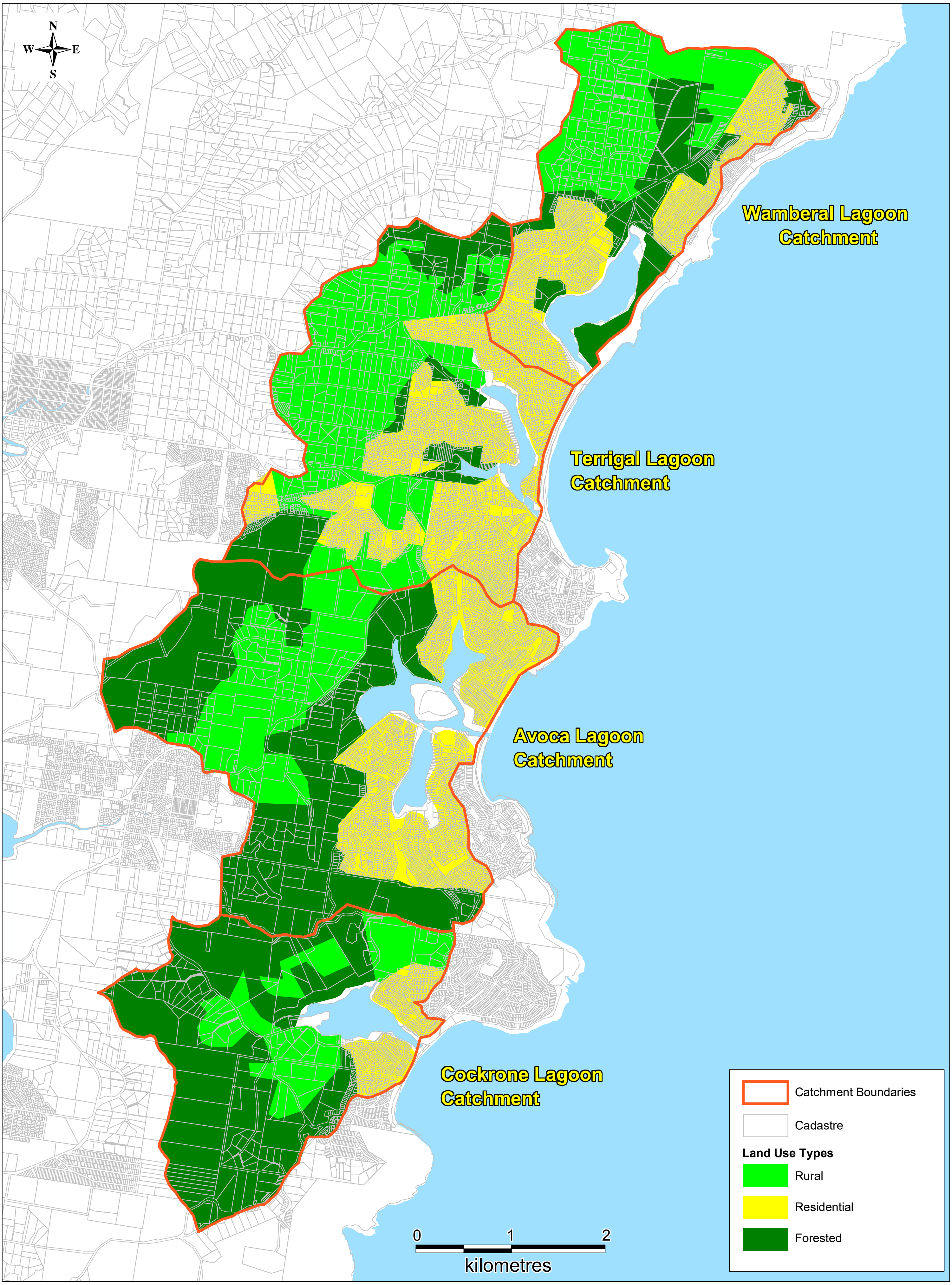
J:\CM\LJ2713\Figures\R2472\Figure 3.2: Land Use Zoning.wor



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Gosford Coastal Lagoons Processes Study

FIGURE 3.3
LAND USE TYPES

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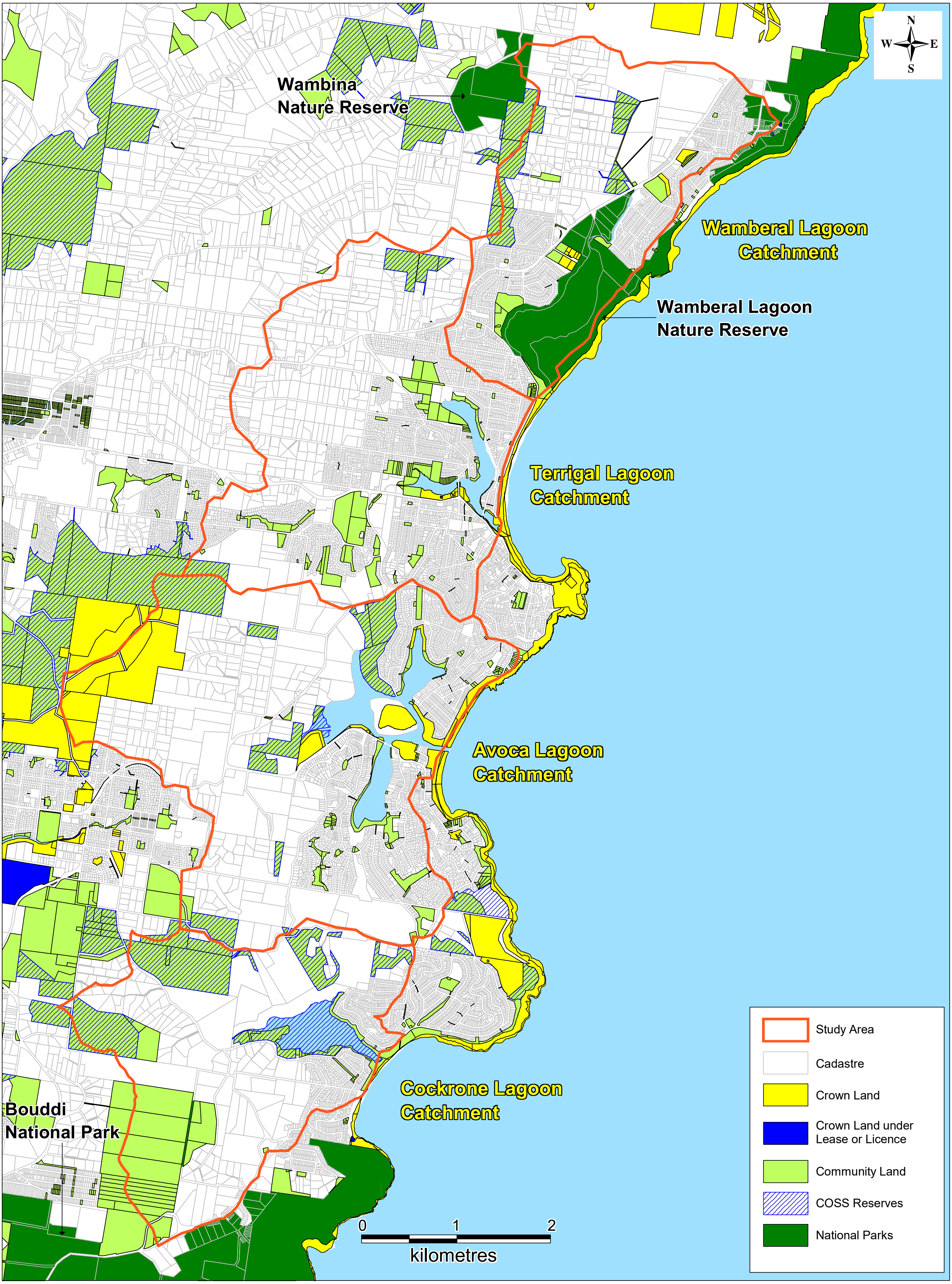

FIGURE 3.4
LAND TENURE

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Processes Study

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July 2010

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FIGURE 3.5
TOPOGRAPHY

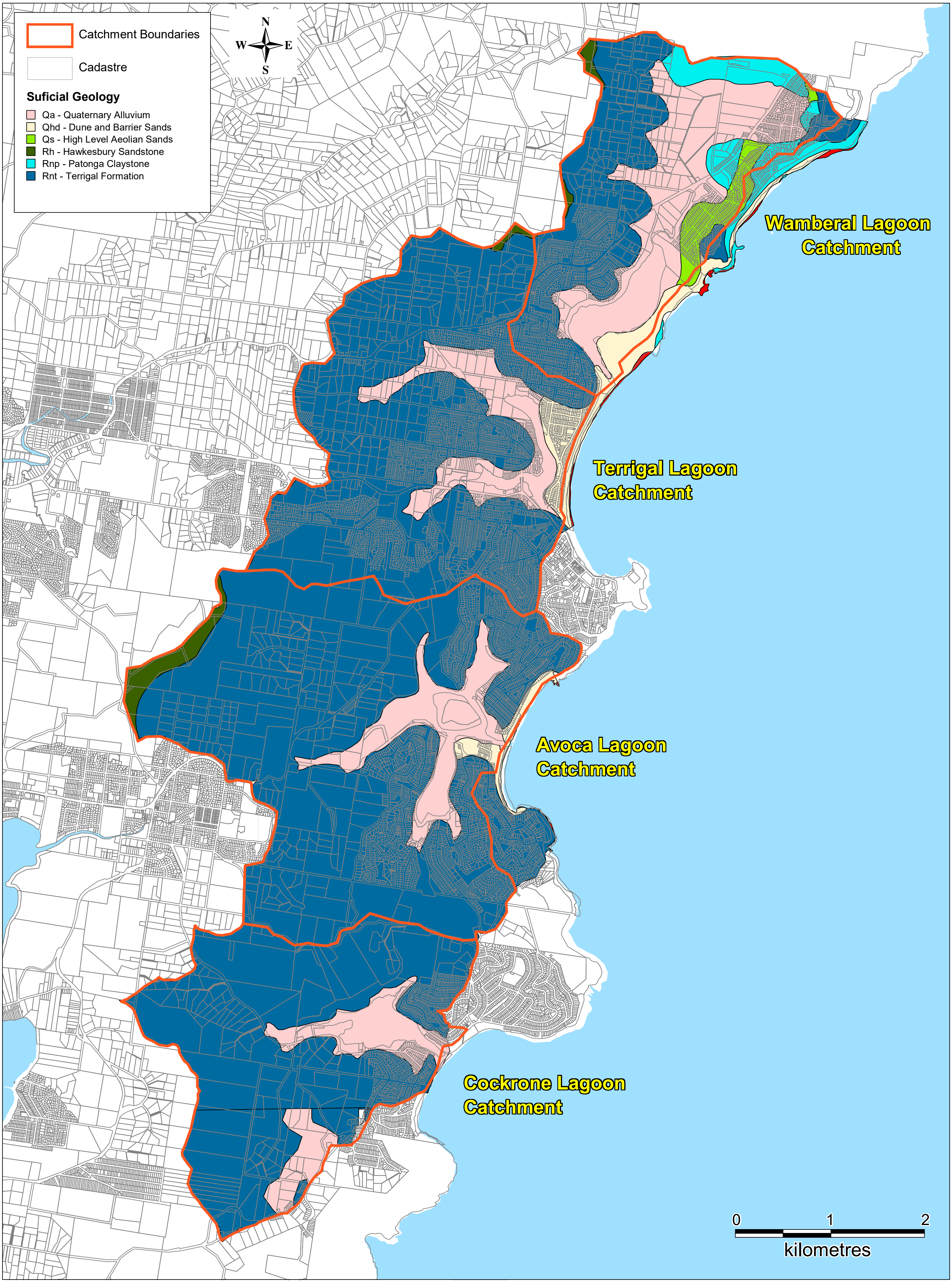

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FIGURE 3.6
GEOLOGY

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J:\CM\LJ2713\Figures\R2472\Figure 3.6: Geology.wor

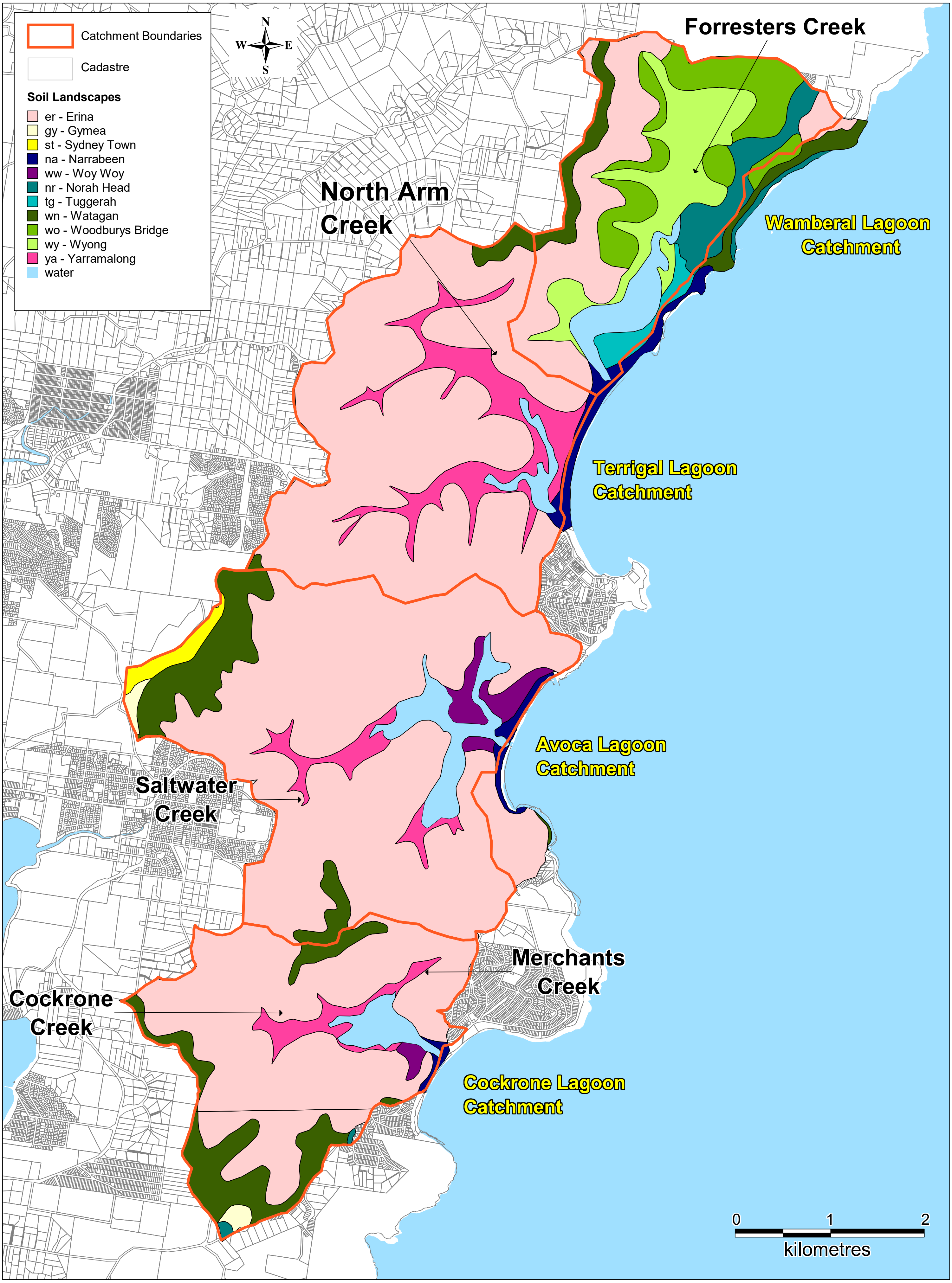

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FIGURE 3.7
SOIL LANDSCAPES

LJ2713/R2472/V2
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J:\CM\LJ2713\Figures\R2472\Figure 3.7: Soil Landscapes.wor

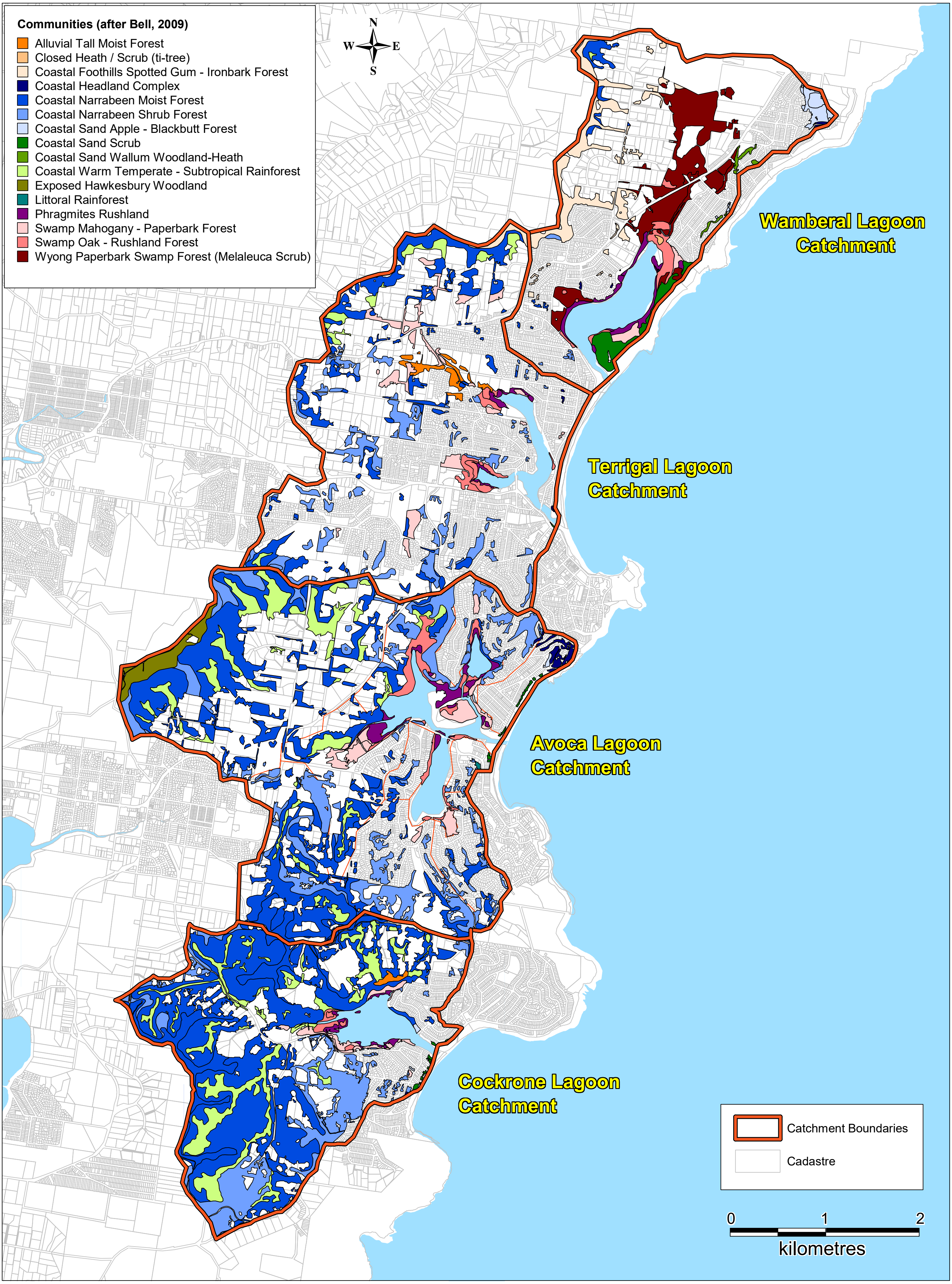

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FIGURE 3.8
TERRESTRIAL VEGETATION

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J:\CM\LJ2713\Figures\Rep2472\Figure 3.8 - Vegetation.wor

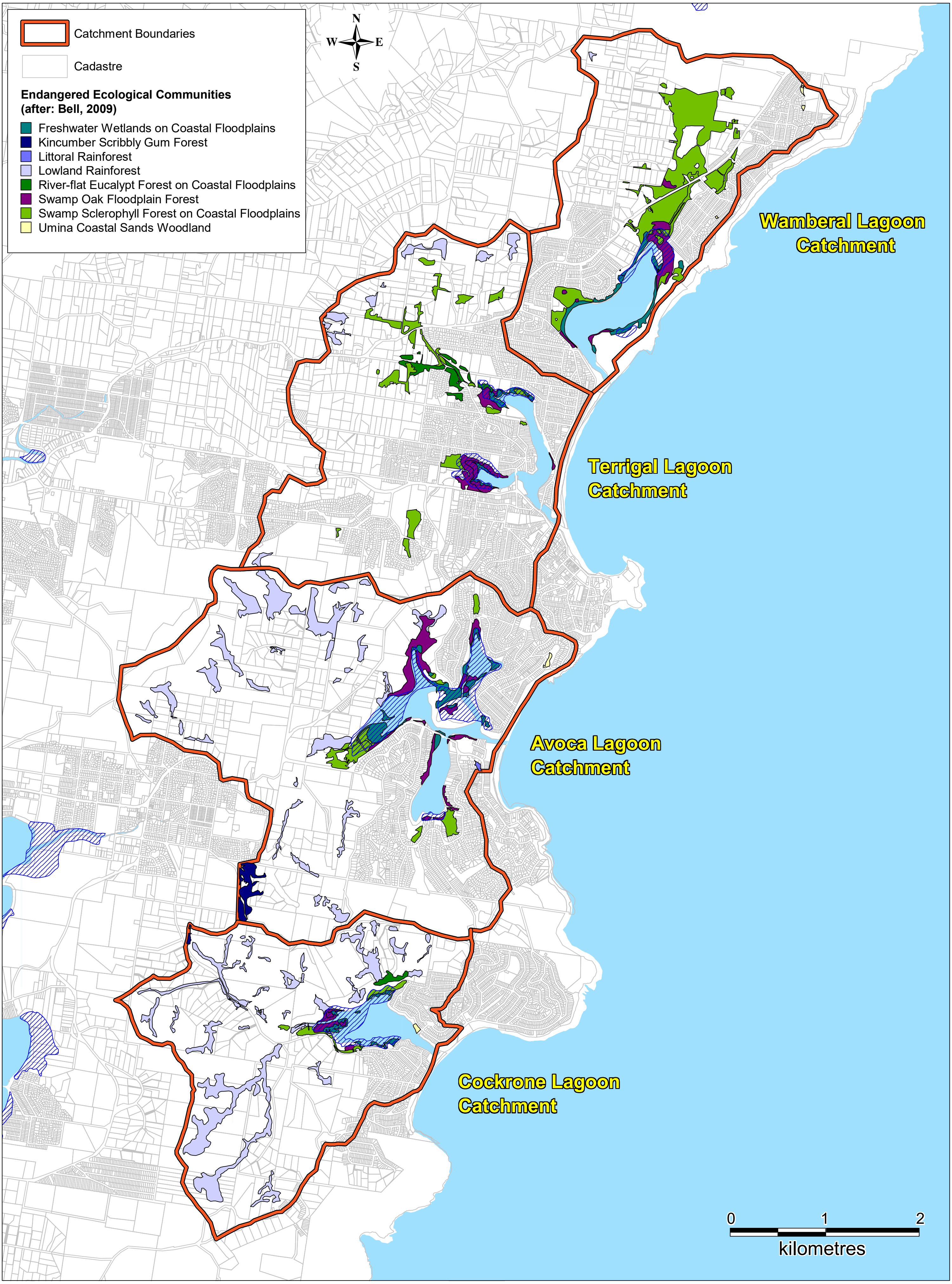

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FIGURE 3.9
ENDANGERED ECOLOGICAL COMMUNITIES

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J:\CM\LJ2713\Figures\Rep2472\Figure 3.9 - EECs.wor

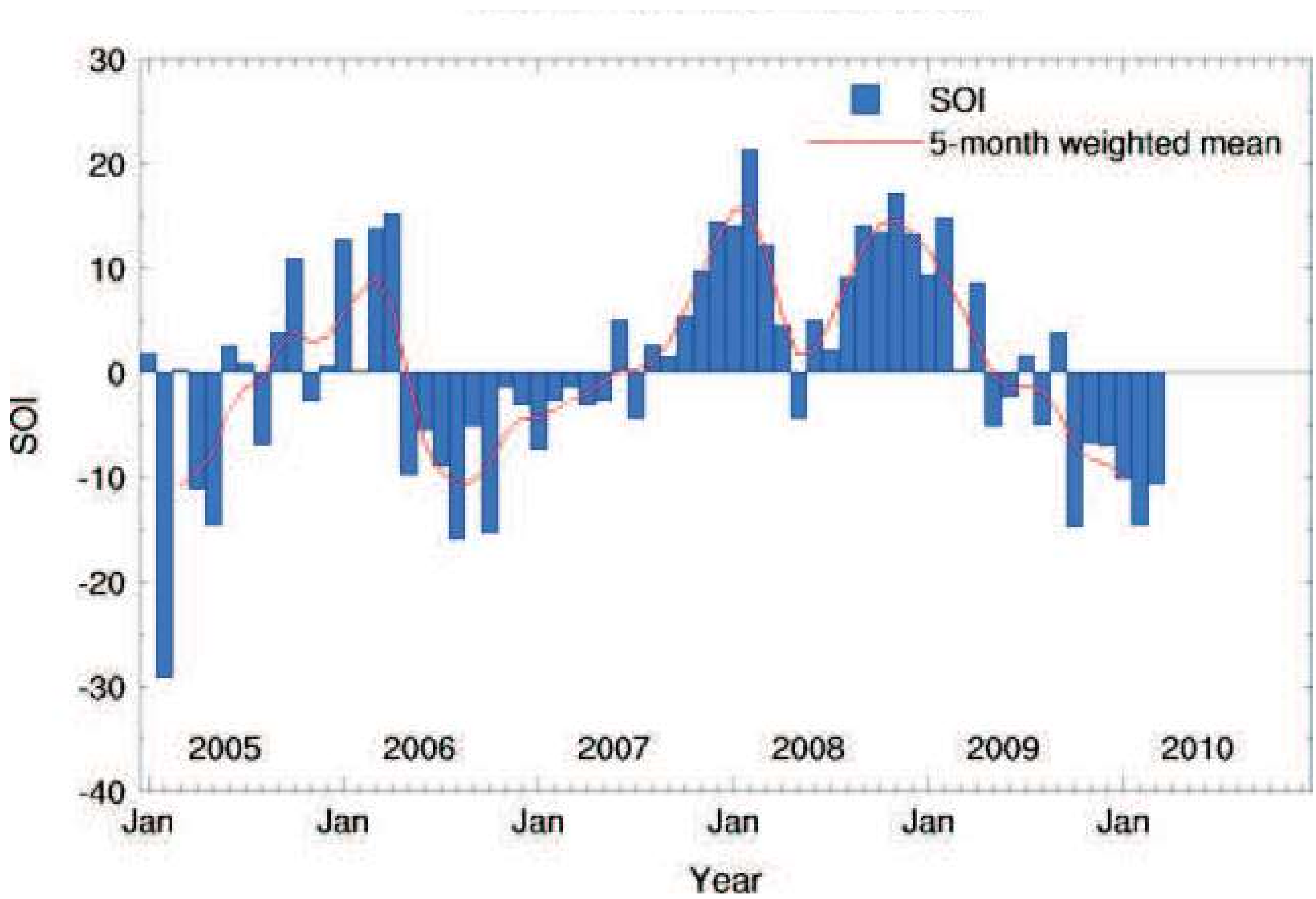

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FIGURE 3.10

SOUTHERN OSCILLATION INDEX FOR EASTERN AUSTRALIA

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FIGURE 3.11
100-YEARS ARI FLOOD EXTENTS

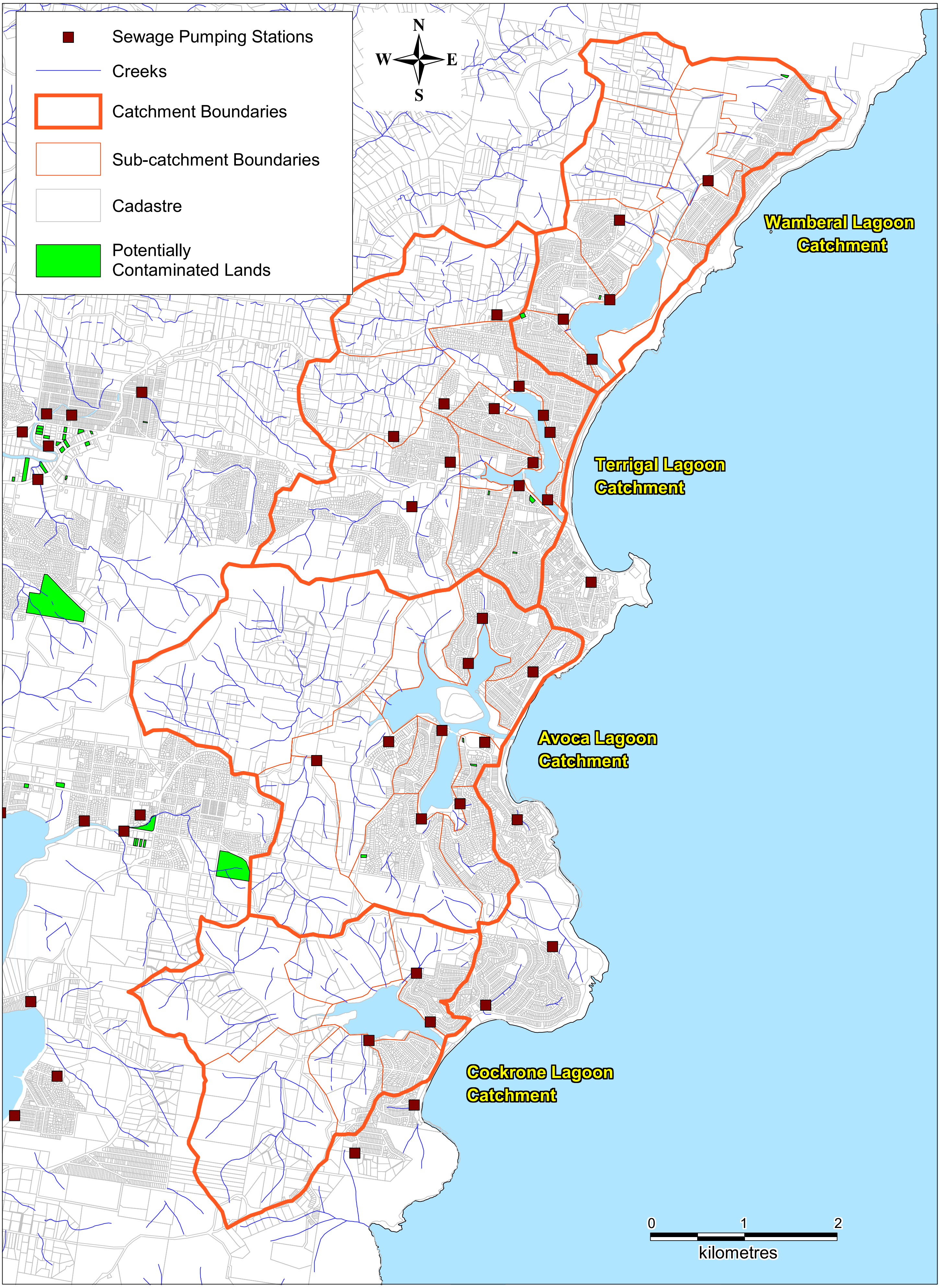

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FIGURE 3.12
POTENTIAL POINT SOURCES OF POLLUTION

J:\CM\LJ2713\Figures\Figure 3.12 - Point Sources Pollution.wor

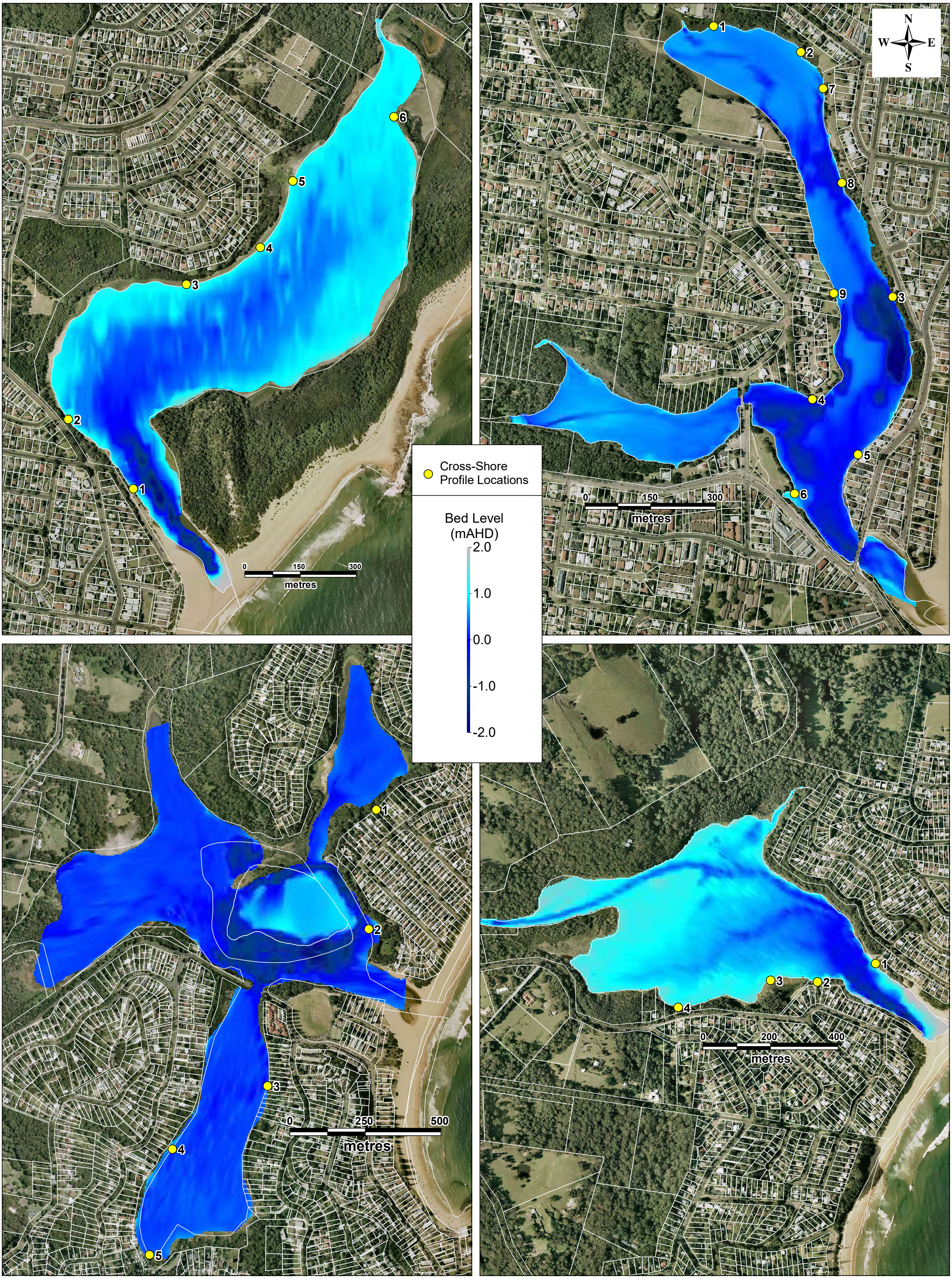
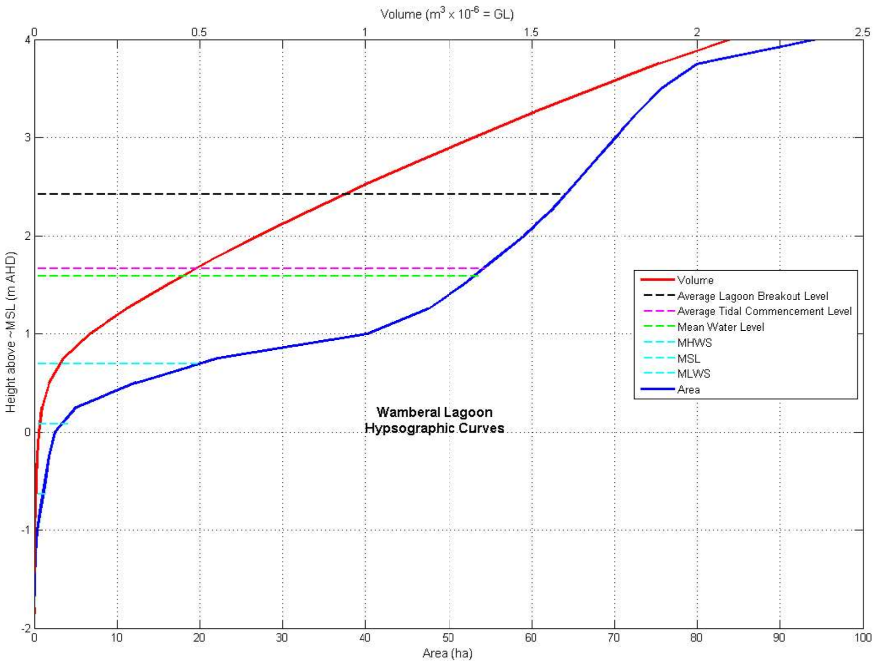
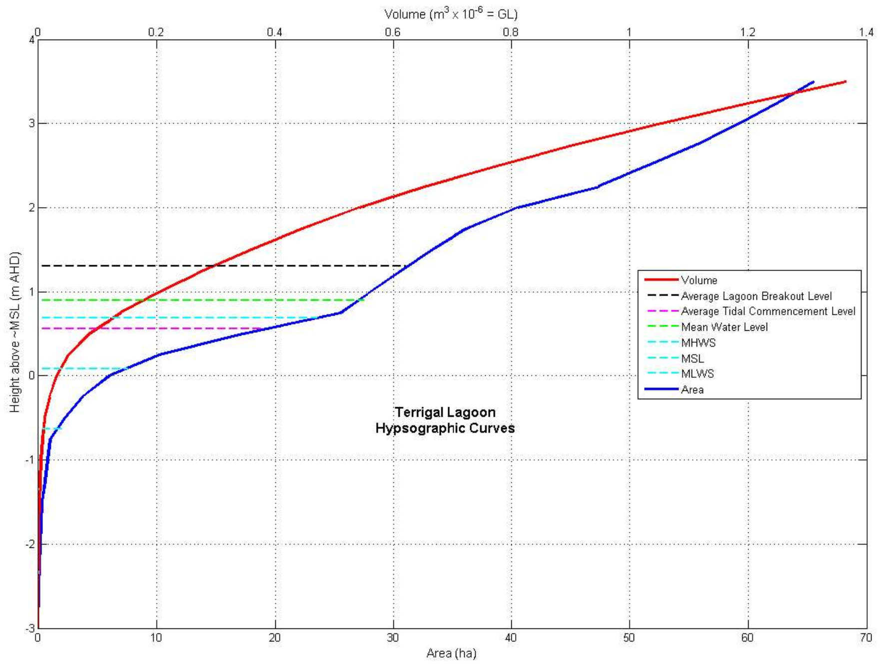
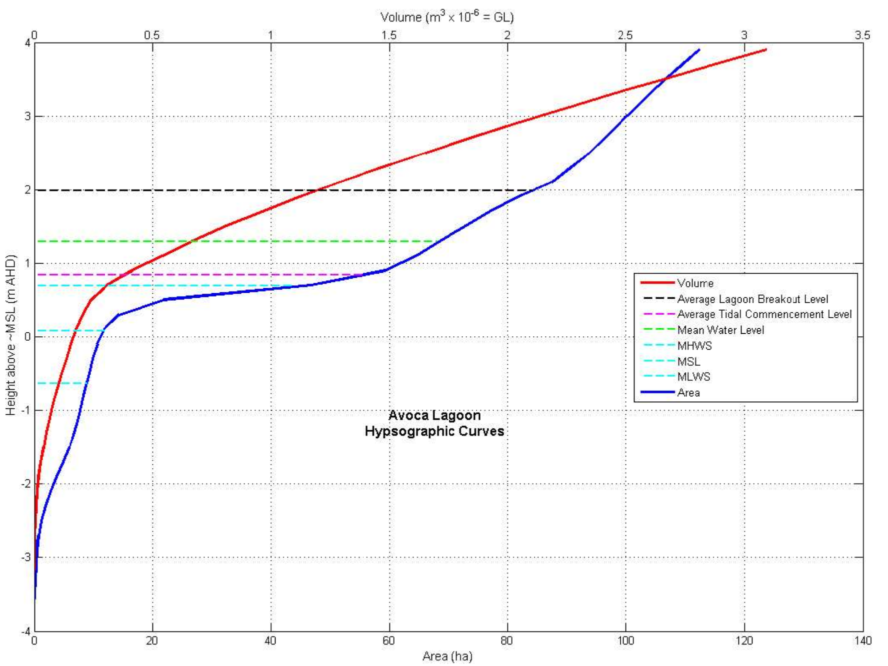


FIGURE 4.1
LAGOON BATHYMETRY







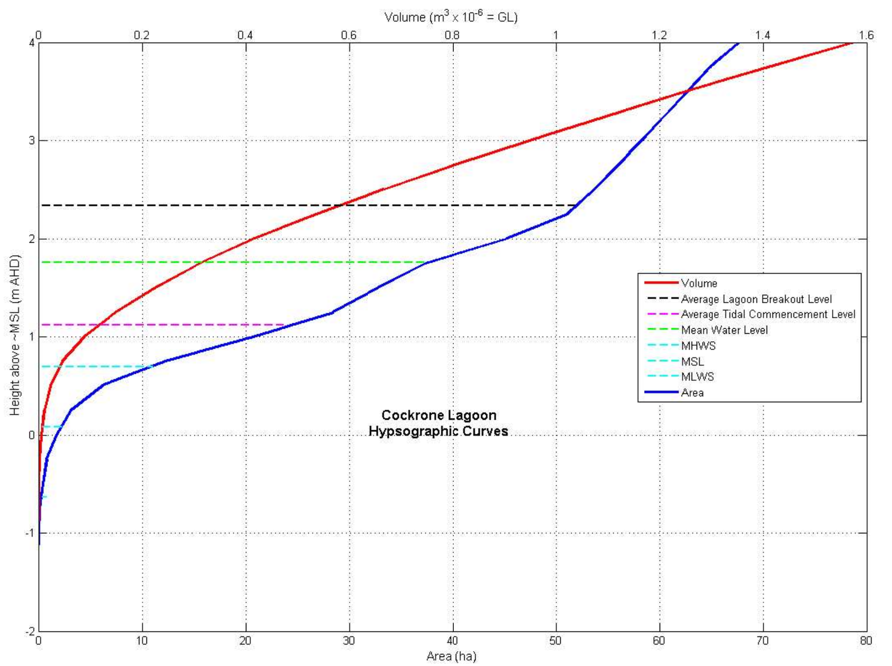


FIGURE 4.2
HYPSOGRAPHIC CURVES

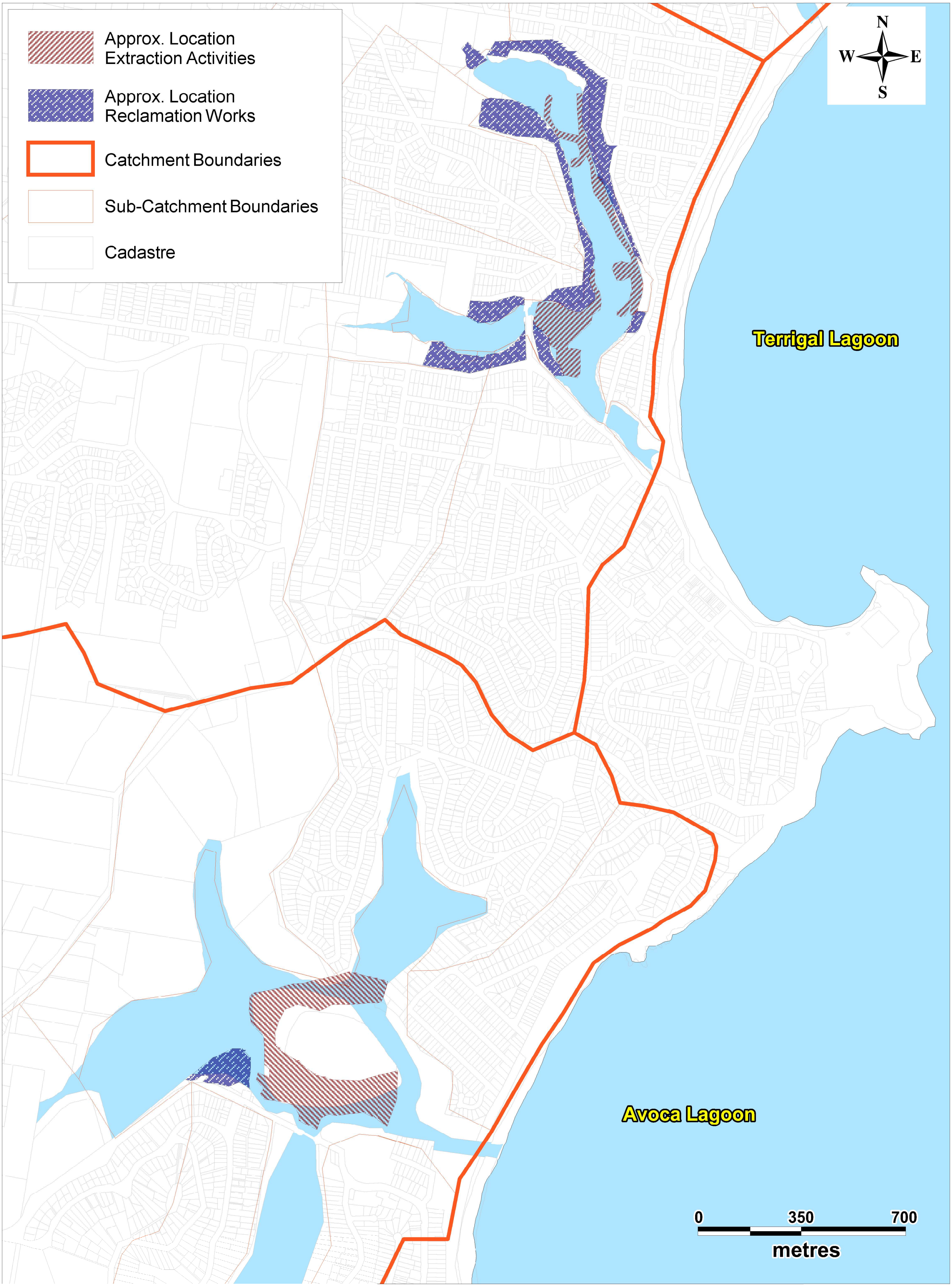


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FIGURE 4.3
HISTORIC EXTRACTION & RECLAMATION WORKS

J:\CM\LJ2713\Figures\Figure 4.3 - Dredging & Reclamation.wor

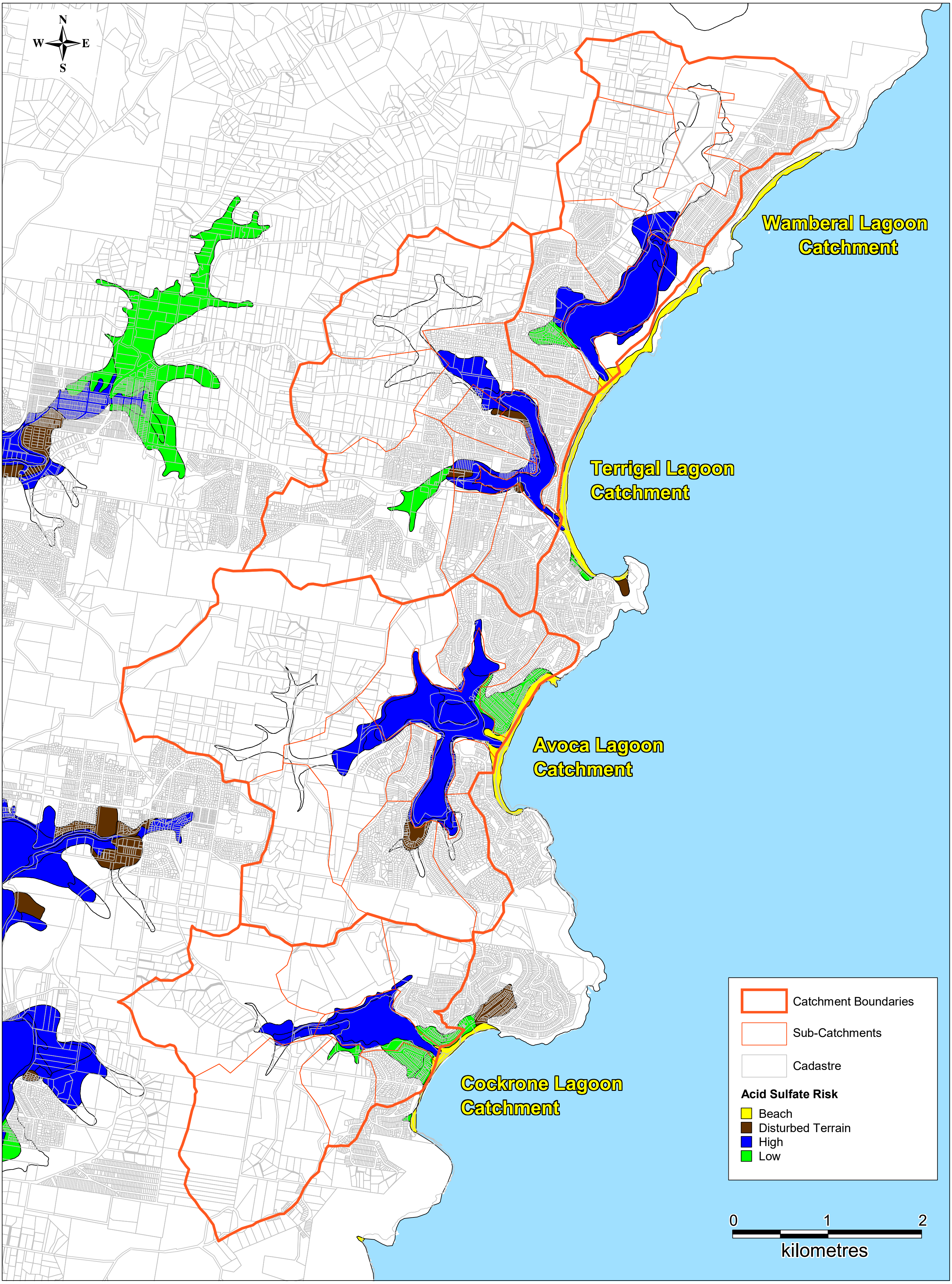

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FIGURE 4.4
ASS RISK MAPPING

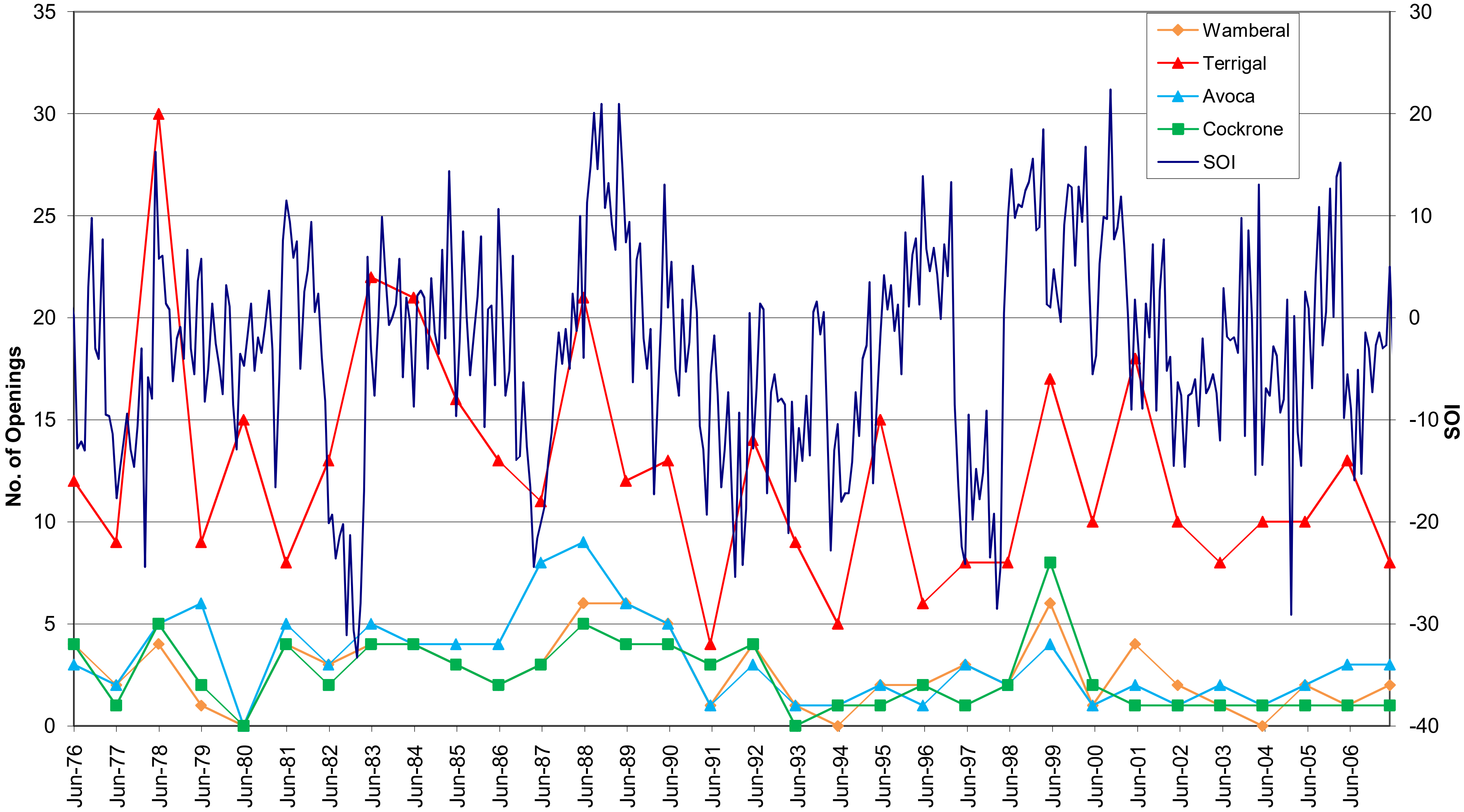
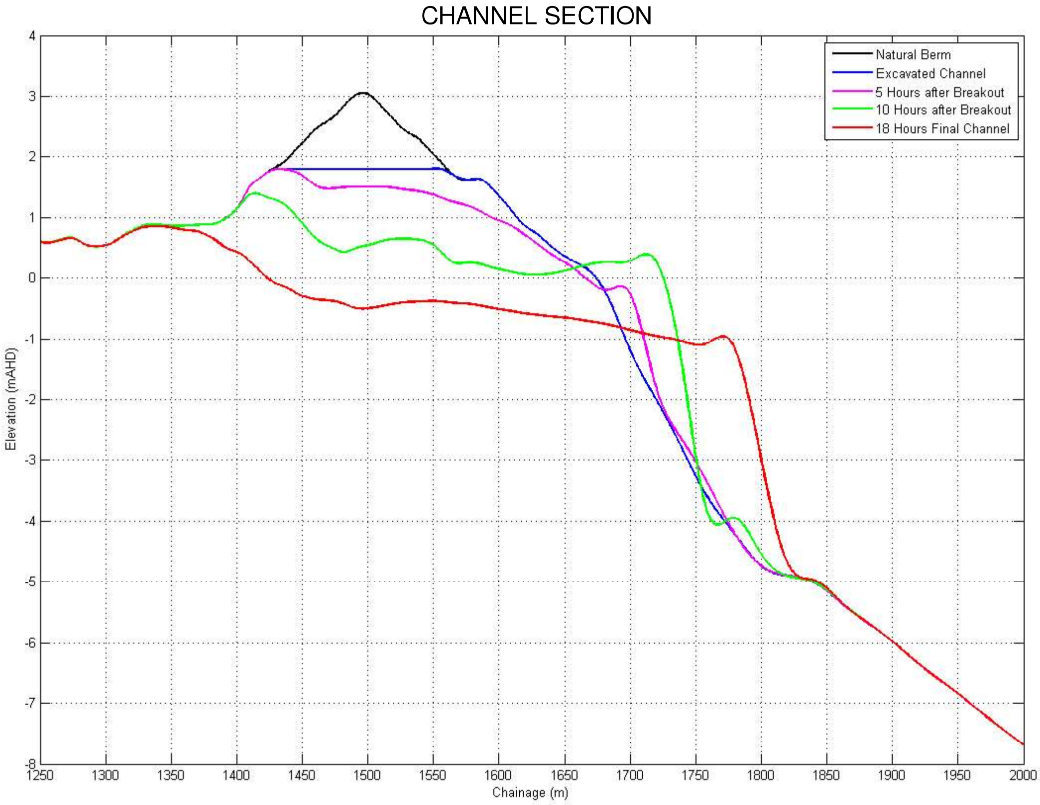


FIGURE 4.5
TREND IN MECHANICAL
ENTRANCE BREAKOUTS



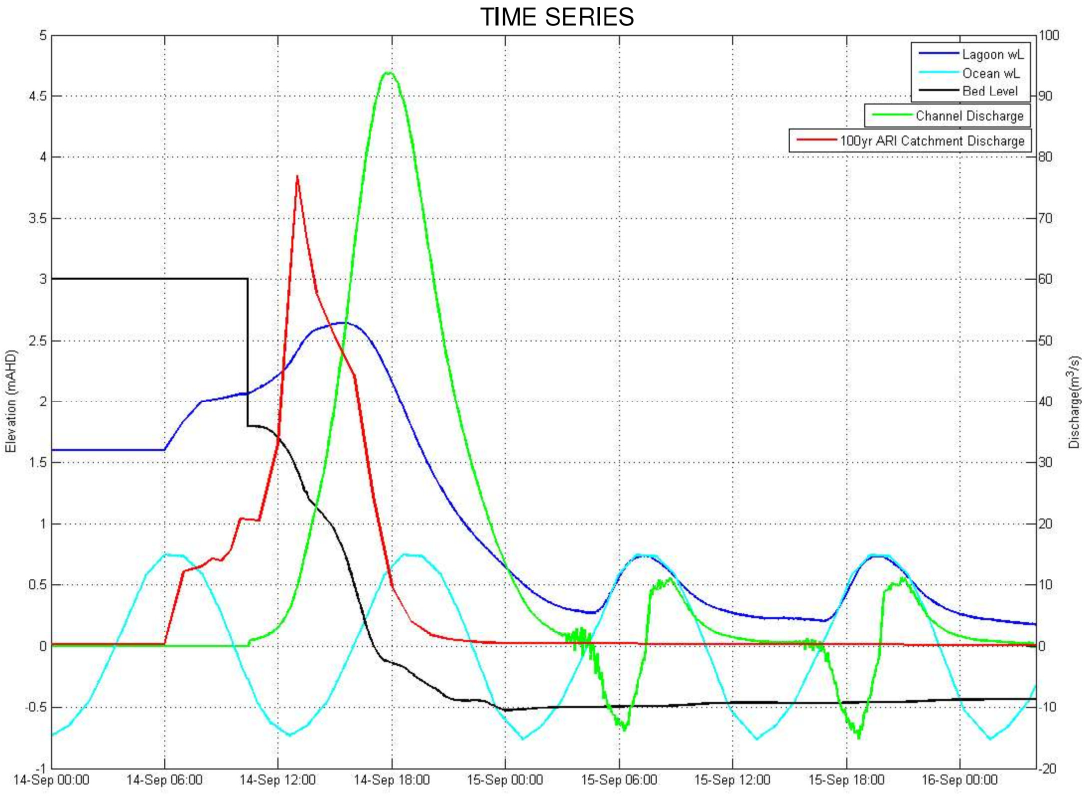


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FIGURE 4.6
ENTRANCE BREAKOUT EVOLUTION

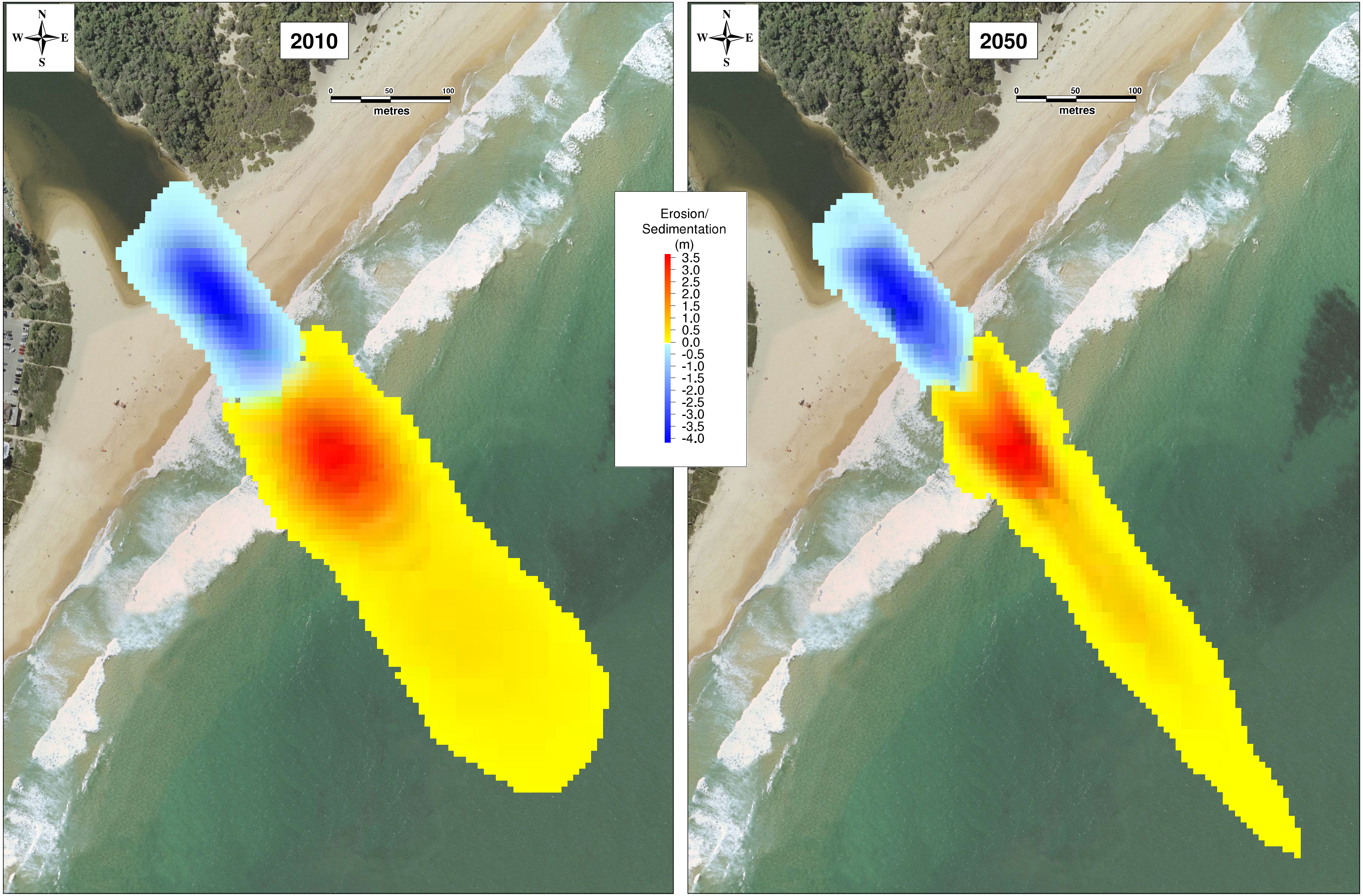

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FIGURE 4.7
100 YEARS ARI BREAKOUT EROSION
WAMBERAL LAGOON

J:\CM\LJ2713\Figures\R2472\Figure 4.7.Wor

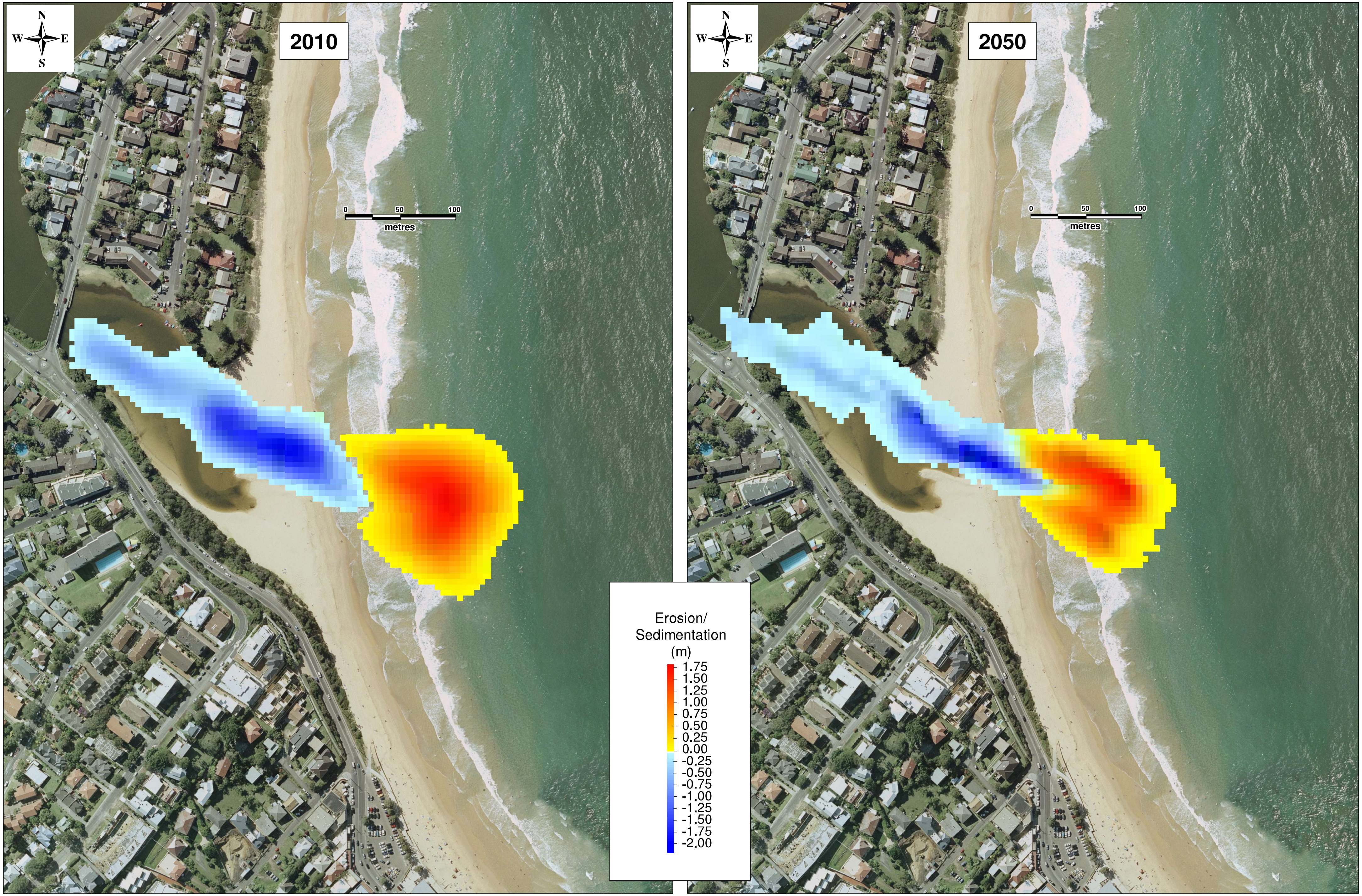

FIGURE 4.8
100 YEARS ARI BREAKOUT EROSION
TERRIGAL LAGOON

J:\CM\LJ2713\Figures\R2472\Figure 4.8.Wor

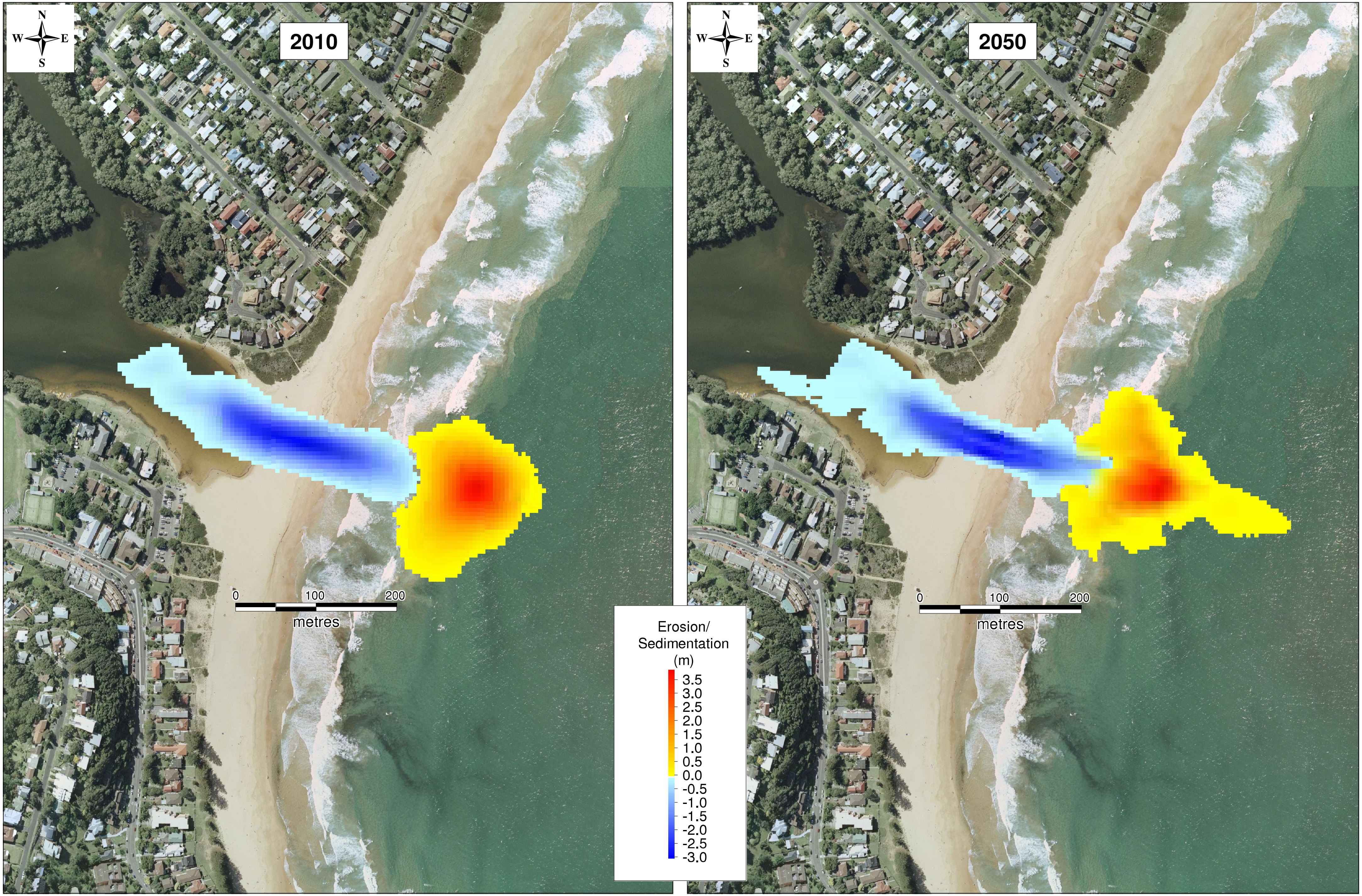

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FIGURE 4.9
100 YEARS ARI BREAKOUT EROSION
AVOCA LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.9.Wor

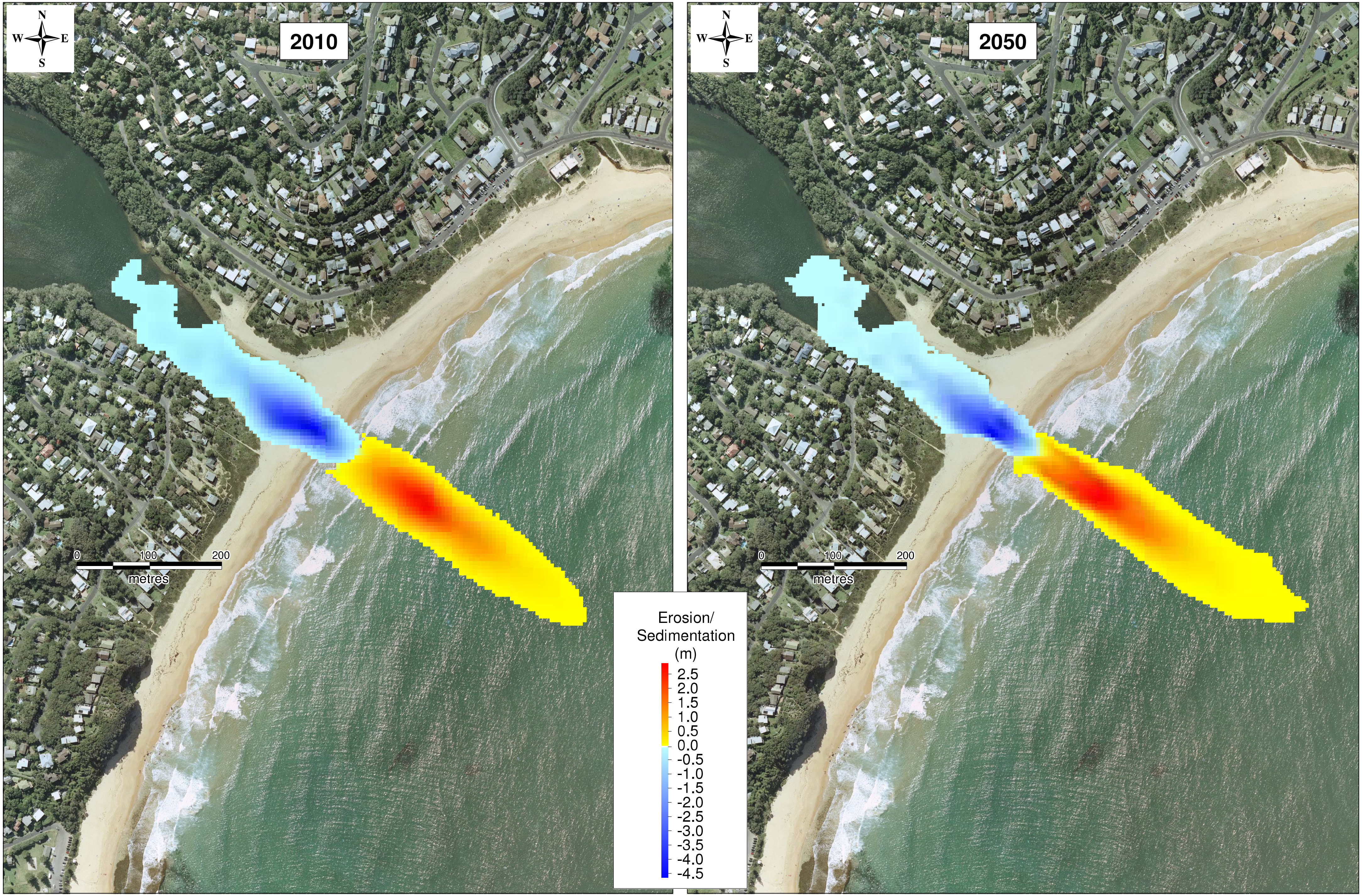

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FIGURE 4.10
100 YEARS ARI BREAKOUT EROSION
COCKRONE LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.10.Wor

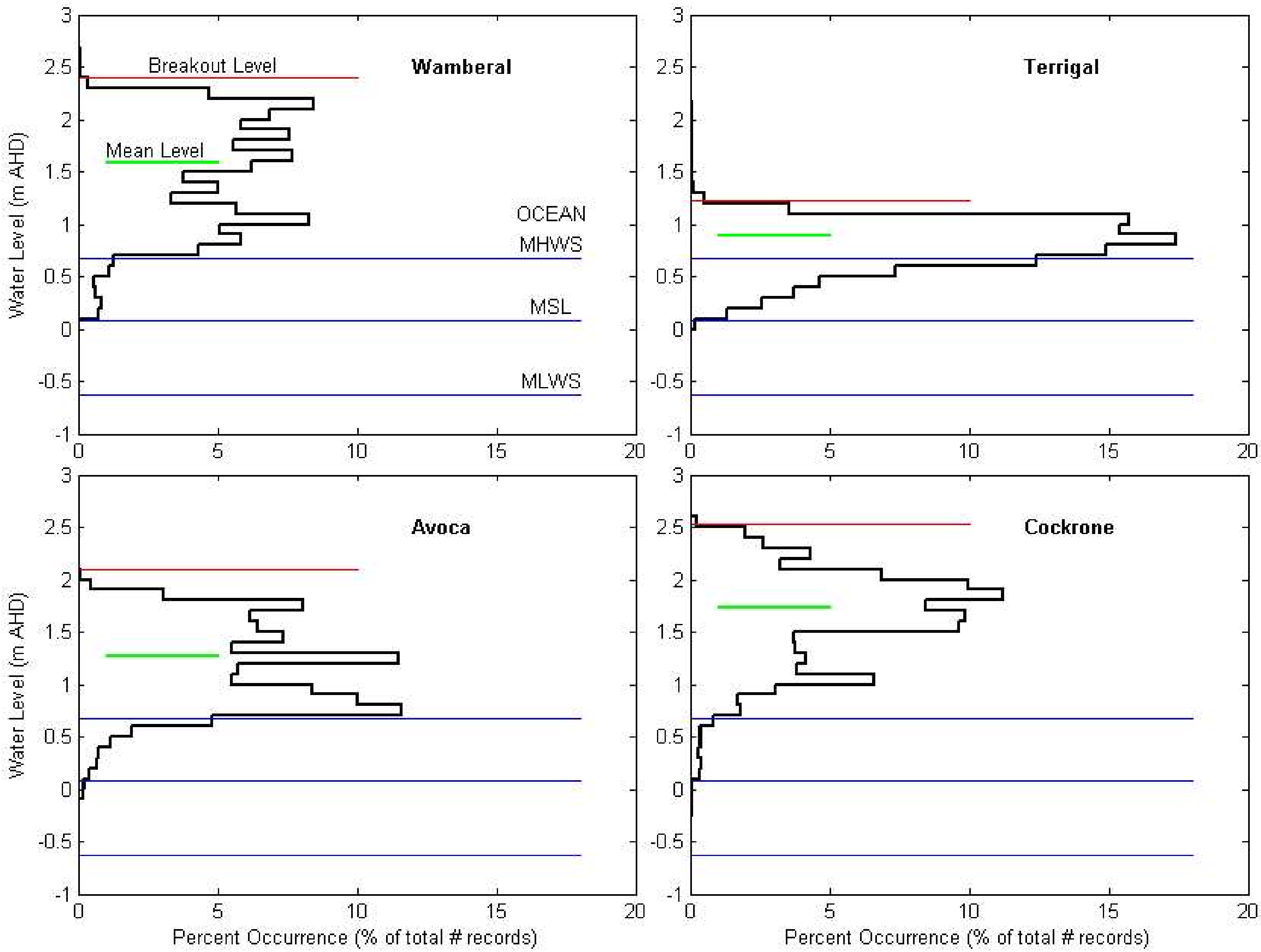

FIGURE 4.11
WATER LEVEL ANALYSIS

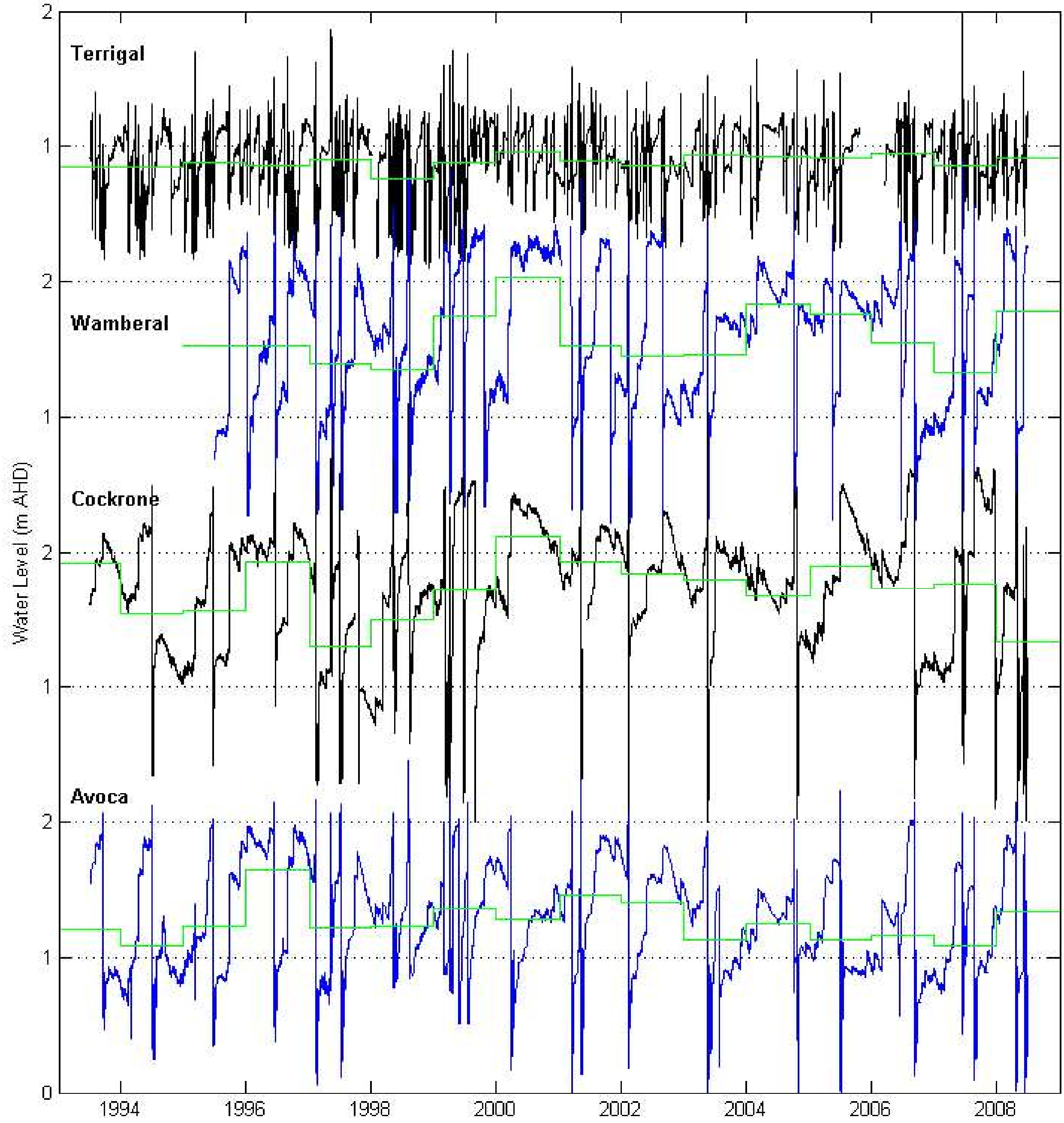

FIGURE 4.12
TIME SERIES WATER LEVEL TRENDS

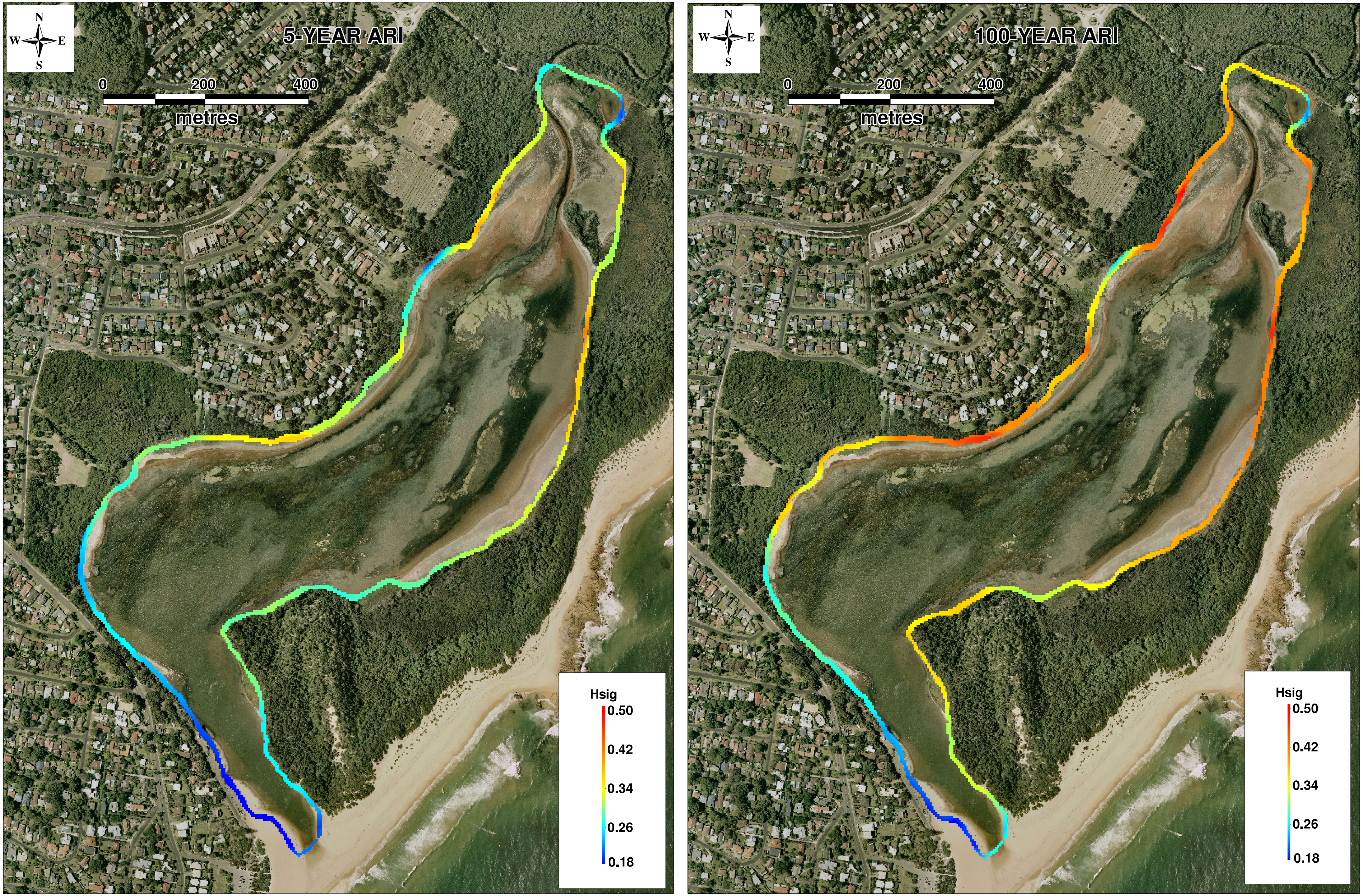

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FIGURE 4.13
5-YEAR AND 100-YEAR ARI SIGNIFICANT WAVE HEIGHTS
WAMBERAL LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.13 .Wor

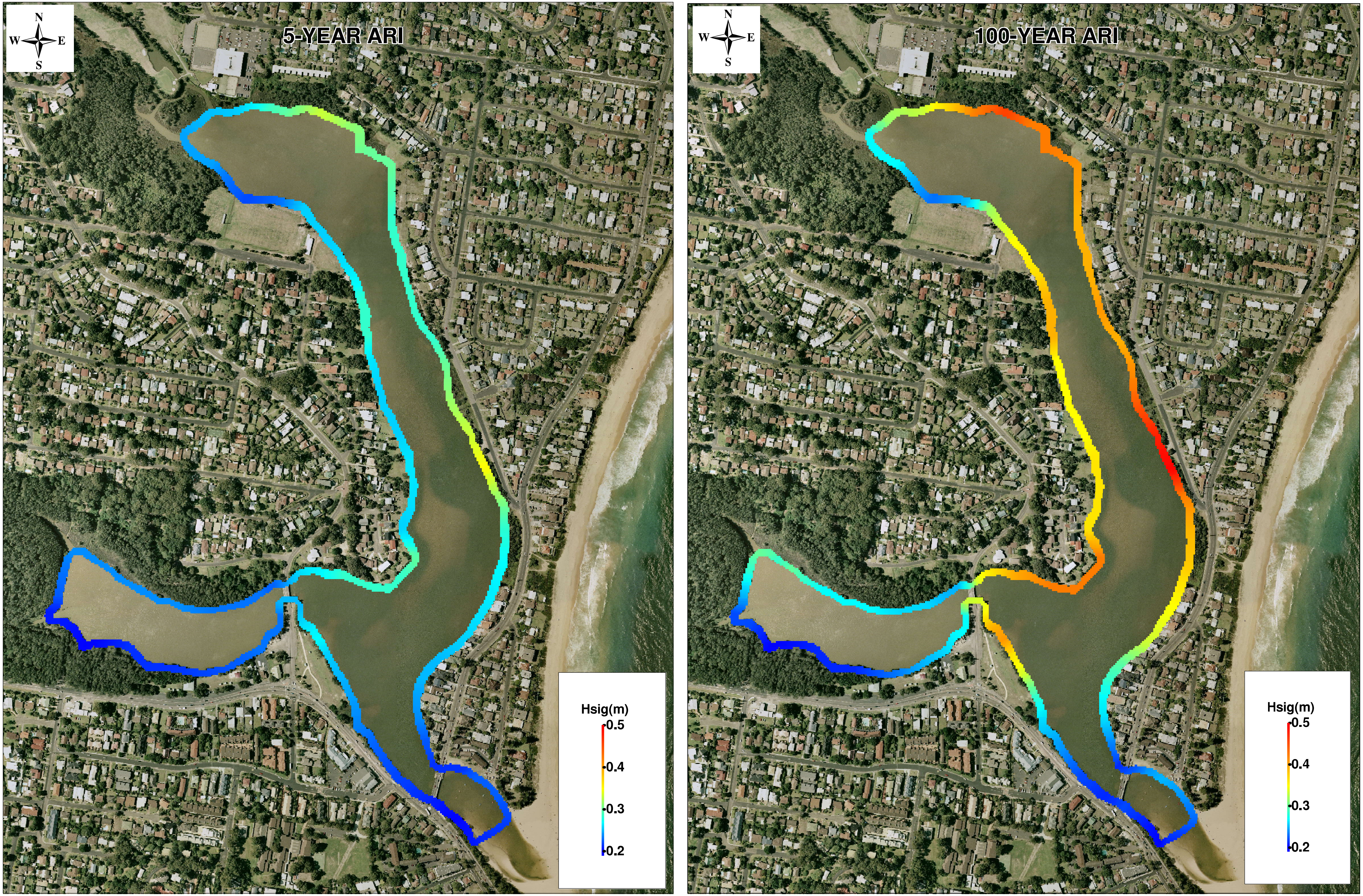

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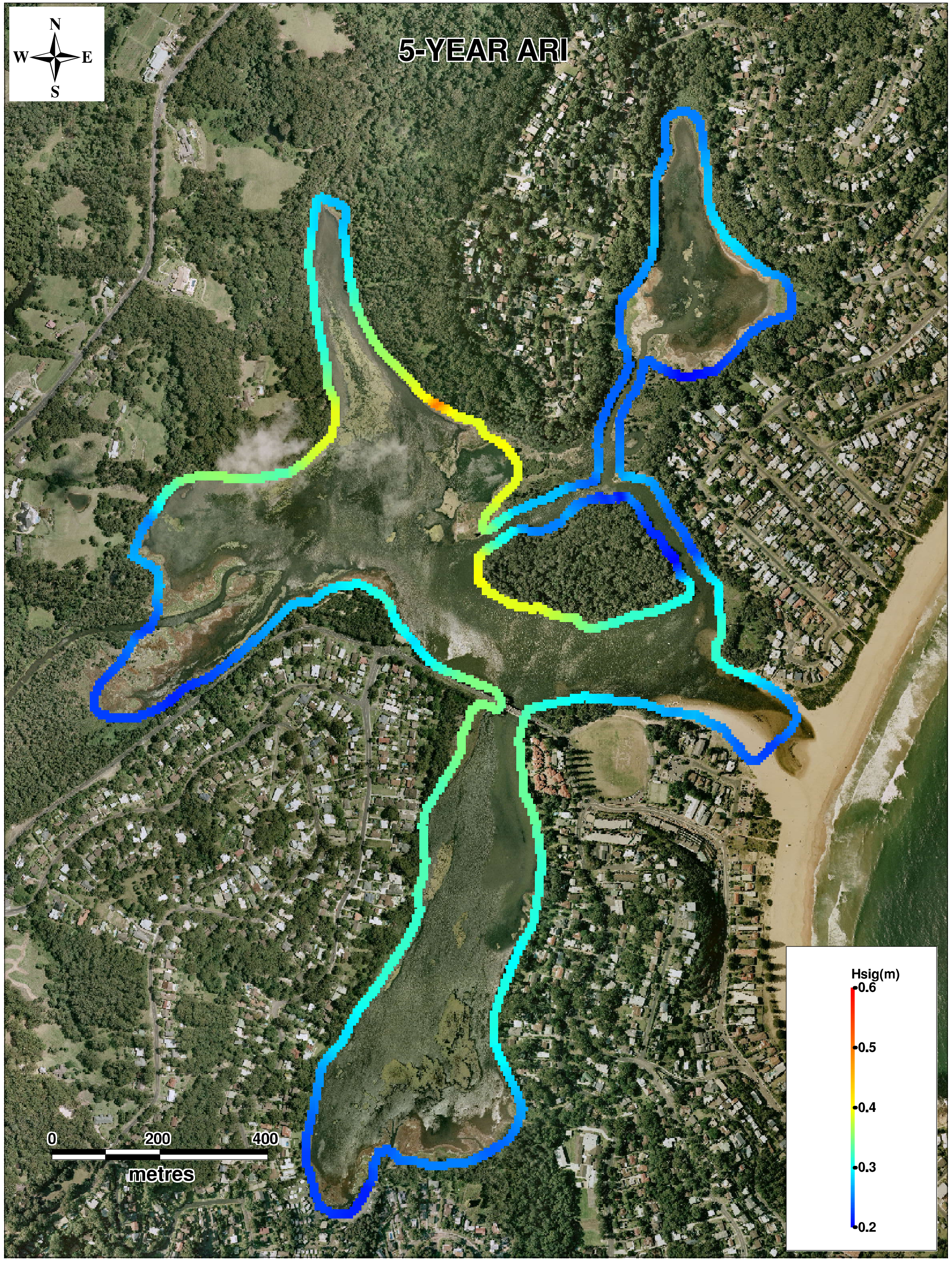
FIGURE 4.14
5-YEAR AND 100-YEAR ARI SIGNIFICANT WAVE HEIGHTS
TERRIGAL LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.14.Wor



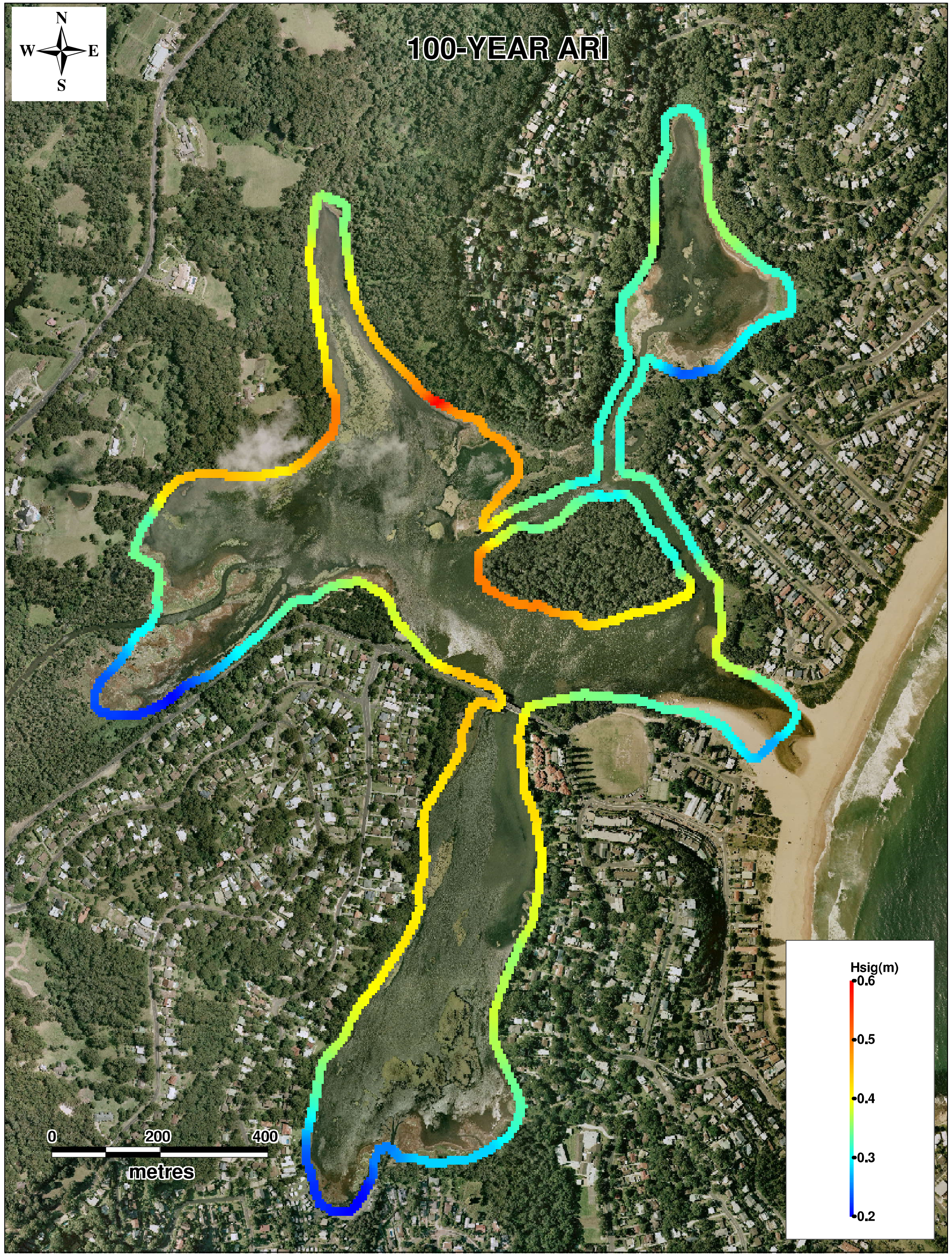


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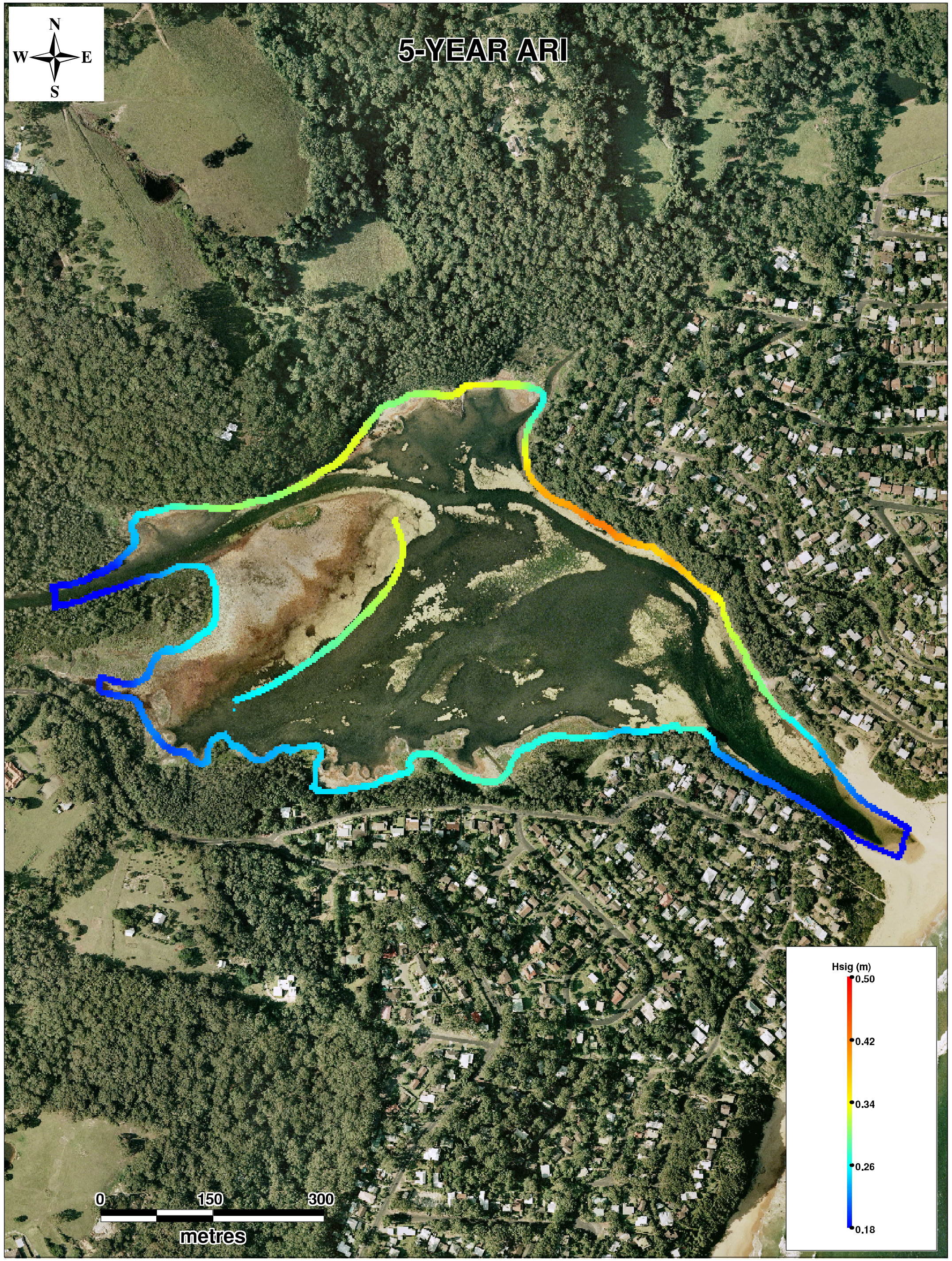
FIGURE 4.15
5-YEAR AND 100-YEAR ARI SIGNIFICANT WAVE HEIGHTS
AVOCA LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.15 .Wor



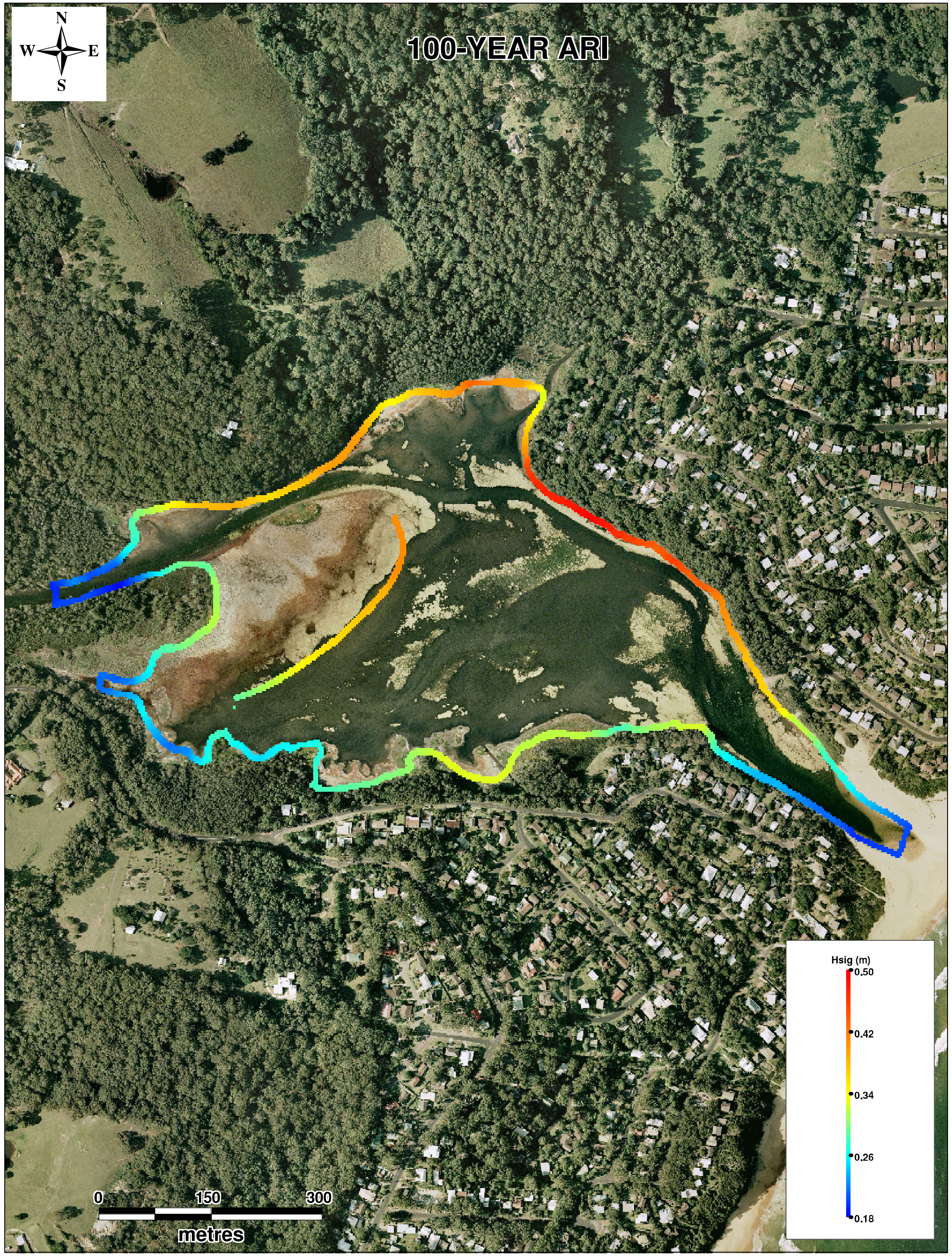


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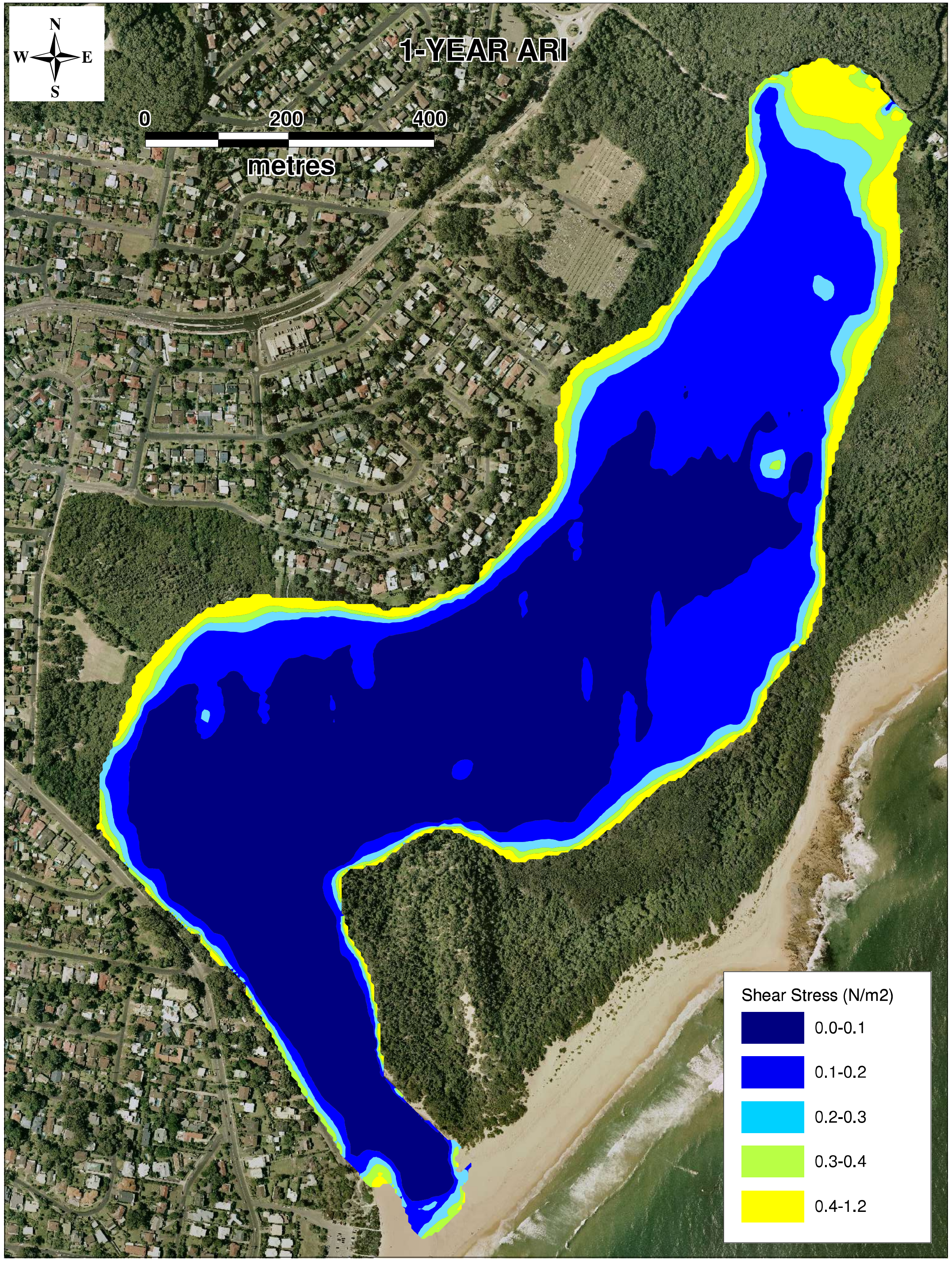
FIGURE 4.16
5-YEAR AND 100-YEAR ARI SIGNIFICANT WAVE HEIGHTS
COCKRONE LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.16.Wor



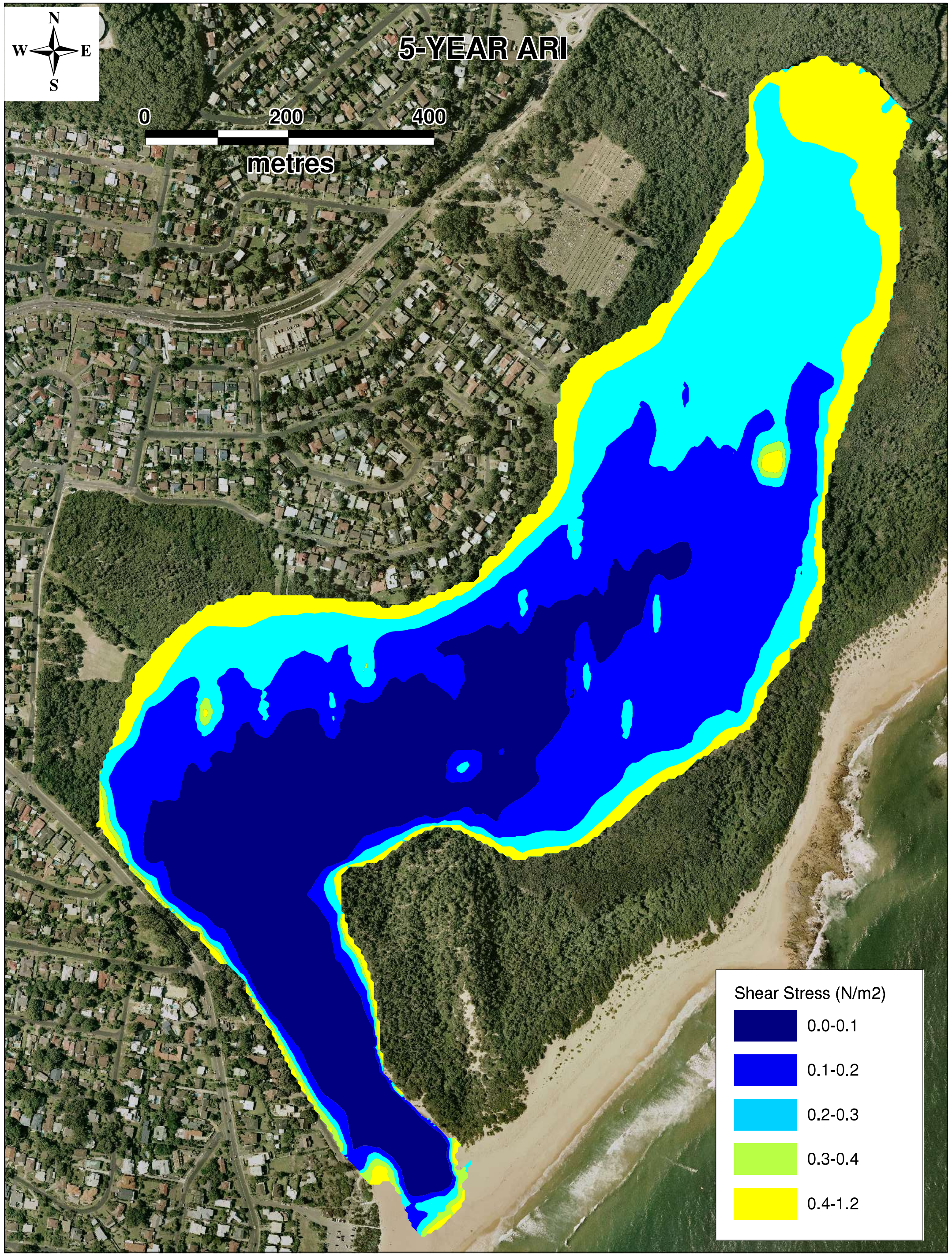
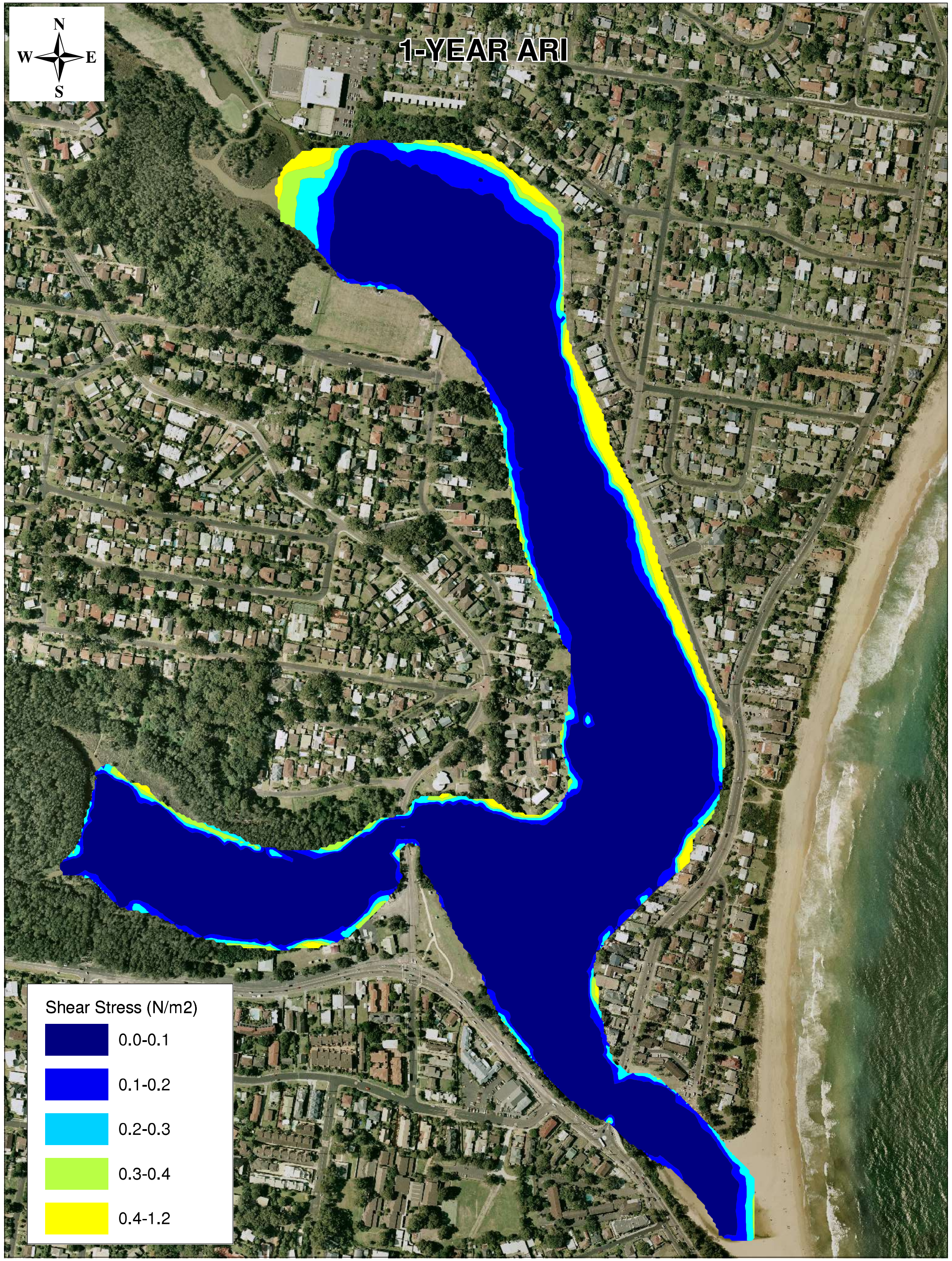


FIGURE 4.17
1-YEAR AND 5-YEAR ARI BED SHEAR STRESS
WAMBERAL LAGOON

J:\CM\LJ2713\Figures\R2472\Figure 4.17.Wor



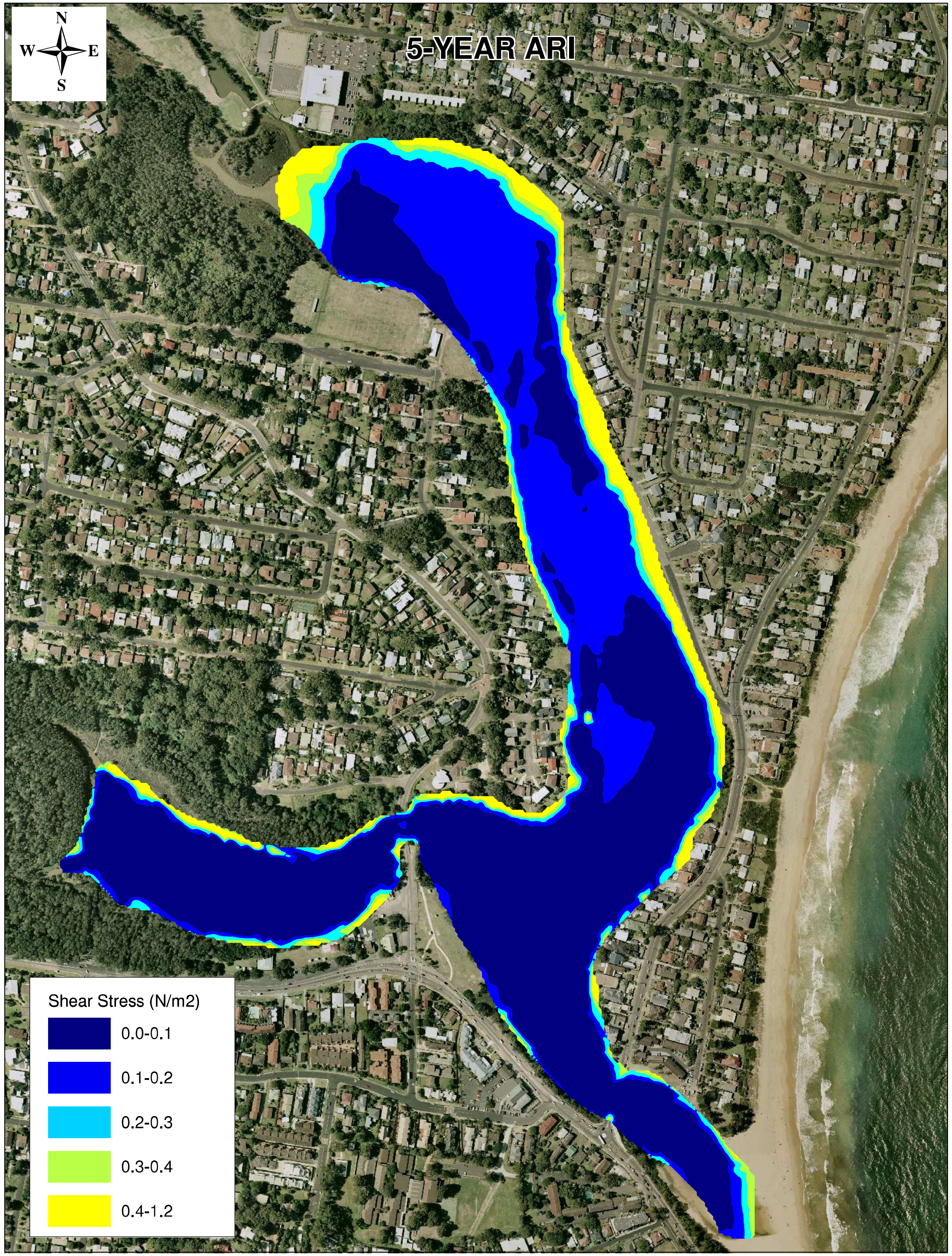


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FIGURE 4.18
1-YEAR AND 5-YEAR ARI BED SHEAR STRESS
TERRIGAL LAGOON

J:\CM\LJ2713\Figures\R2472\Figure 4.18.Wor

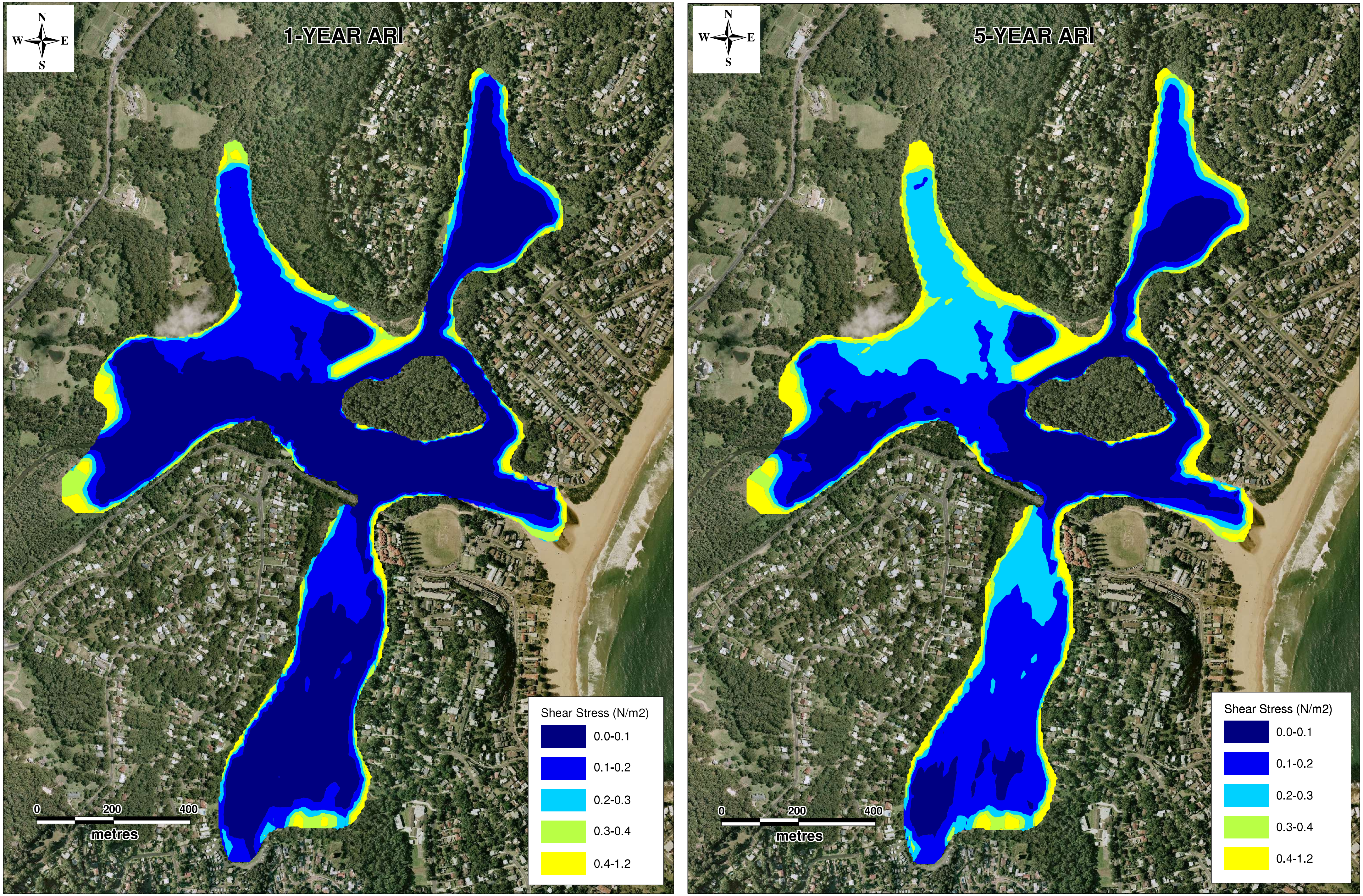
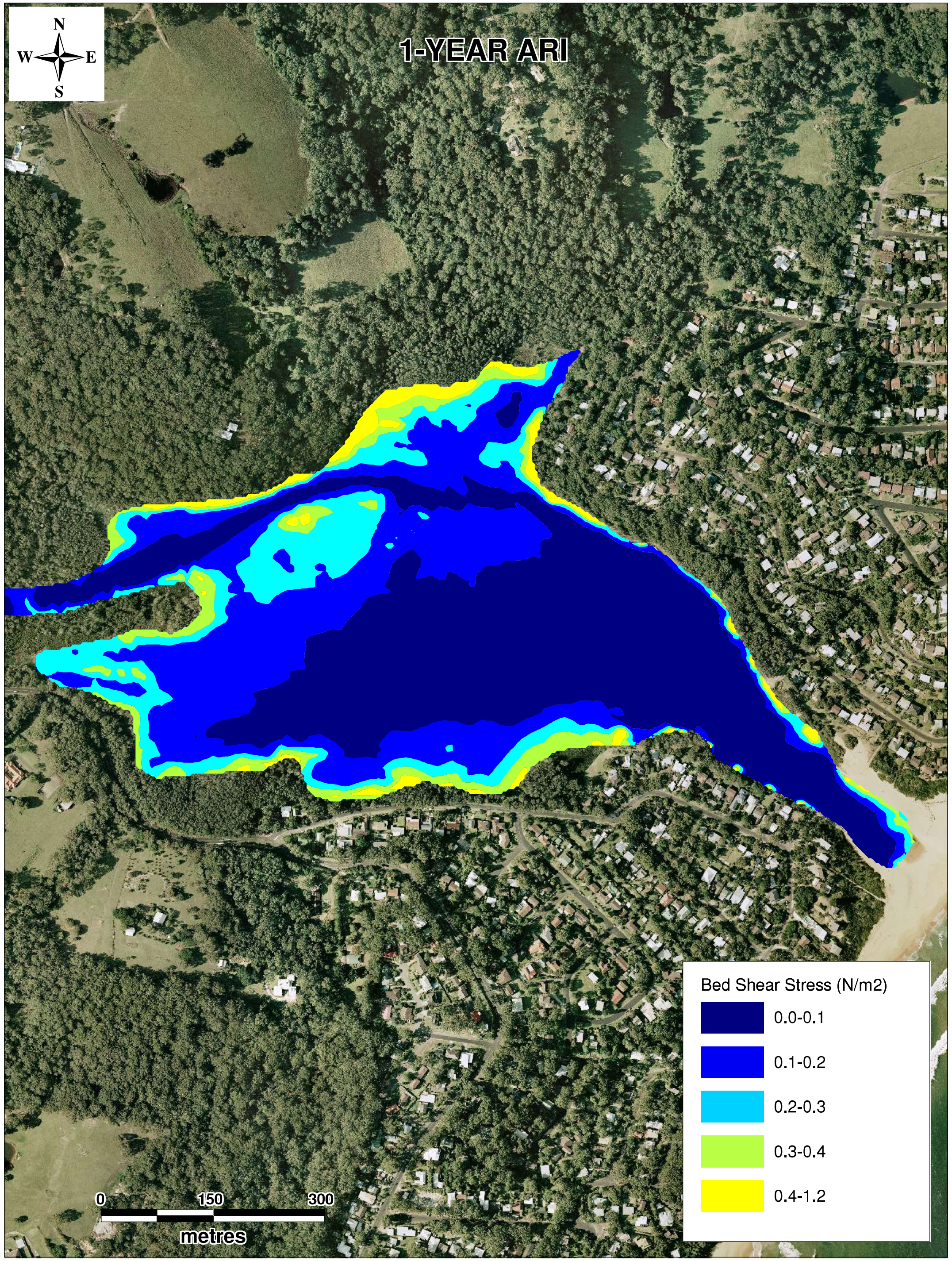


FIGURE 4.19
1-YEAR AND 5-YEAR ARI BED SHEAR STRESS
AVOCA LAGOON



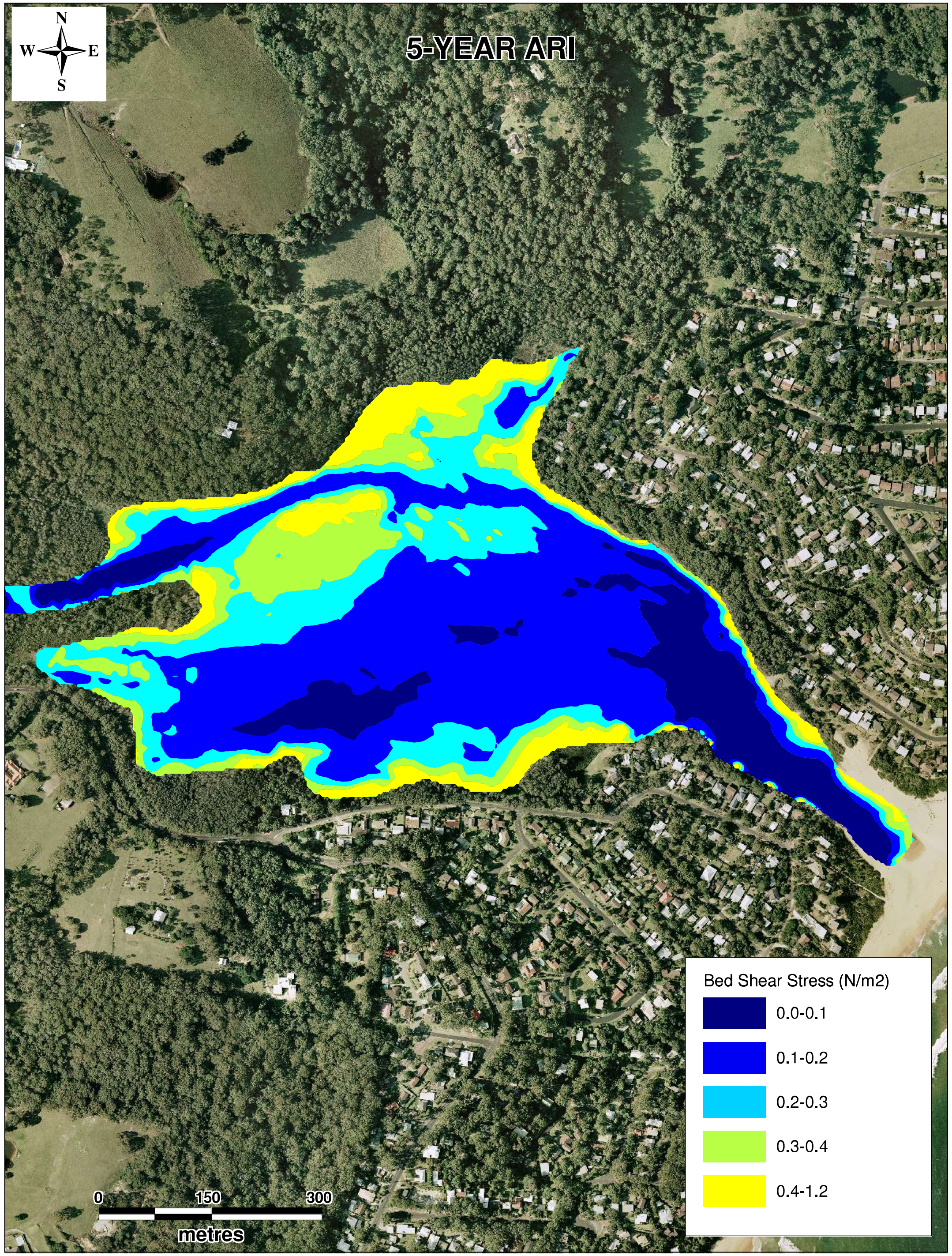


FIGURE 4.20
1-YEAR AND 5-YEAR ARI BED SHEAR STRESS
COCKRONE LAGOON

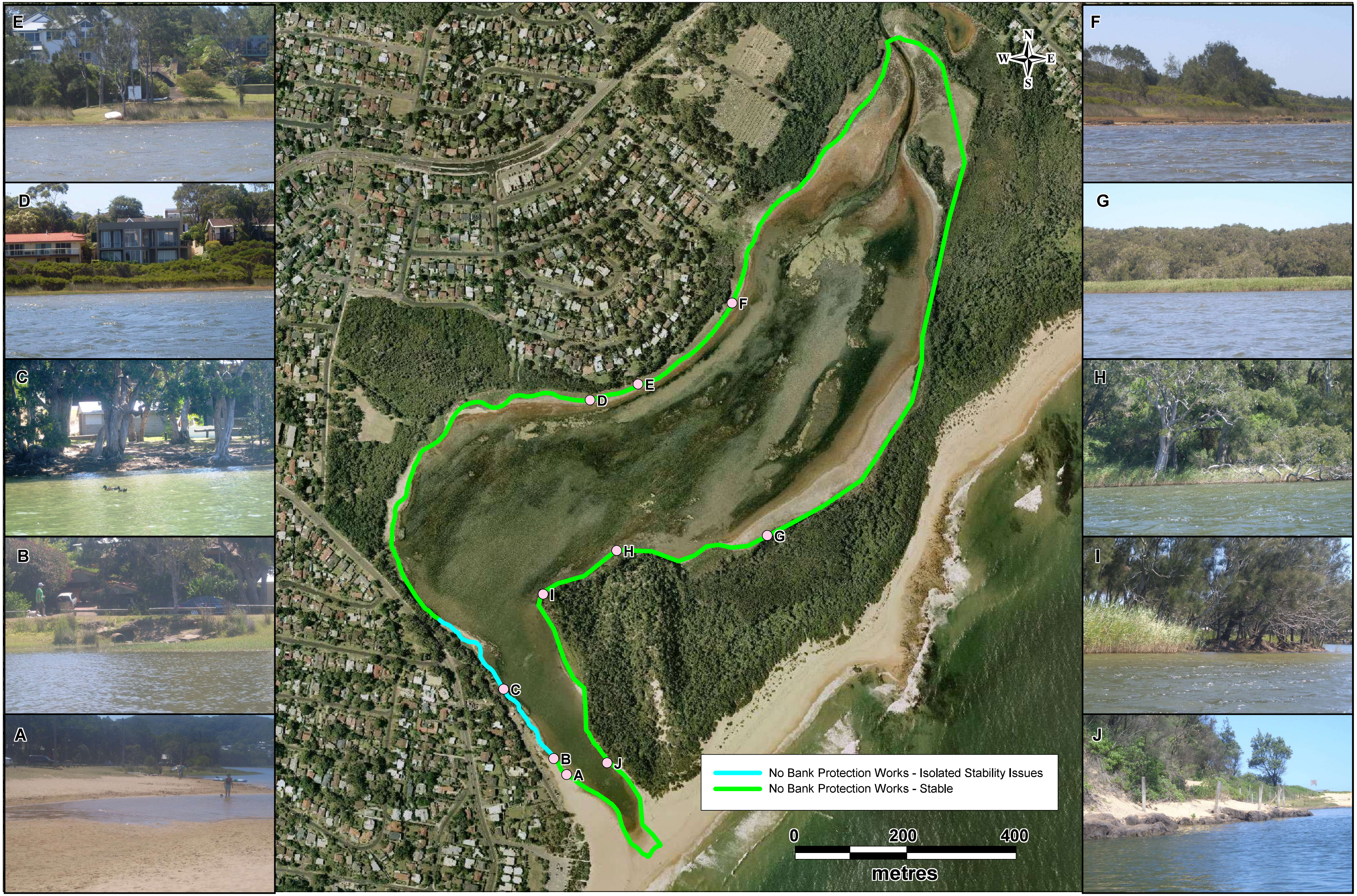


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FIGURE 4.21
WAMBERAL LAGOON FORESHORE STABILITY ASSESSMENT

J:\CM\LJ2713_GCC_Lagoons\Figures\Rep2472\Figure 4.21 - Wamberal Foreshore Assessment.WOR

FIGURE 4.22
TERRIGAL LAGOON FORESHORE STABILITY ASSESSMENT

J:\CM\LJ2713_GCC_Lagoons\Figures\Rep2472\Figure 4.22 - Terrigal Foreshore Assessment.WOR

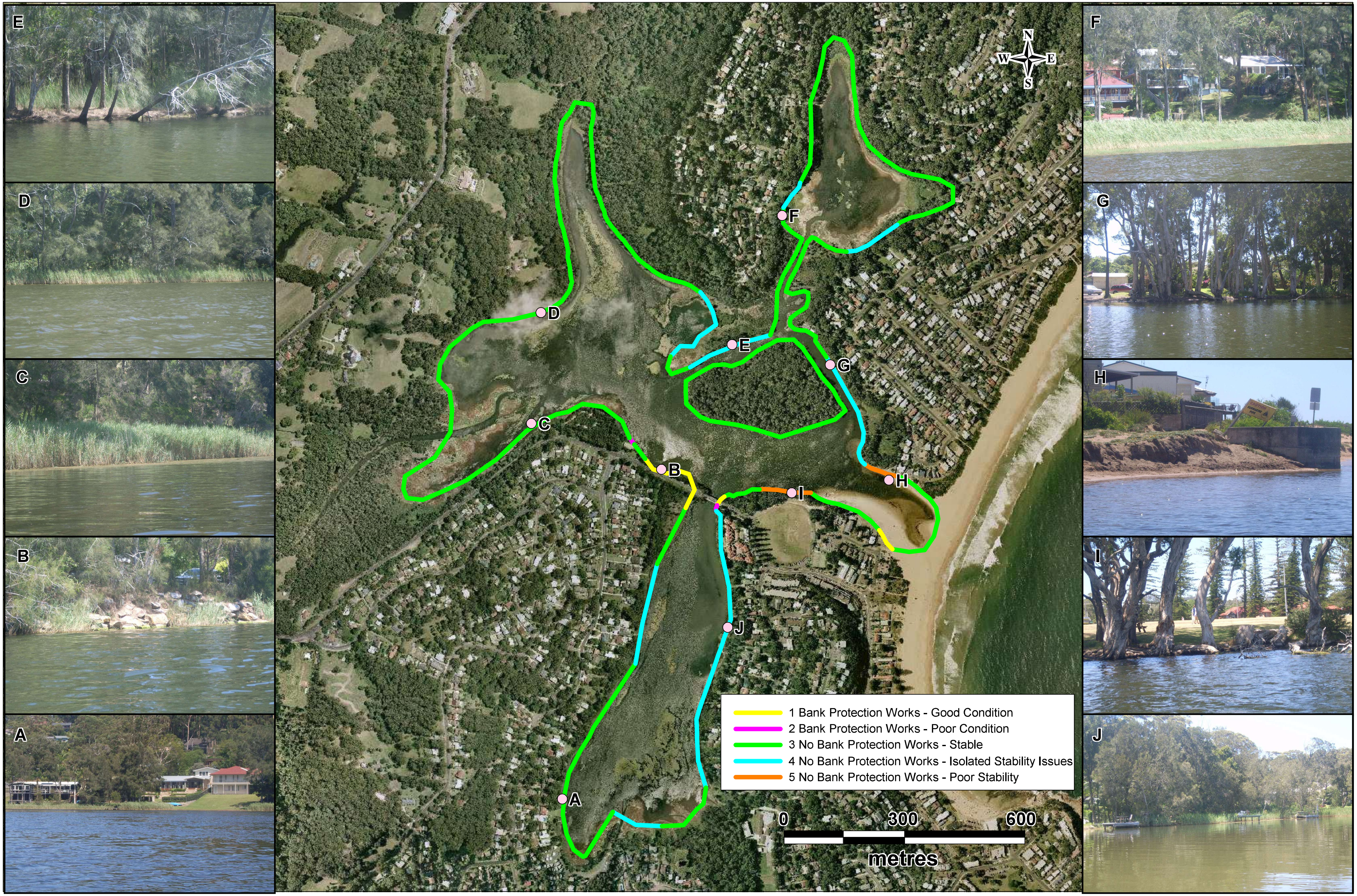

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FIGURE 4.23
AVOCA LAGOON FORESHORE STABILITY ASSESSMENT

J:\CM\LJ2713_GCC_Lagoons\Figures\Rep2472\Figure 4.23 - Avoca Foreshore Assessment.WOR

FIGURE 4.24
COCKRONE LAGOON FORESHORE STABILITY ASSESSMENT

J:\CM\LJ2713_GCC_Lagoons\Figures\Rep2472\Figure 4.24 - Cockrone Foreshore Assessment.WOR

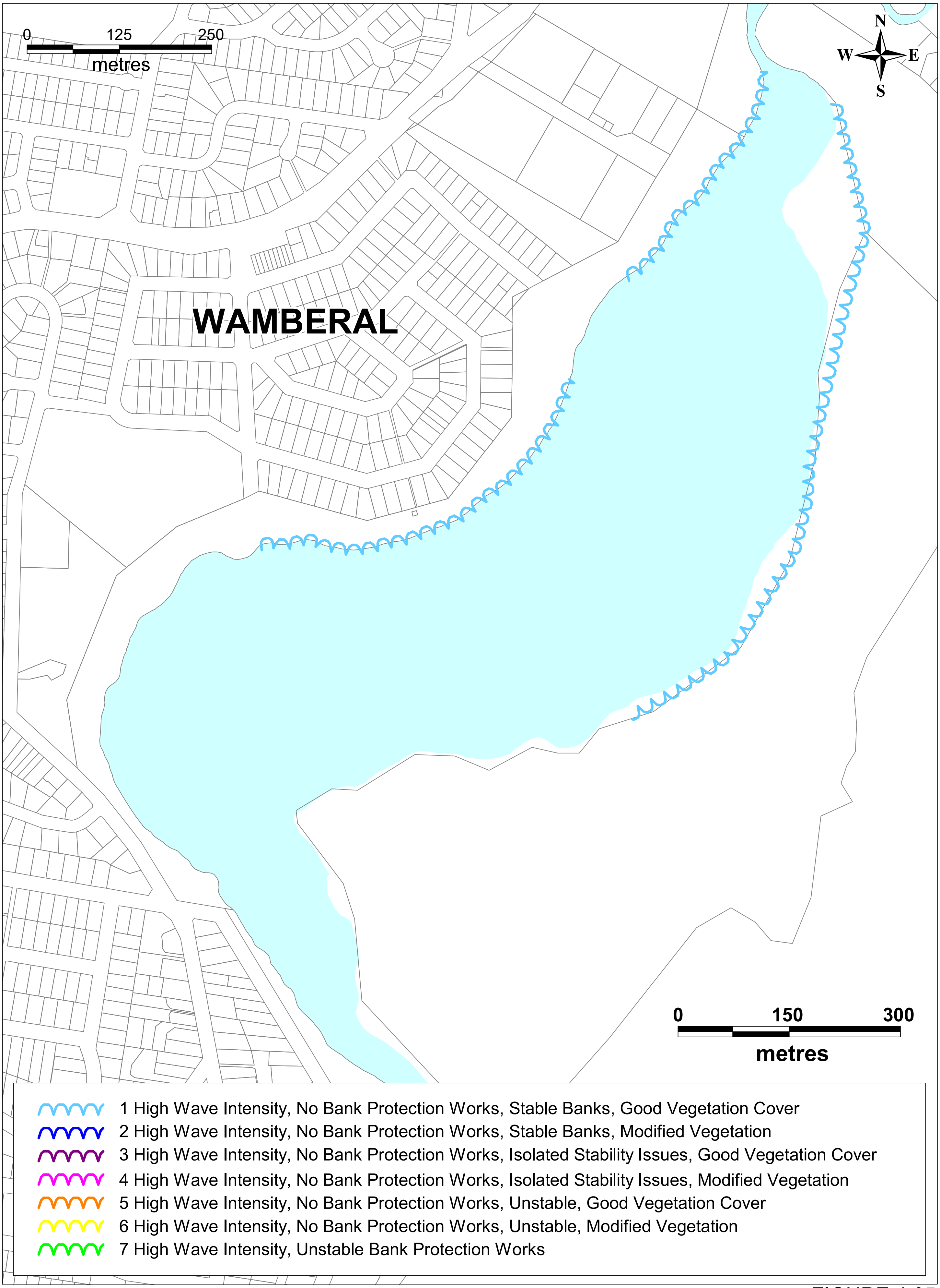

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FIGURE 4.25
FUTURE EROSION RISK
WAMBERAL LAGOON

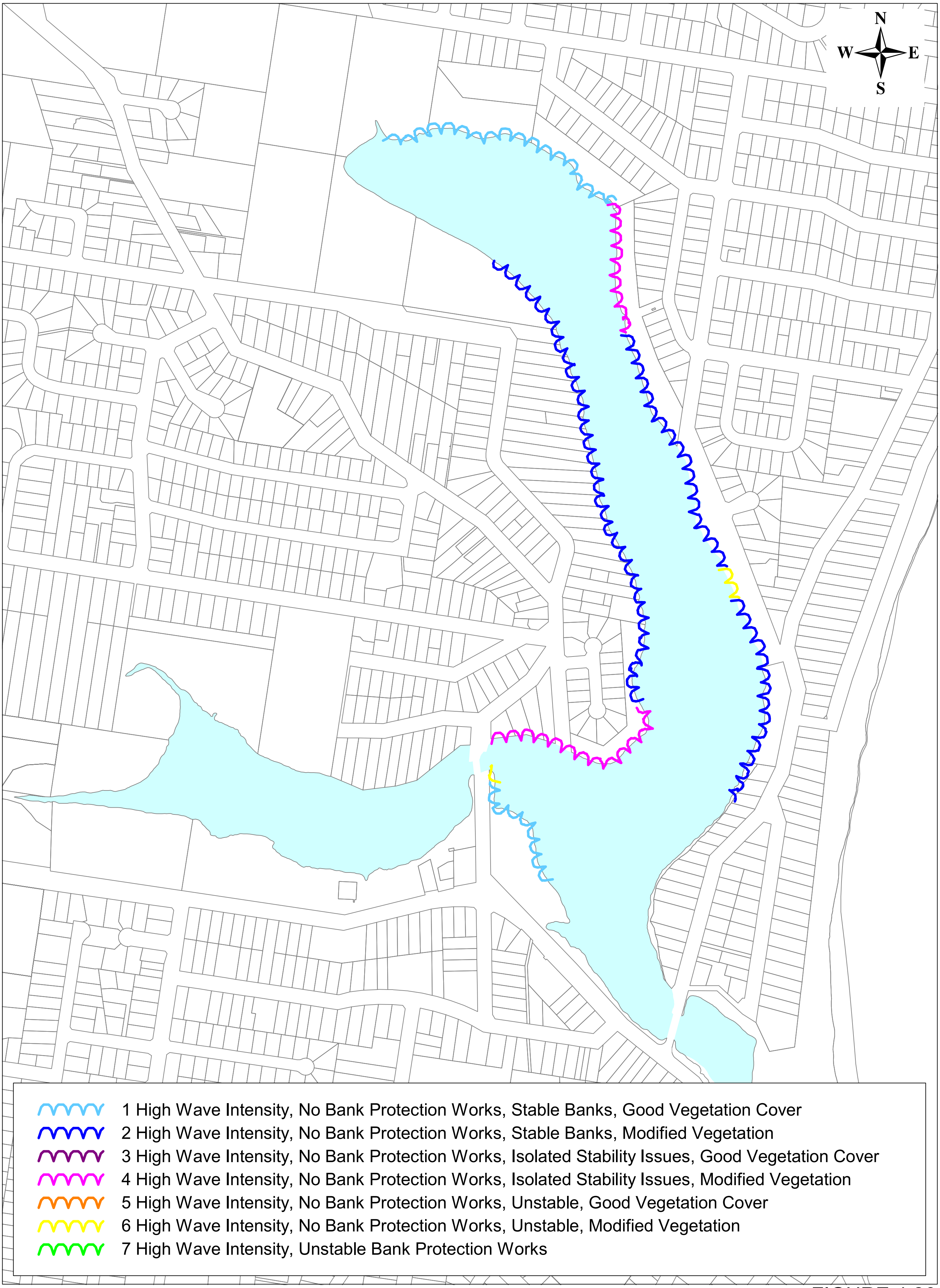


FIGURE 4.26
FUTURE EROSION RISK
TERRIGAL LAGOON

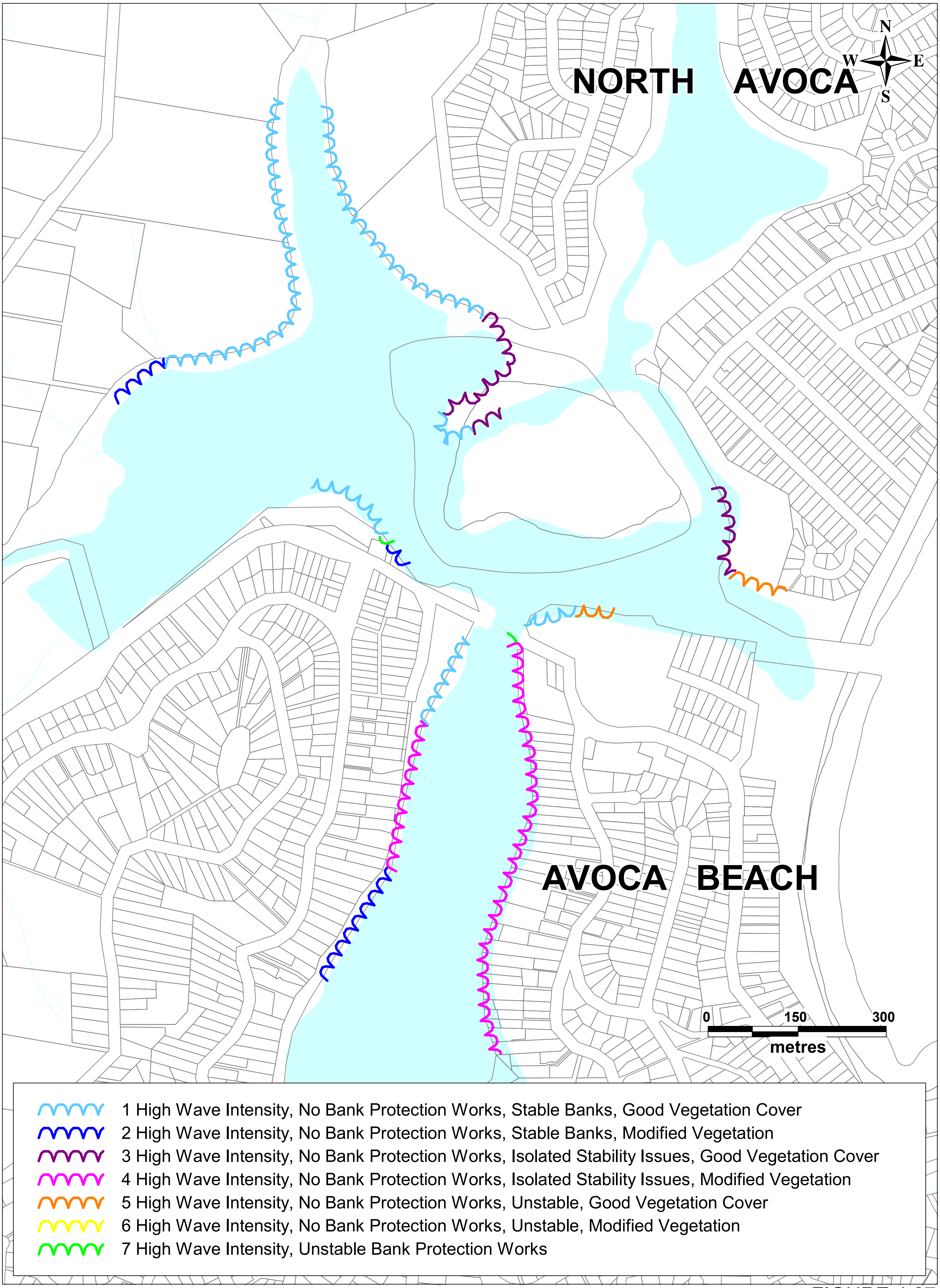


FIGURE 4.27
FUTURE EROSION RISK
AVOCA LAGOON

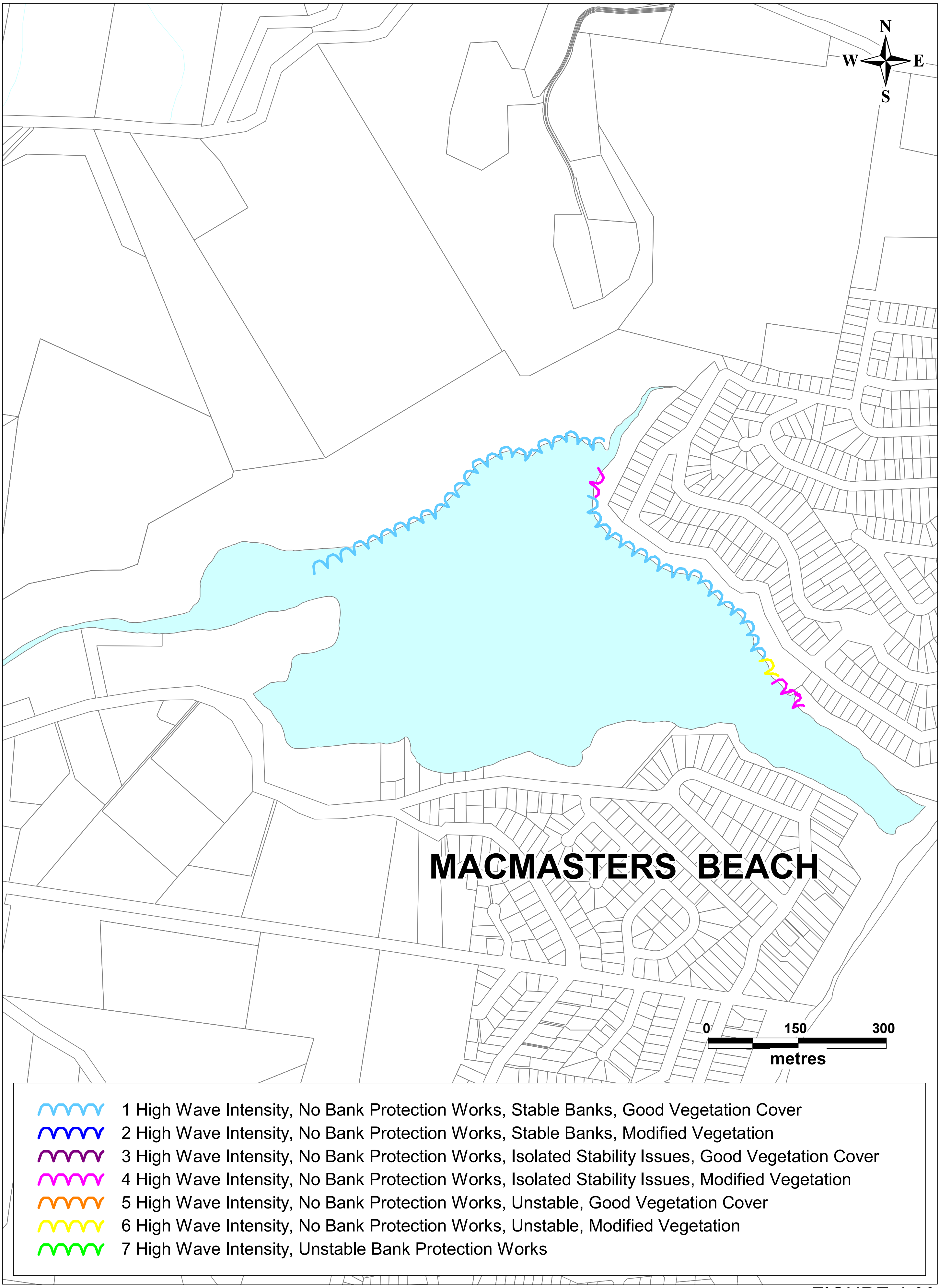
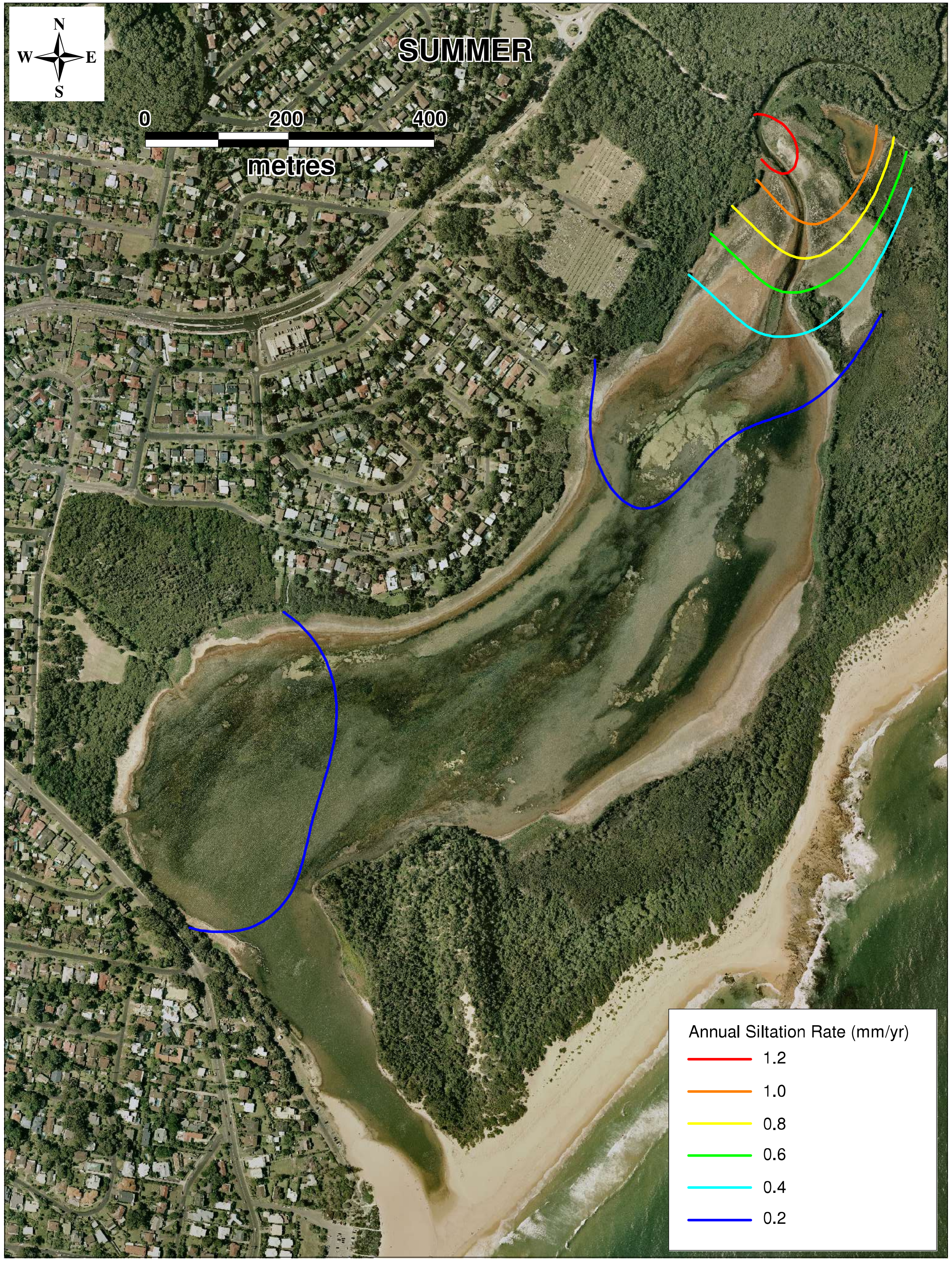


FIGURE 4.28
FUTURE EROSION RISK
COCKRONE LAGOON



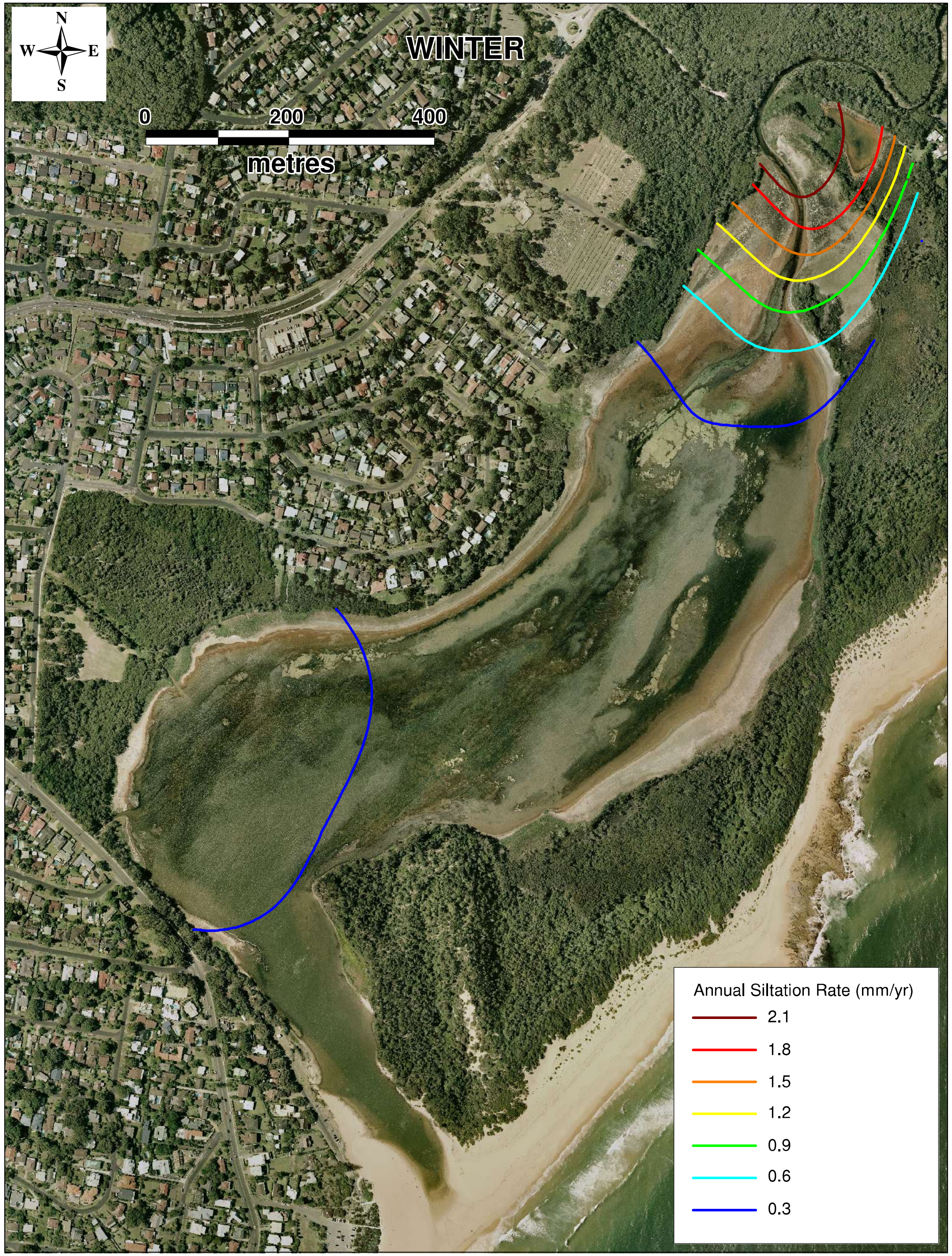


FIGURE 4.29
ANNUAL SILTATION RATES FOR SUMMER AND WINTER
WAMBERAL LAGOON

J:\C\LJ2713\Figures\R2472\Figure 4.29.Wor

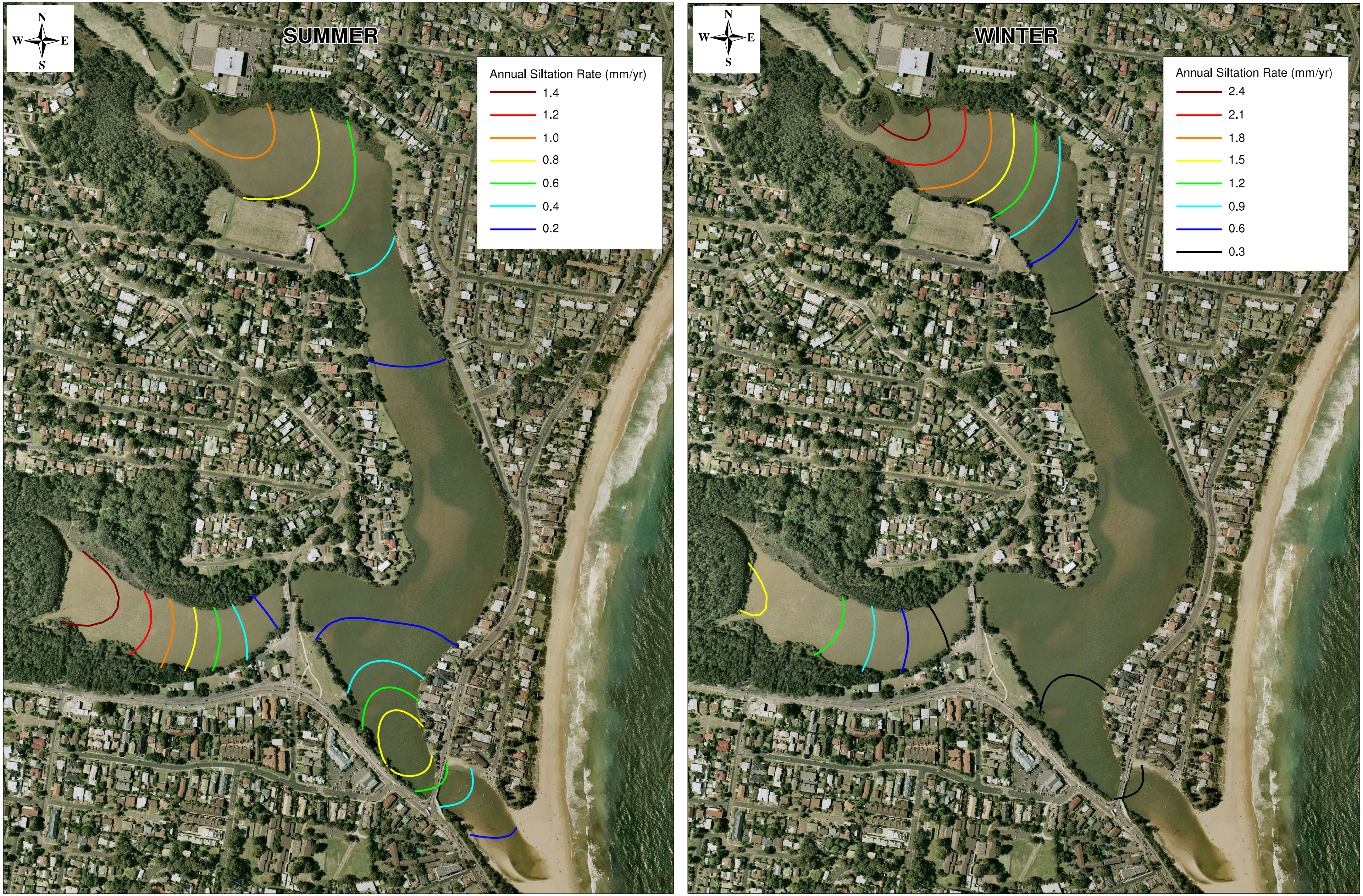


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FIGURE 4.30
ANNUAL SILTATION RATES FOR SUMMER AND WINTER
TERRIGAL LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.30.Wor

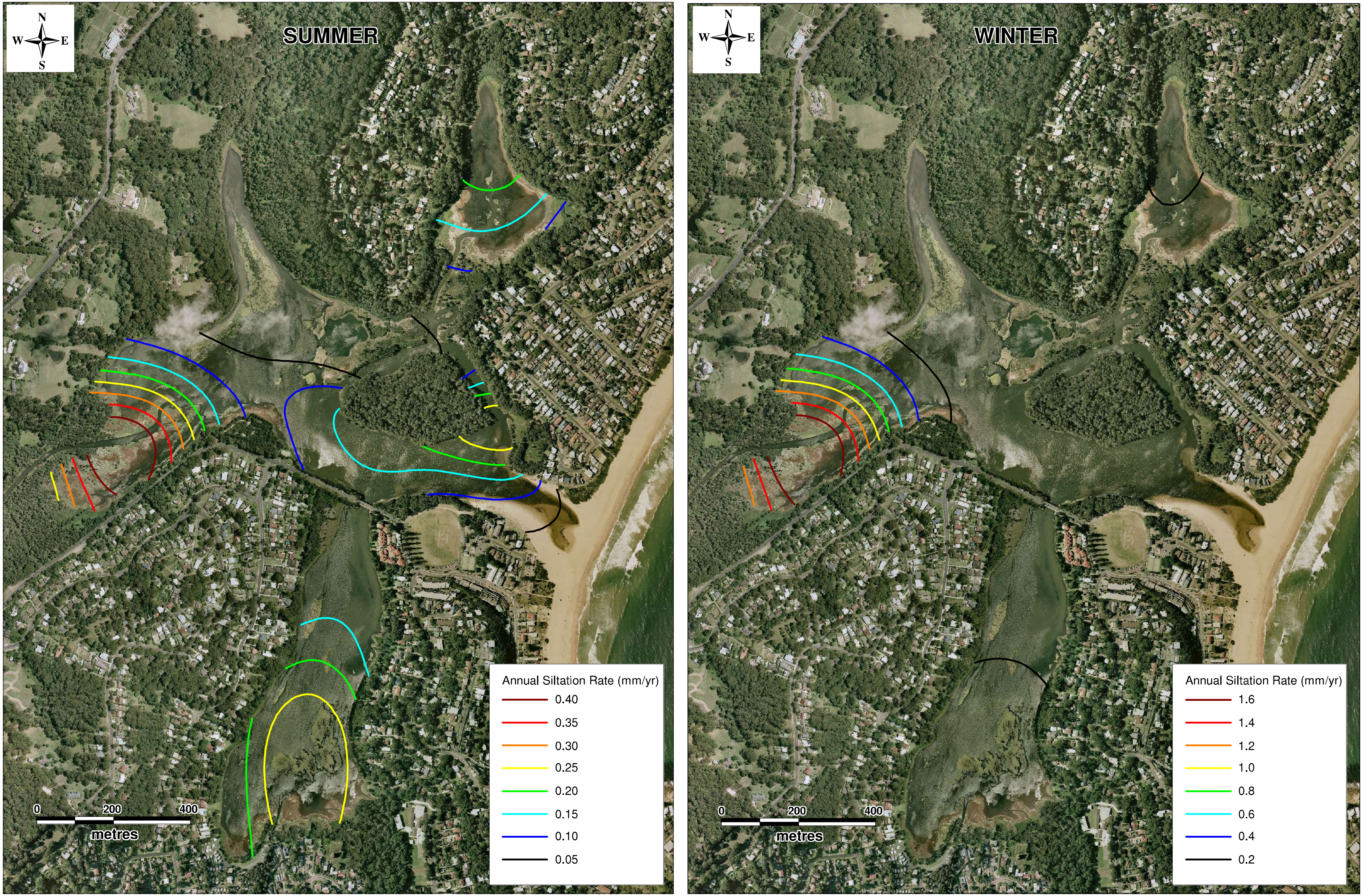

FIGURE 4.31
ANNUAL SILTATION RATES FOR SUMMER AND WINTER
AVOCA LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.31.Wor

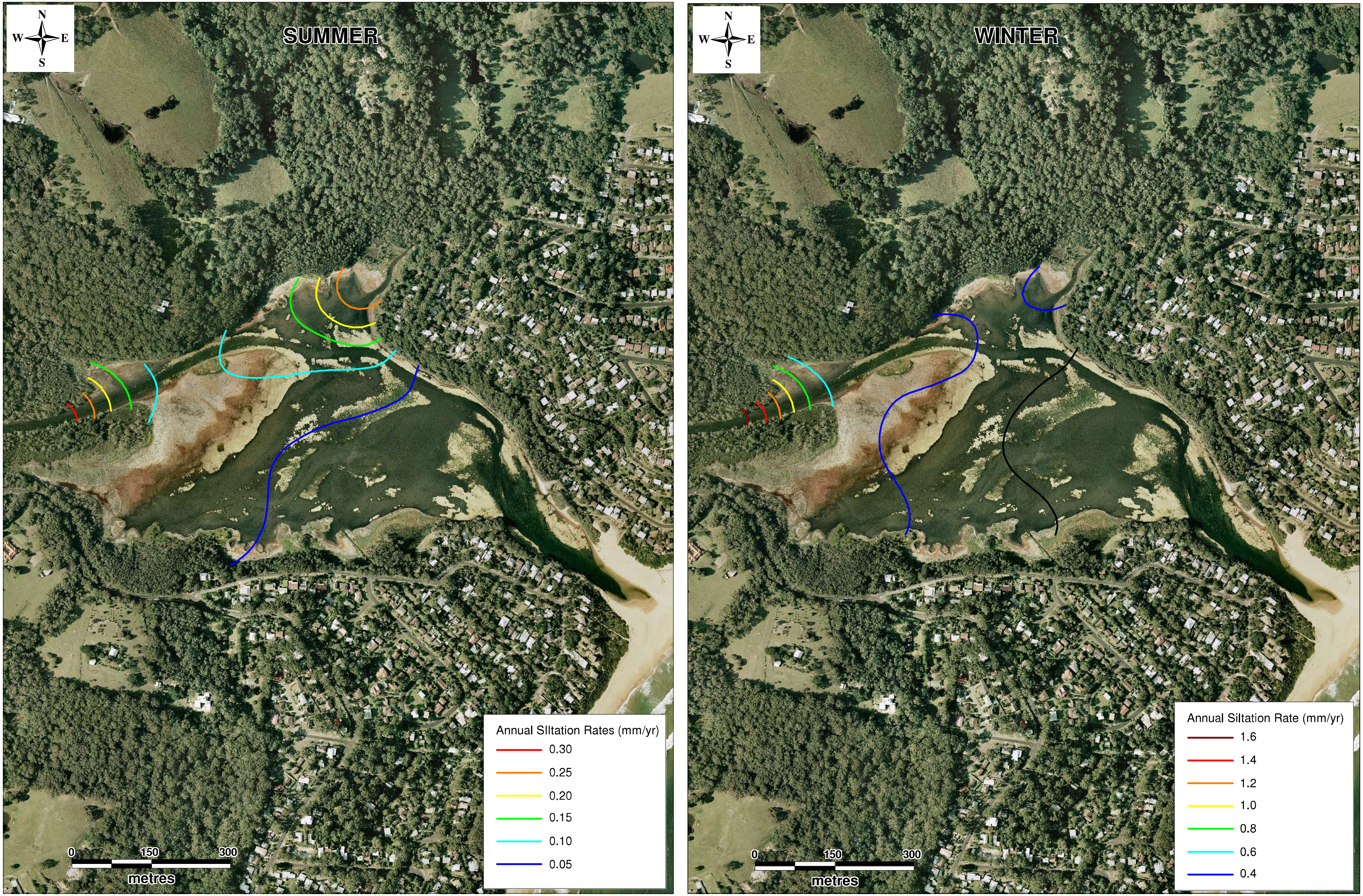

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FIGURE 4.32
ANNUAL SILTATION RATES FOR SUMMER AND WINTER
COCKRONE LAGOON
J:\CM\LJ2713\Figures\R2472\Figure 4.32.Wor

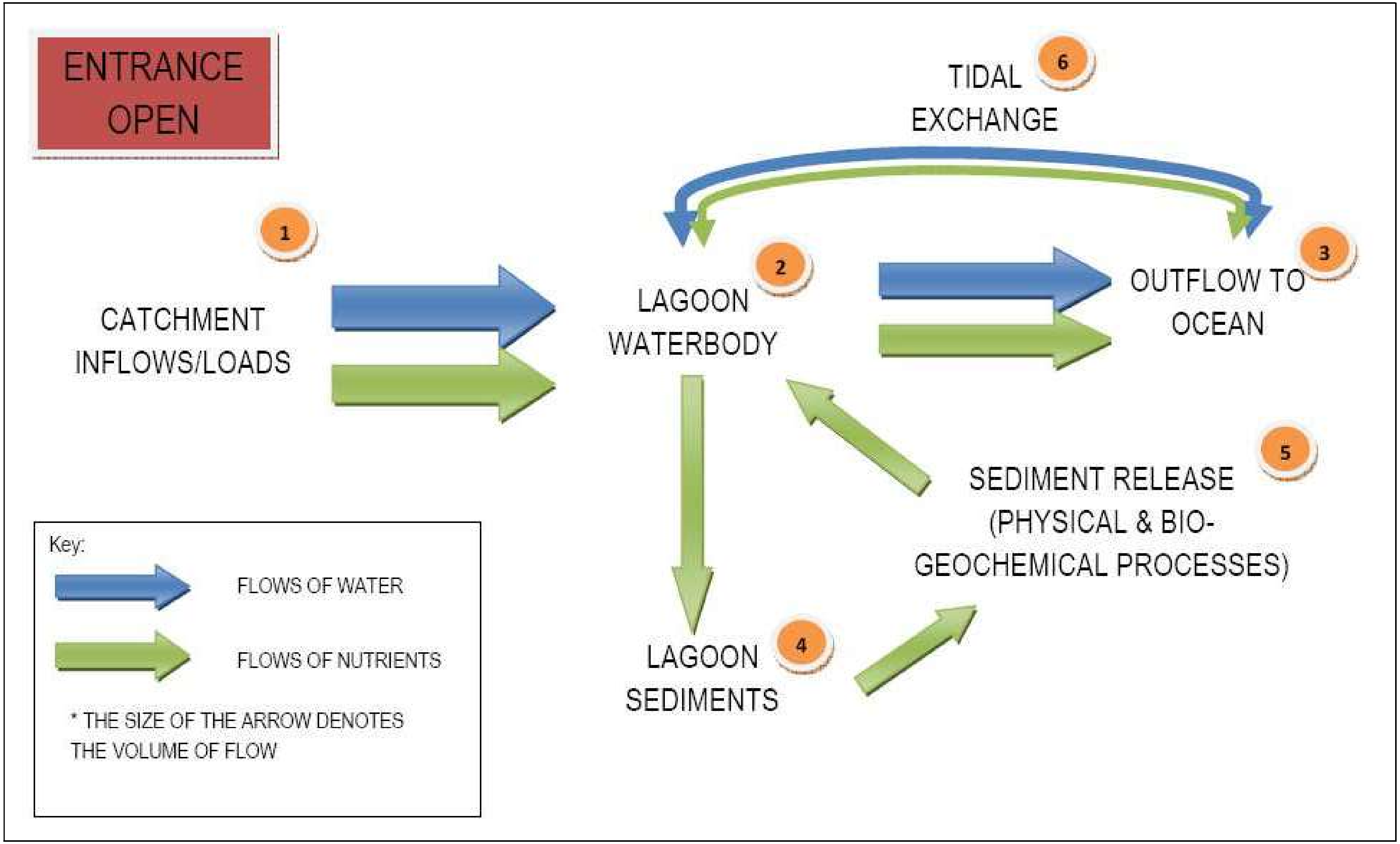

FIGURE 5.1
WATER QUALITY PROCESSES – ENTRANCE OPEN

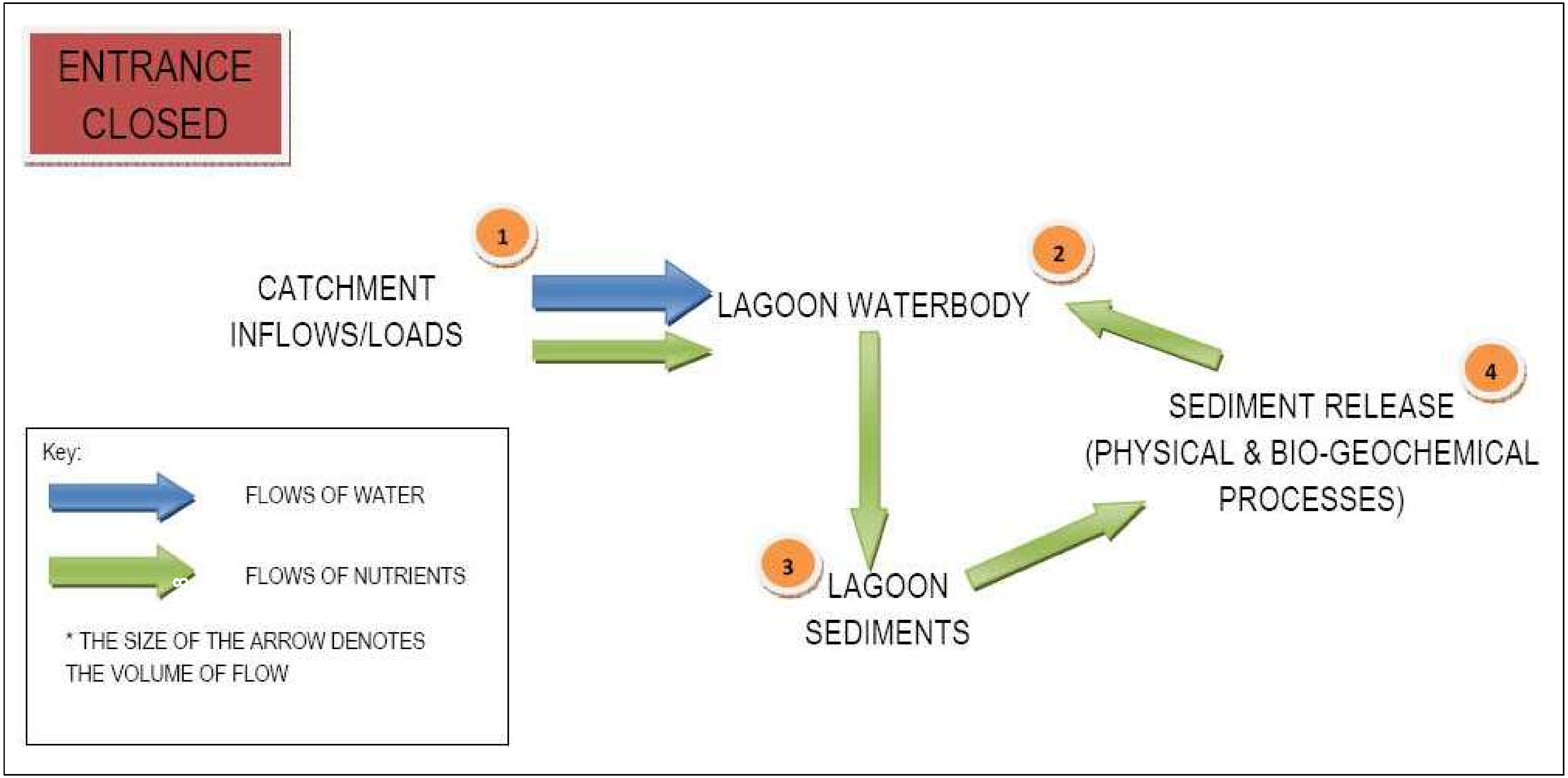

FIGURE 5.2
WATER QUALITY PROCESSES – ENTRANCE CLOSED

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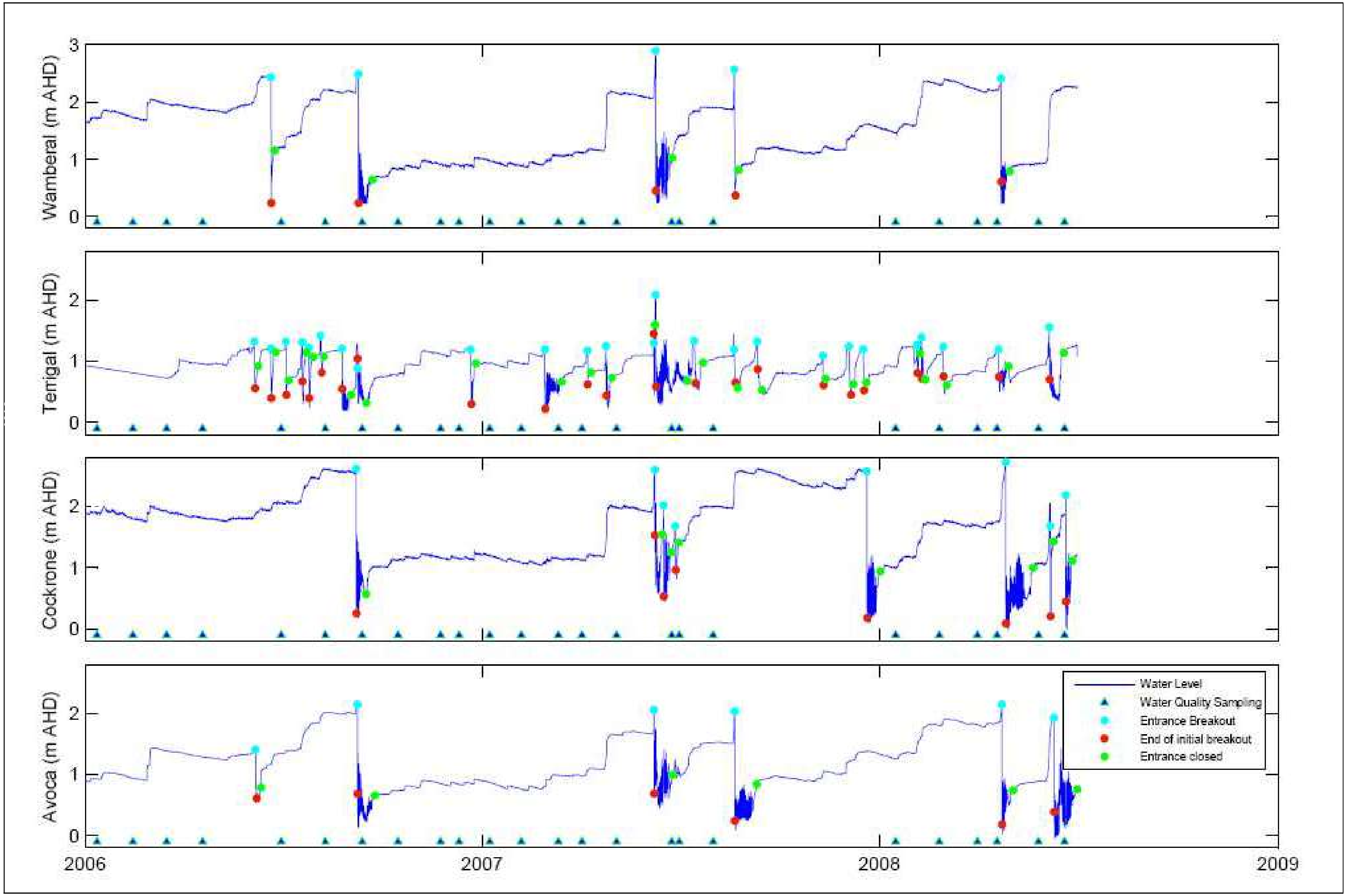

FIGURE 5.3
COMPARISON OF SAMPLING DATES AND
ENTRANCE CONDITION

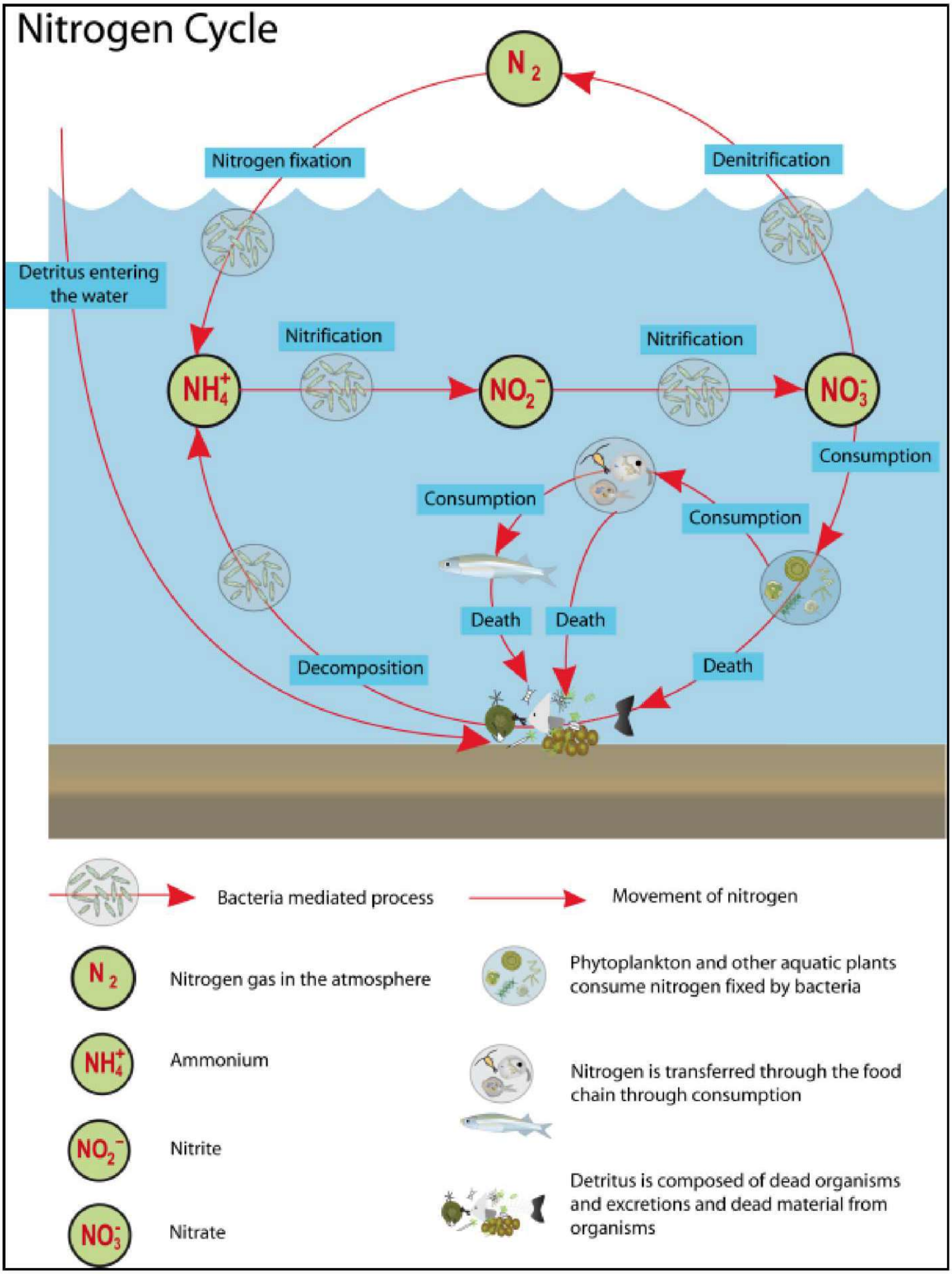

FIGURE 5.4
CONCEPTUAL MODEL –
NITROGEN CYCLE

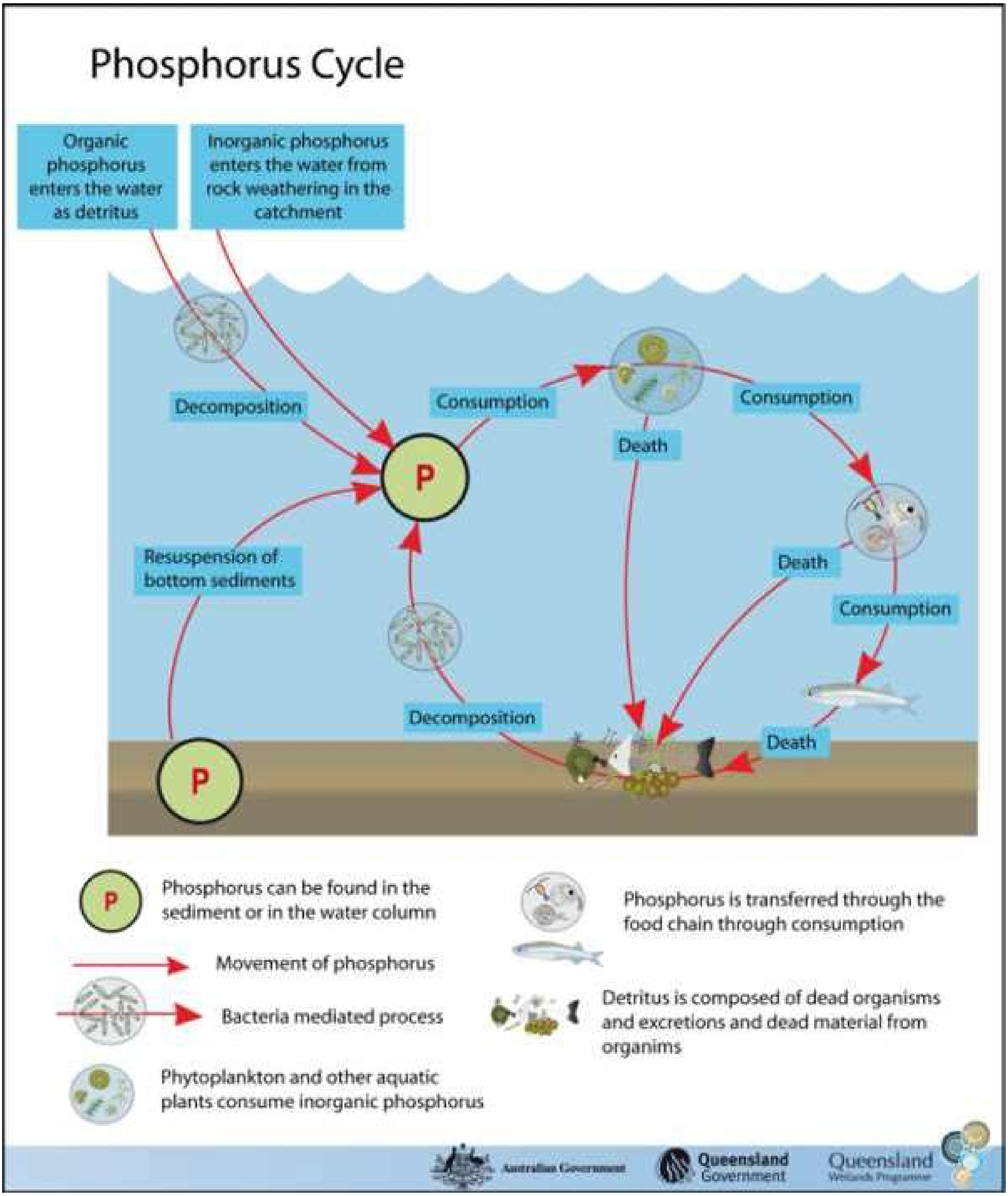

FIGURE 5.5
CONCEPTUAL MODEL – PHOSPHORUS CYCLE

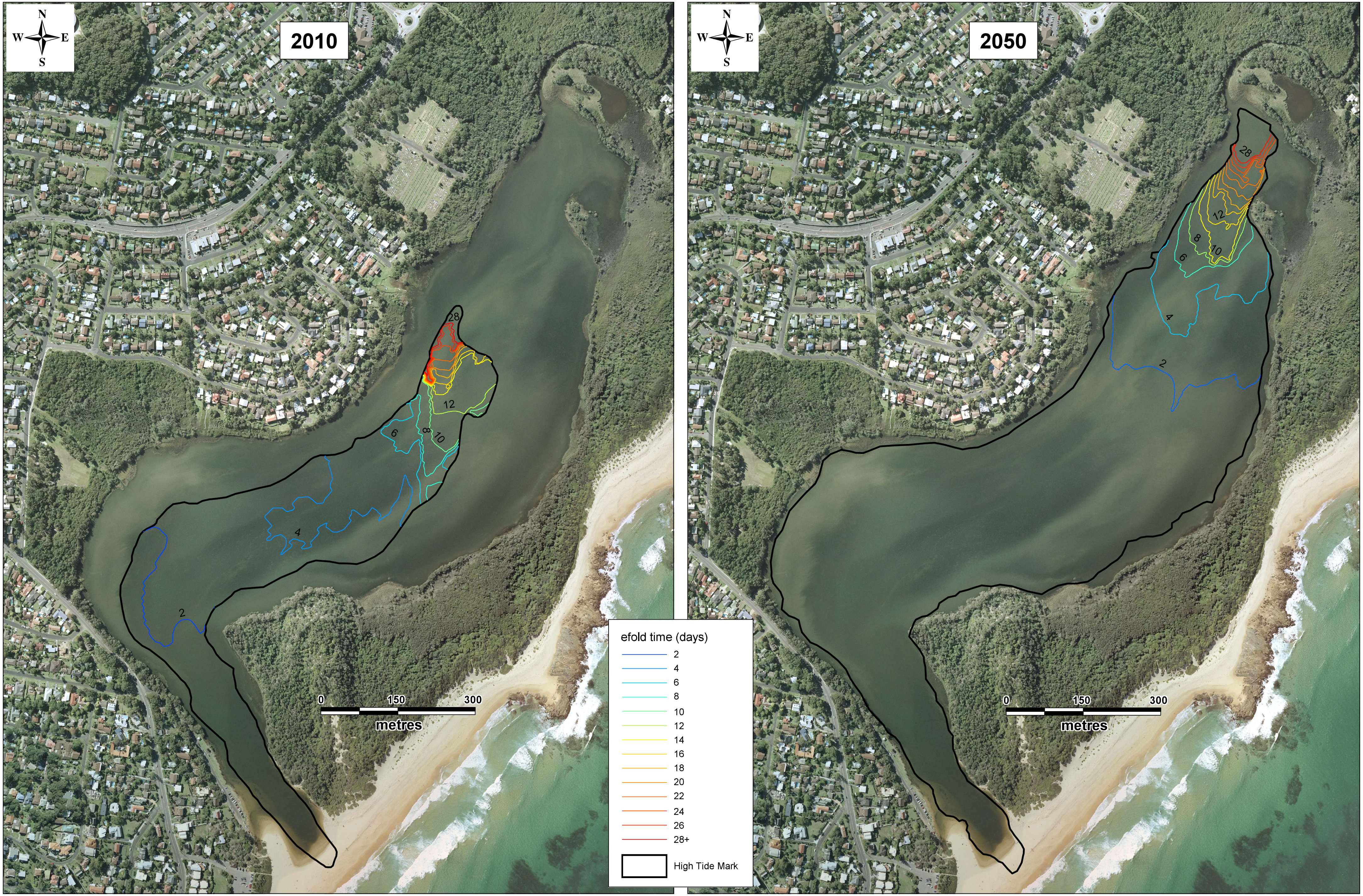

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FIGURE 5.6
EFOLD - FLUSHING TIMES
WAMBERAL LAGOON

J:\CM\LJ713\R2472\Figure 5.6 - Flushing times Wamberal.Wor

FIGURE 5.7
EFOLD - FLUSHING TIME
TERRIGAL LAGOON

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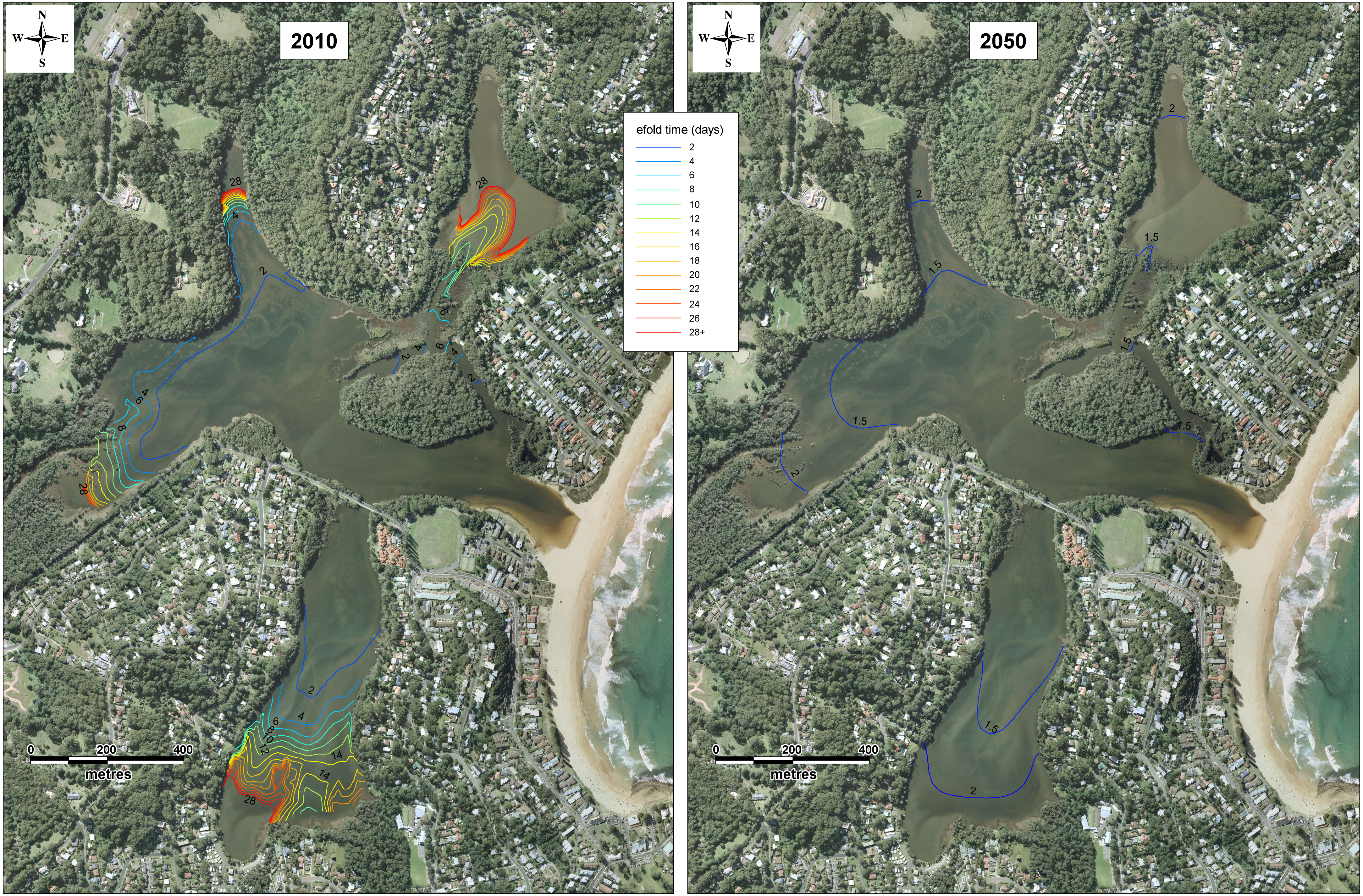

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FIGURE 5.8
EFOLD - FLUSHING TIME
AVOCA LAGOON

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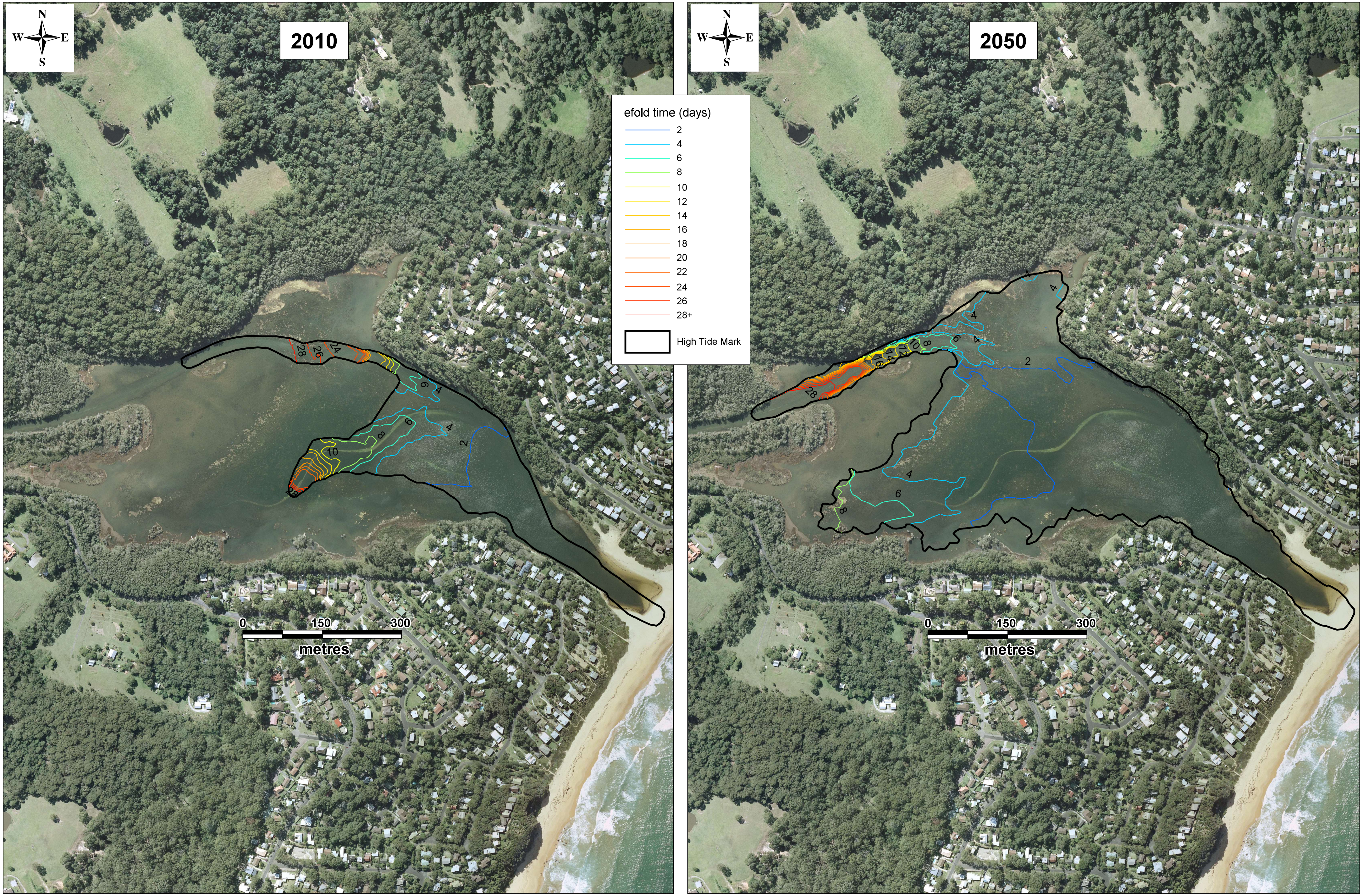

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FIGURE 5.9
EFOLD - FLUSHING TIME
COCKRONE LAGOON

J:\CM\LJ713\R2472\Figure 5.9 - Flushign Plot Cockrone.Wor

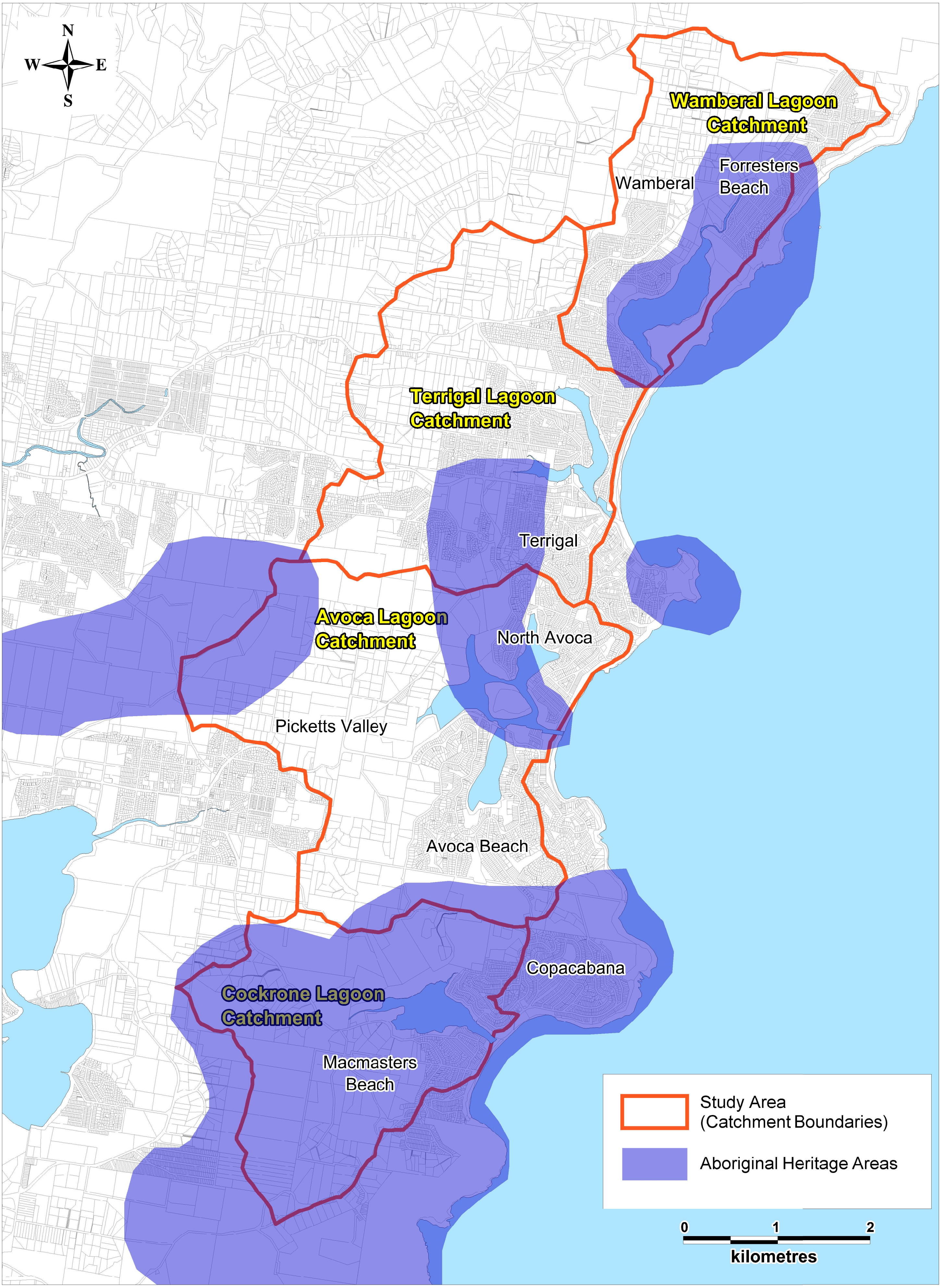

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FIGURE 7.1
HIGH POTENTIAL
ABORIGINAL HERITAGE AREAS

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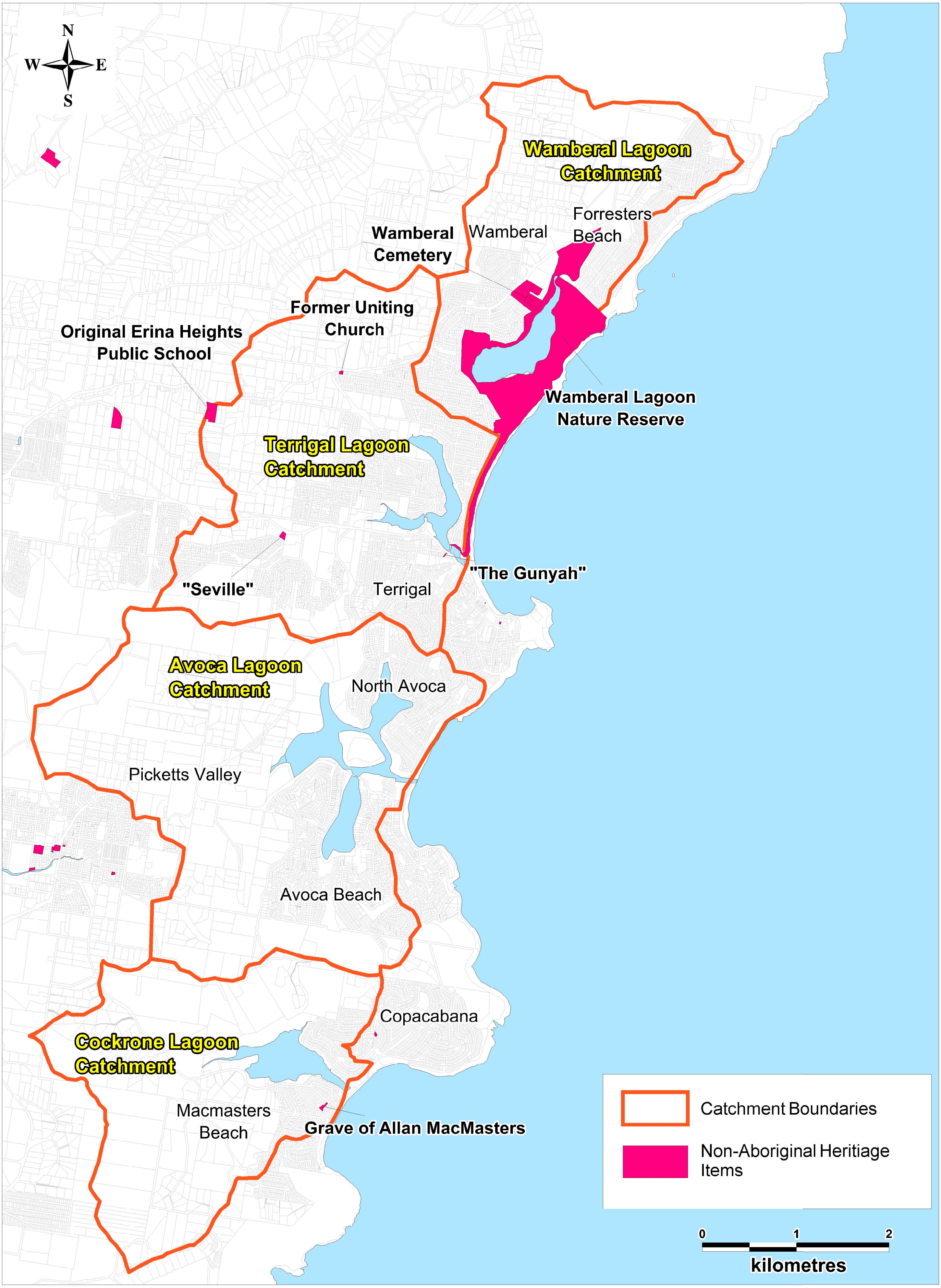

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FIGURE 7.2
NON-ABORIGINAL HERITAGE ITEMS

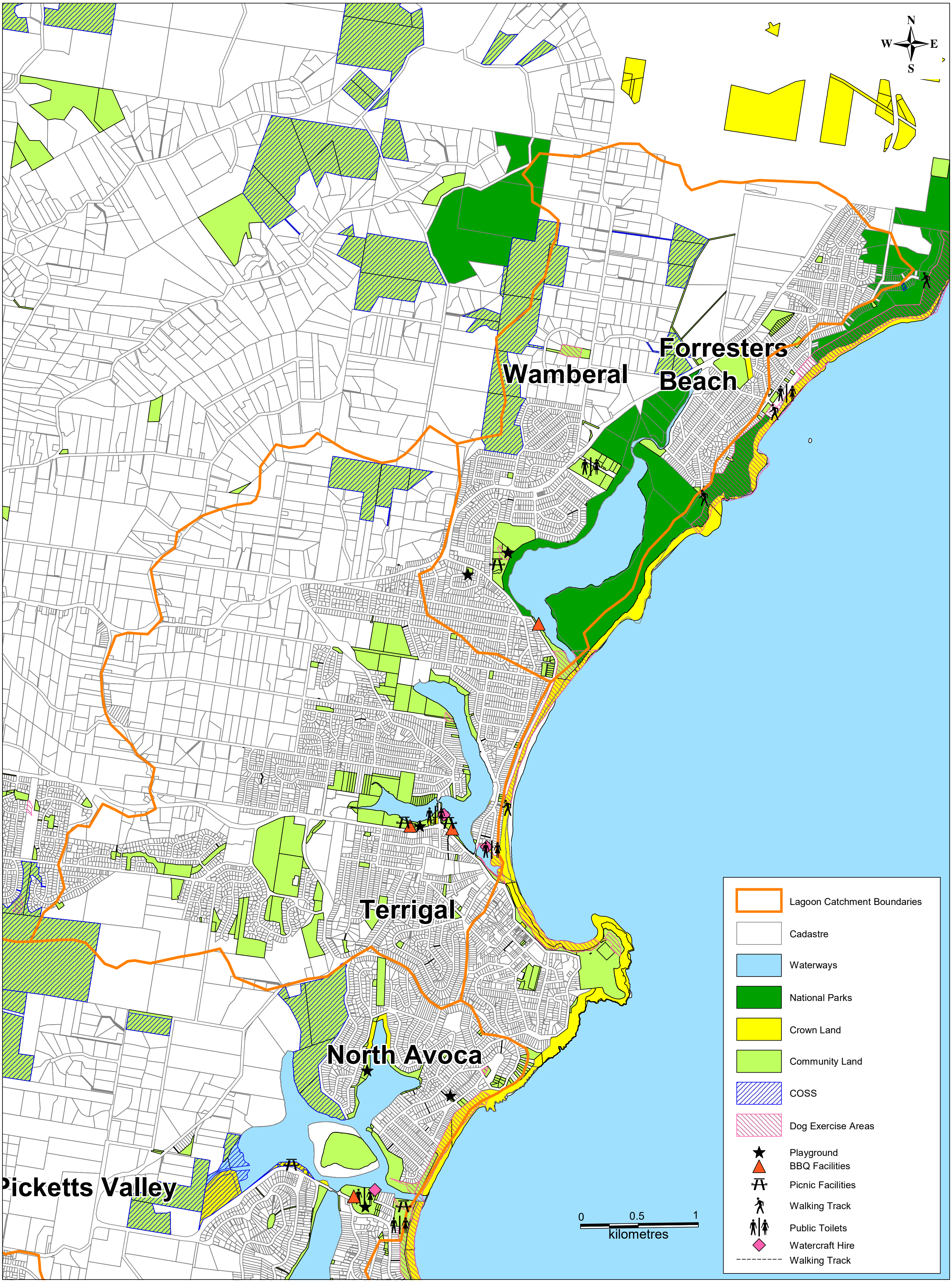

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FIGURE 8.1
RECREATIONAL AND PUBLIC FACILITIES - WAMBERAL AND TERRIGAL LAGOONS

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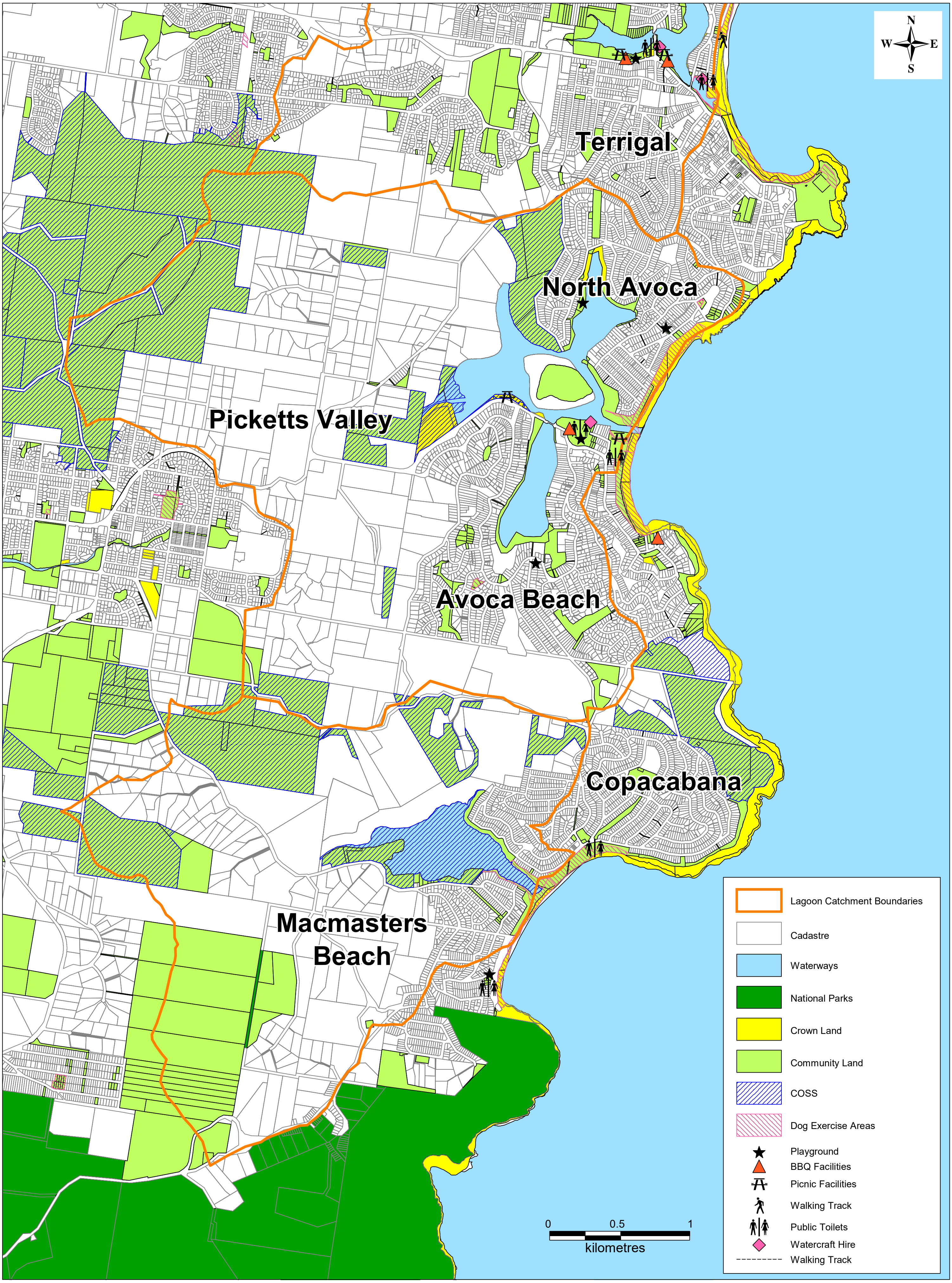

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FIGURE 8.2
RECREATIONAL AND PUBLIC FACILITIES - AVOCA AND COCKRONE LAGOONS

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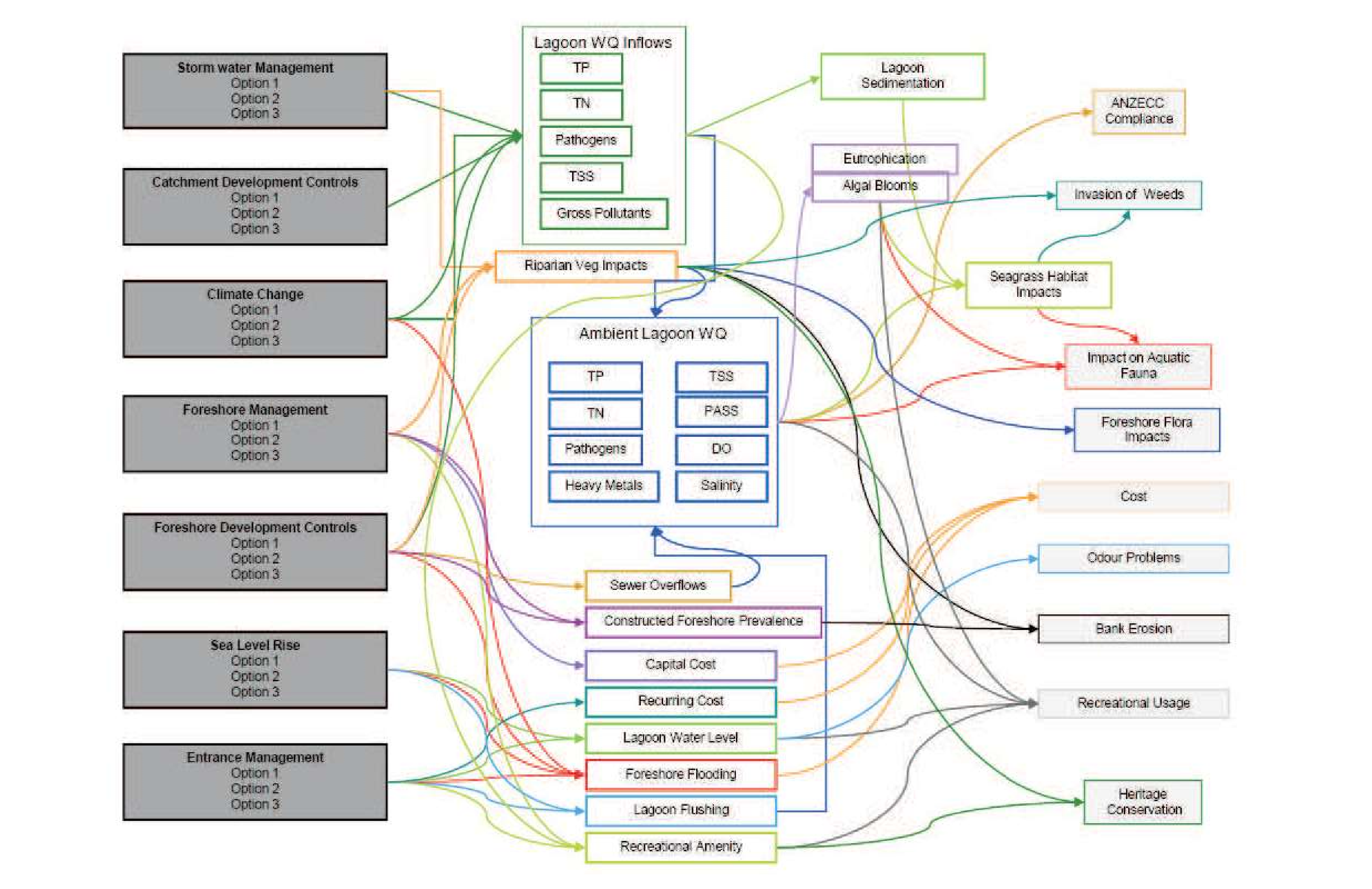

FIGURE 9.1
CONCEPTUAL MODEL OF INTERACTIONS