Determining potential for pollutant impacts in dynamic coastal waters: comparing morphological settings

A thesis

submitted in partial fulfilment

of the requirements for the degree

of

Doctor of Philosophy

at

The University of Waikato

by

TIMOTHY ROGER PRITCHARD

KO TE TANGATA

THE UNIVERSITY OF

WAIKATO

Te Whare Wānanga o Waikato

2012

“*All are churned up together by powerful currents….*” (Daily Mail 2007)

*Yamba beach scene, New South Wales, Australia, during August 2007**

Coastal morphologies are responsible for strange phenomena at many scales, some more conspicuous than others

*Photo Courtesy of Icon Images

ABSTRACT

The coastal focus and beach culture of Australia's population in general, and the people of New South Wales in particular, mean that coastal systems are both highly prized and subjected to great pressures. The vast majority of the wastewater generated by the 7.3 million people of New South Wales is discharged directly to the ocean. The dispersion and fate of waterborne pollutants and their potential to impact coastal ecosystems are fundamentally determined by the dynamics of the coastal boundary layer (CBL). This turbulent interface between the coastline and the deep oceans is defined and classified for the first time in this thesis. Coastal morphologies and changes in the orientation of the coastline promote turbulence and strong gradients with extreme variability and heterogeneity over a broad range of scales. Conceptual models are presented to characterise New South Wales coastal boundary layer processes.

The broad aims of this thesis are to investigate the coastal boundary layer processes that affect dispersal and advection of pollutants, and to develop conceptual models and tools to facilitate coastal management.

Remote sensed ocean colour and sea surface temperature observations define meso-scale CBL phenomena, and this study demonstrates their application to support management decisions in relation to marine algal (phytoplankton) blooms. However, considerable scope exists to improve regional algorithms to deliver better ocean colour products for the optically complex (Case 2) waters of the inner coastal boundary layer.

Past failures to consider the CBL (morphological) settings of pollutant discharges to coastal waters have led to inefficient pollutant discharge systems and potential environmental impacts. Two case studies, investigate the principal forcing mechanisms and demonstrate the importance of morphology in controlling the dispersion and retention times of pollutants.

The first case study is focused on Sydney coastal waters where pollutant loadings are greater in magnitude and different in character than elsewhere in New South Wales. Here population pressures generate large wastewater loadings but the distances to offshore discharge locations are large compared to the scale of coastal roughness (headlands and bays) and the water is deep, thus reducing the risk of local retention of pollutants and increasing the potential for rapid dilution. By considering simulations of near field effluent plume behaviour in relation to long term ambient nutrient patterns specific periods of the year and depth intervals have been identified when outfalls would have an increased opportunity to influence bloom development, especially the upper half of the water column during late summer. However, algal blooms appear to be principally driven by seasonal oceanic nutrient enrichment. The research presented in this thesis, together with companion research previously published by the author and routine ongoing monitoring, indicate the viability of disposal of the Sydney's excess sewage effluent (after source control and re-use options have been exhausted) via existing deepwater outfalls.

In contrast, inner CBL settings with coastal irregularities (e.g. headlands and bays) have a greater propensity to trap pollutants. A new hydrodynamically relevant morphological classification of New South Wales bays, headlands and islands provides both broad context for case studies and guides preliminary

assessments for other locations. This classification reveals a borderline propensity for flow separation and re-circulation in the lee of Corambirra Point which is the focus of the second case study off Coffs Harbour in northern NSW. Direct observations and 3D finite difference hydrodynamic (Eulerian) and particle tracking (Lagrangian) model simulations quantify transient re-circulation associated with local current accelerations and a persistent shear zone located in the wake to the south of Corambirra Point. The flux of ambient water across the prescribed outfall alignment increases eighteen fold, over a shear zone spanning a cross-shore distance of just 1.4km (from 1.6km to 3km offshore). In contrast, the potential for re-entrainment and trapping of effluent in transient re-circulation cells was demonstrated to be insignificant. The proposed location of the outfalls was 1.5km offshore whereas the greatest gain per unit extension of the proposed discharge point coincides with the centre of the shear zone located ~2km offshore.

These case studies illustrate specific coastal boundary layer effects and indicate how an understanding of the spatial and temporal scales of these effects can be used to target more specific assessments of potential pollutant impacts. Simple morphological risk assessment tools are also presented to identify factors and processes which limit the exposure of sensitive environments to high pollutant concentrations and loads. Eddy retention effects are generally not incorporated in existing near field models but potential re-entrainment effects in wake zones can be assessed through the eddy retention value, which is introduced in this thesis. Although the approach presented here is focused on New South Wales coastal waters, the framework serves as a basis for general application elsewhere, and as a foundation for further refinement for application to NSW coastal waters.

Existing scientific literature indicates that coastal boundary layer processes also shape the distributions of the biological species and communities. This further motivates the development of a process based understanding of coastal boundary layer dynamics as a fundamental platform to support environmental protection and biodiversity conservation initiatives.

ACKNOWLEDGEMENTS

The research reported in this thesis was undertaken on a part-time basis. I appreciate the support and flexibility provided by my employer the New South Wales Office of Environment and Heritage (OEH and former organisations).

Completion of this thesis would not be possible without the support of a large number of people, especially my supervisors Professor Terry Healy, Dr Klaus Koop, Dr Kerry Black and Dr Willem de Lange, my family, friends and work colleagues.

Professor Terry Healy was my Chief Supervisor for most of my candidature, imposing his high standards and demonstrating his renowned personal and professional commitment to post graduate research supervision. I am one of a last of a very long succession of grateful postgraduate students who have benefited from his supervision. He will be greatly missed.

Dr Kerry Black's expertise and drive set me on my course and supported my research in many ways including provision of hydrodynamic models (3DD), training in their use, and insightful reviews and suggestions. Furthermore, I'd like to thank Kerry and his partner Moira Healy for their great hospitality and friendship during my studies in New Zealand and Lombok.

My director at the Office of Environment and Heritage, Dr Klaus Koop, provided enduring and enthusiastic encouragement and created opportunities for me to accommodate study amongst demanding and sometimes conflicting work commitments; without Klaus's extremely generous personal support I would not have undertaken and completed this thesis.

Dr Willem de Lange kindly took on responsibilities of Chief Supervisor when Professor Terry Healy passed away towards the end of my candidature. I am grateful for his contributions in shepherding of my thesis through to completion.

One of the greatest rewards of this endeavor has been the opportunity to journey through a great breadth of scientific literature using wonderful search engines that were unimaginable during my distant undergraduate days. Another has been the opportunity to collaborate with other researchers especially those acknowledged as co-authors of the papers I have published during my candidature. I have benefited greatly from formal and informal reviews comments and discussion with a range of researchers and technical experts, such as Dr Randall Lee, Clive Holden, Dr John Parslow, Dr George Cresswell and the anonymous reviewers of journal publications. Constructive review comments by Professors Roger Nokes and Chari Pattiaratchi are also gratefully acknowledged.

Last but not least I'd like to thank my family who supported me through everything, especially the women in my life: my wife Sue, my three daughters, Laura, Tess and Genevieve, and my mother Jackie.

PREFACE

The main body of this thesis comprises three chapters (Chapters 5-7) which include papers that have been published in international peer reviewed scientific journals or book chapters:

Chapter 5

Pritchard, T.R. and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.

Chapter 6

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T. R., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Affect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.

Chapter 8

Pritchard, T.R., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Refereed Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

Findings from Chapter 9 have also been published, as attached in Appendix 3.

Pritchard, T.R., Black,K.P., Lee, R.S. and Koop, K. (2011) Coastal boundary layer effects on pollutant dispersion. Coasts and Port 2011 Conference, Perth, WA, 27-30th September 2011. Institute of Engineers, Australia.

Much of the material presented here has been presented and discussed at major scientific meetings and conferences, as outlined in Appendix 1 (18 presentations).

Discussion within this thesis also draws heavily on previously published research by the author, which is referenced in Appendix 2 and, in some cases, provided in Appendix 3. T. Pritchard authored or co-authored 17 refereed publications during the period of candidature.

Except where referenced or acknowledged the material within this thesis was produced from my own ideas and work undertaken with the supervision of Professor Terry Healy, Dr Kerry Black, Dr Klaus Koop and Dr Willem de Lange.

This research was supported by New South Wales Office of Environment and Heritage (including former incarnations of this organisation).

This thesis is also provided electronically in .doc and .pdf versions, formatted for double sided printing.

TABLE OF CONTENTS

LIST OF FIGURES

Pritchard, T.R. and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.

Pritchard, T.R., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

LIST OF TABLES

LIST OF ACRONYMS

ABS	Australian Bureau of Statistics
ADCP	Acoustic Doppler Current Profiler
ADWF	Average Dry Weather Flow
AMCANZ	Agriculture & Resource Management Council of Australia & New Zealand
ANZECC	Australian & New Zealand Environment & Conservation Council
AVHRR	Advanced Very High Resolution Radiometer
BACI	Before and After Control Impact
BRAN	BlueLink ReANalysis
CARS	Coastal And Regional Seas around Australia atlas
CD	Compact Disc
CHCC	Coffs Harbour City Council
CHEIS	Coffs Harbour Environmental Impact Statement
CMODIS	Chinese Moderate Resolution Imaging Spectroradiometer
CN	Curve Number
CSIRO	Commonwealth Science and Industrial Technology Organisation
CTD	Conductivity Temperature Depth
CTW	Coastal Trapped Waves
CZCS	Coastal Zone Colour Scanner
DECC	NSW Department of Environment and Climate Change
DECCW	NSW Department of Environment Climate Change and Water
DGPS	Differential Global Positioning System
EMP	Environmental Monitoring Program
EAC	East Australian Current
ENSO	El Nino Southern Oscillation
EPA	Environment Protection Authority (NSW)
GIS	Geographical Information System
GPS	Global Positioning System
IMCRA	Interim Marine and Coastal Regionalisation for Australia
IOCOCG	International Ocean Colour Ocean Coordination Group
NOAA	US National Oceanographic and Atmospheric Administration
OEH	NSW Office of Environment and Heritage
OGCM	Ocean General Circulation Models
ORS	Ocean Reference Station
PAR	Photosynthetically Available Radiation
PH	Port Hacking
L-THIA	Long-Term Hydrologic Impact Assessment
ML	Mega Litres
MERIS	MEdium Resolution Imaging Spectrophotometer
MODIS	MODerate resolution Imaging Spectrophotometer
N	Nitrogen
NSW	New South Wales
P	Phosphorus
RDI	Research and Development Instruments Pty Ltd
RAN	Royal Australian Navy
SeaWiFS	Sea-viewing Wide Filed-of-view Sensor
SoE	State of Environment
SST	Sea Surface Temperature
SWC	Sydney Water Corporation
TAO	Tropical Atmosphere Ocean project
US	United States
USEPA	United States Environment Protection Authority
UV	Ultra Violet
XBT	eXpendable Bathy Thermograph

1. INTRODUCTION

1.1 Background

The vast majority of the wastewater generated by the 7.3 million people of New South Wales (NSW) is discharged directly to the ocean. Coastal waters are under pressure because about 85% of NSW people live near the coast, mostly concentrated in the coastal strip straddling the cities of Newcastle, Sydney and Wollongong (Figure 1.1) (SOE 2006, 2009). Sydney Water Corporation alone pumps about 390 billion litres of wastewater directly to the ocean every year and over 92% of this receives only primary treatment prior to discharge (SWC, 2005). To the north and south of Sydney, smaller quantities of more highly treated sewage effluent are discharged from outfalls mostly at the shoreline.

The coastal focus and beach culture of Australia's population in general, and the people of NSW in particular, means that coastal systems are both highly prized and subjected to great pressure (James et al., 2006). The coastal zone is an asset which supports a vibrant tourist industry; most overseas visitors to Australia have a destination in coastal NSW (ABS 2000 & Tourism NSW, 1999 – see SoE2000). Both commercial and domestic sectors, therefore, demand a high level of protection. Sewage discharges to the ocean have been a focus for extreme community outrage while the appearance of algal blooms has caused alarm and public outcry (Figure 1.2).

The inherent value of the main constituents of sewage (water and nutrients) has been recognized and re-use has been promoted by the NSW Government. Despite this, in the Australian context, existing re-use is minimal and options for large scale re-use appear prohibitively costly in the near and medium terms, due to the existing infrastructure, health concerns, the low price of potable water and the current socio-economic climate. Significant quantities of treated sewage will, therefore, continue to be discharged to the ocean for the foreseeable future.

Coastal catchments also continue to discharge anthropogenic pollutants to NSW coastal waters. Further urban development will increase pollutant loadings to coastal waters from both diffuse and point sources within coastal catchments. As yet poorly defined fluxes of atmospheric pollutants also enter coastal waters at the sea surface while groundwater and sediment fluxes can exchange pollutants at the sea floor.

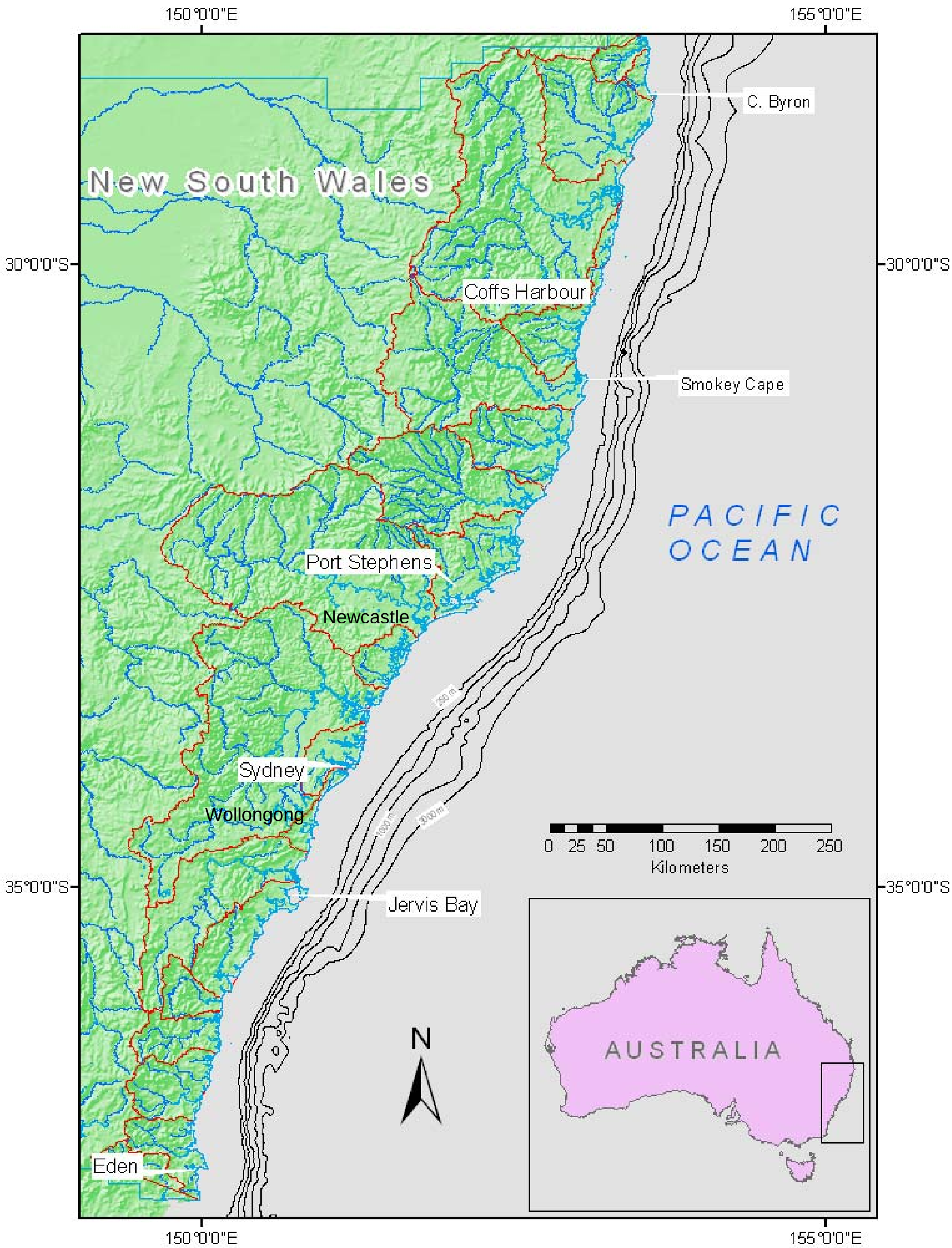


Figure 1.1: New South Wales coastal catchments, shoreline configuration and shelf bathymetry

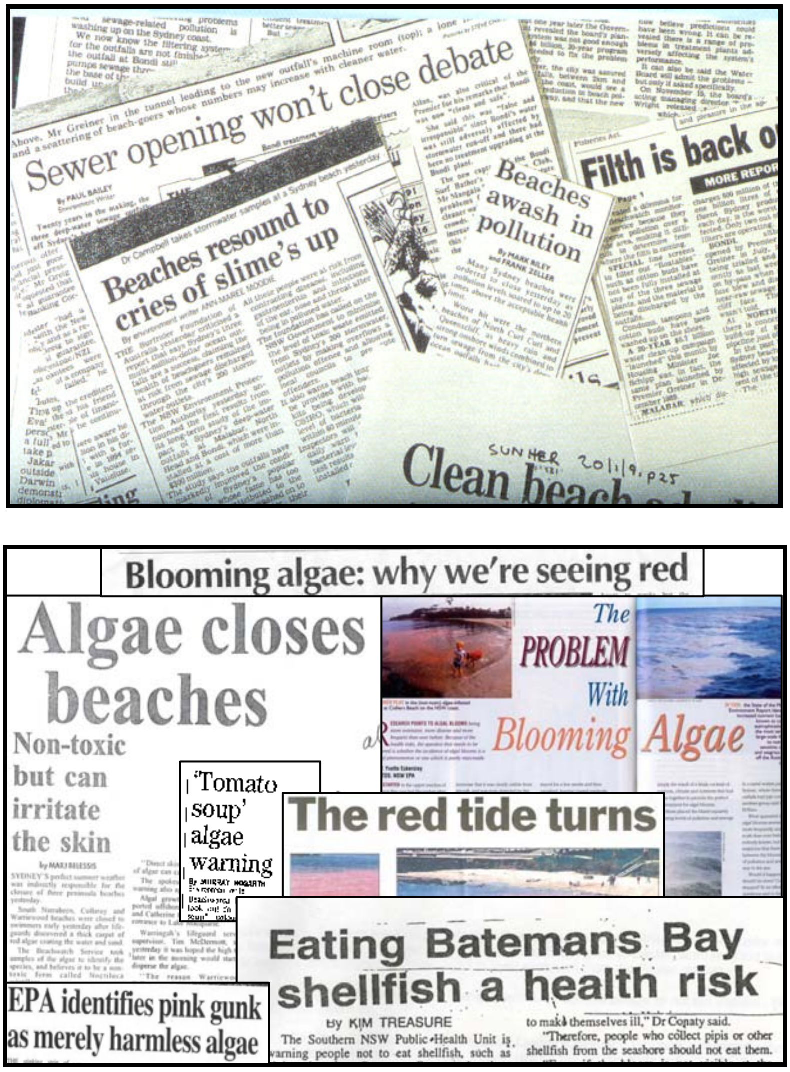


Figure 1.2: Media and community outrage over ocean outfall issues (top) and outpourings of concern over eutrophication issues (bottom) in New South Wales coastal waters

The dispersion and fate of these pollutants and their potential to impact coastal environments are fundamentally determined by the dynamics of the receiving waters. Coastal morphology constrains and controls flows. In particular, headlands and changes in the orientation of the coastline disrupt stream flows, resulting in wakes, and turbulent re-circulation cells. Many of these features result in the formation of a coastal boundary layer.

The NSW continental shelf is relatively narrow and shelf waters are exposed to a diverse range of driving mechanisms. At a large scale, NSW coastal waters are dominated by a western boundary current – the East Australian Current – which flows southward along a relatively narrow continental shelf. In the north, warm, oligotrophic East Australian Current waters flow parallel to isobaths until the orientation of the coastline changes between Sugarloaf Point and Port Stephens. Here the East Australian Current separates from the shelf, shedding turbulent eddies which extend southwards from Port Stephens to about Jervis Bay. Superimposed on these primary forcing mechanisms are the effects of coastal trapped waves, internal waves, wave induced turbulence, and transport (nearshore). Winds are an important driver for shallow nearshore flows, which can be modified by estuarine discharges, headlands, embayments, nearshore islands reefs and other bathymetric features.

The greatest pollutant loadings to NSW coastal waters occur off Sydney where alongshore bathymetry is relatively uniform. In contrast, relatively low pollutant loadings to the ocean occur in northern NSW, such as Coffs Harbour, but these areas are experiencing rapid urban development.

Ecological responses to pollutant and many other stressors remain poorly understood at both species and community levels. However, it is clear that hydrodynamics are fundamental to understanding relationships between stressors and impacts in marine ecosystems. Flows and vertical density structures control distributions of both pollutants and biota. The dilution, dispersion and fate of pollutants is driven by turbulent mixing and advection while biological distributions are affected by physical connectivity, retention times, settlement rates, and the physicochemical variability of marine habitats which is often determined by the passage of water bodies.

Advection (mean transport) generally decreases with proximity to the coast due to bottom friction and the roughness of the coastline slowing alongshore flows. The solid boundary against the coast also inhibits cross shelf flows but may promote baroclinic flows such as upwelling dynamics. Turbulence can develop near the coast due to interactions with inner shelf bathymetry, irregular coastlines and estuarine outflows. In this coastal boundary layer flows are retarded and residence times increase relative to offshore regional flows.

Human activities are concentrated on land so loadings and stressors are generally greatest close to the coast (e.g. wastewater discharges; polluted estuarine outflows; introduced species in ports; and, recreational fishing). Clearly, the hydrodynamic characteristics of the coastal boundary layer are critical in determining the fates and impacts of pollutants and the distribution of biota. For example, physical processes are critical in determining concentrations and distributions of pollutants, the spread of introduced species, and the biological connectivity between marine protected areas.

1.2 Aims and Objectives

The aims of this thesis are to investigate the processes within the coastal boundary layer that affect dispersal and advection of pollutants and, in doing so, develop conceptual models to facilitate coastal management.

To achieve these aims, the specific objectives of this study were to:

- ⇨ classify coastal boundary layer types observed off New South Wales based on coastal bathymetry, satellite sensed data, aerial photography, and observations of local and regional flow dynamics

- ⇨ determine the utility of remotely sensed ocean colour and sea surface temperature (SST) data to characterise broad scale ecosystem and coastal boundary layer processes and to investigate applications to support coastal management

- ⇨ investigate CBL processes, their relationship to coastal morphology, and their role in controlling the dispersion, fate and potential impacts of pollutants discharged to the New South Wales coastal waters

- ⇨ develop a hydrodynamically relevant morphological classification of headlands, islands and open bays for New South Wales

- ⇨ investigate physical processes and dispersion characteristics for specific pollutant discharges to New South Wales coastal waters through case studies off Sydney (outer coastal boundary layer) and Coffs Harbour (inner coastal boundary layer)

- ⇨ identify applications of the coastal boundary layer classification for coastal management and develop and demonstrate simple risk assessment tools to identify factors and processes which can mitigate potential pollutant impacts

1.3 Structure of Thesis

In order to address the objectives listed above, the thesis is structured as follows:

Chapter 2 evaluates major terrestrial pollutant sources in terms of loadings, concentrations and patterns of delivery. Likewise, existing knowledge of the physico-chemical environment and current understanding of processes and impacts are summarised as a background to this study.

Chapter 3 describes sources of new data, quality assurance, and tools used for analysis of new and existing data to develop predictive understanding.

The coastal boundary layer concept is introduced in ***Chapter 4*** as a framework to structure and focus investigations of the effects of interactions of flows and coastal morphologies. Conceptual models are presented to characterise New South Wales coastal boundary layer processes.

Broad scale characteristics of nearshore waters are explored through remotely sensed data in ***Chapter 5*** to provide a context for selection and extrapolation of case studies and to explore processes operating in the outer coastal boundary layer.

Two case studies investigate in detail the principal forcing mechanisms and the importance of morphology in controlling the dispersion and retention times of pollutants and the potential for ecological impacts.

The first case study is focused on Sydney coastal waters (***Chapter 6***) where pollutant loadings are greater in magnitude and different in character than elsewhere in NSW due to existing and historical population pressures. Here the coastline is relatively open in contrast to the second case study in Chapter 8 which focuses on the effects of inner coastal boundary layer processes.

Chapter 7 develops a hydrodynamically relevant morphological classification of New South Wales bays, headlands and islands to target morphological settings that may be pre-disposed to wake effects. This provides a means to target case studies, prioritise environmental assessments and inform the possible extrapolation of findings from specific studies;

The second case study (***Chapter 8)*** is drawn from northern NSW coastal waters where a new outfall was required off Coffs Harbour to accommodate rapid urban development. Here, flows interact with a headland and irregularities in inner shelf bathymetry.

Findings from this thesis and previous studies are drawn together in ***Chapter 9*** to explore and evaluate the Coastal Boundary Layer (CBL) classification first proposed in Chapter 4. This chapter also explores how coastal boundary layer processes shape the distributions of the biological species and communities that can be impacted by pollutants. Finally, the management implications are considered and developed, illustrating the importance of a process based understanding of the coastal boundary layer.

Chapter 10 highlights the findings and implications of these studies in the context of current scientific and management paradigms and concludes with suggestions for future research.

1.4 References

ABS 2000 & Tourism NSW, 1999 – see SoE2000

James,D., Donnelly,P., Green,W., Mason,E., Neirinckx, A., Ochiel,V., Rice,B., Chapman,G., Ferrier,S., **Pritchard, T.**, Fenton, M. (2006) The CCA Integrated Decision Framework: guide for sustainable land use planning, prepared for the Comprehensive Coastal Assessment, New South Wales Department of Planning, Sydney. ISBN 1 74029 220 0. http://www.planning.nsw.gov.au/PlansforAction/Coastalprotection/ComprehensiveCoastalAssessment/tabid/171/language/en-AU/Default.aspx

SOE 2006. New South Wales State of the Environment 2006, ISSN 1320-6311. http://www.environment.nsw.gov.au/soe/soe2006/index.htm

SOE 2009. New South Wales State of the Environment 2009, http://www.environment.nsw.gov.au/soe/soe2009/

SWC, 2005. Environmental Indicators Compliance Report, Sydney Water Annual Report 2005, ISSN 1328-0554.

2. BACKGROUND

The NSW coastline is 1,900 km in length, ranging from warm subtropical in the north to cool temperate in the south. The dominant influences in New South Wales (NSW) marine waters are oceanographic (NSW SoE, 2006).

A major western boundary current – the East Australian Current (EAC) - streams southward from the Coral Sea and interacts with continental shelf morphology of coastal NSW, defining two broad regions (Figure 2.1). Northern NSW shelf waters, such as those off Coffs Harbour, experience strong and persistent EAC flows which carry warm, oligotrophic waters and associated tropical species (Ridgeway and Dunn, 2003). At about latitude 31˚S the continental shelf narrows, the orientation of the coastline changes, and the EAC often separates from the continental slope to flow southeastward. South of this separation point lies a second broad region where EAC and Tasman Sea waters mix, promoted by mesoscale eddies which are shed from the EAC. Central and southern NSW shelf waters, such as those off Sydney, fall within this region and are affected by the passage of these eddies as well as occasional southward excursions of the main EAC flow. In southern NSW, Tasman Sea influences become more prominent, especially during winter (Ridgeway and Dunn, 2003; Middleton, 1995).

A compendium of multi-disciplinary research related to the dominant oceanographic feature – the EAC – was published in Deep Sea Research in 2011, including findings related to: broad-scale climate-induced effects, EAC eddy dynamics, boundary current transport, the influence the EAC has on connectivity in relation to life history strategies, plankton distribution, fisheries habitats, and, the effects of climate change (Suthers et al., 2011).

NSW spans highly diverse environments supporting high biological diversity and endemism (IMCRA, 1998), which are subjected to pollutant loading and human disturbances.

Pollutant loadings to NSW coastal waters originate from diffuse catchment and atmospheric sources as well as from point sources such as ocean outfalls for sewage effluent. In the context of this study estuary mouths can be regarded as point sources to coastal waters although they deliver pollutants derived from mainly diffuse sources distributed across coastal catchments. These loadings, together with variable natural fluxes of organic and inorganic materials result in environmental disturbances, which drive changes (impacts) in communities of organisms. Physical, chemical and biological processes mediate the effects of these loadings and thus control the ecological responses.

In this chapter major pollutant sources are identified together with salient features of receiving environments. Observed impacts are then summarised and information gaps are identified to focus the objectives of this thesis.

2.1 Major Pollutant Sources

2.1.1 Diffuse Sources

Pollutants originate from a myriad of sources across coastal catchments including roads, sewer overflows, spills, industrial activities, building sites, and agricultural activities especially land clearing (erosion), and fertiliser and pesticide use.

Urban catchments export sediments, nutrients, hydrocarbons, heavy metals, pathogens, and other toxic and occasionally persistent chemicals to coastal water bodies while rural catchments typically export sediments, nutrients, pesticides and herbicides. These pollutant loadings can result in reduced diversity of species, loss of pollution-sensitive species, and increased levels of persistent toxicants in sediments and marine species (NSW SoE, 2006).

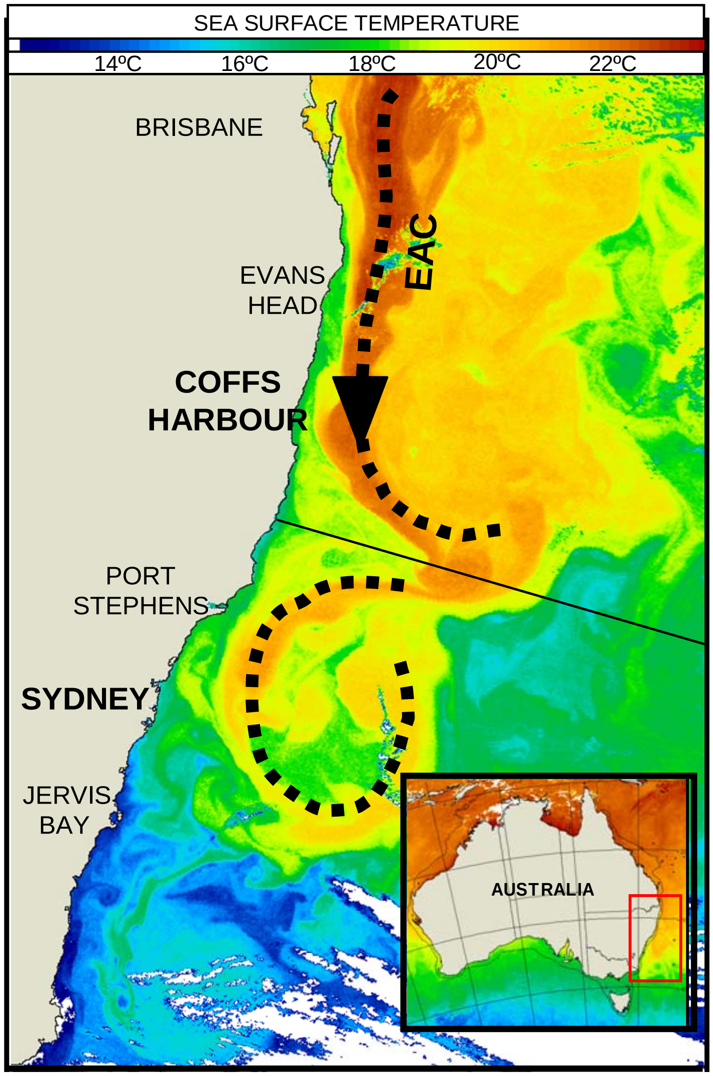


Figure 2.1 Remotely sensed sea surface temperatures (NOAA AVHRR) showing dynamic East Australian Current features in relation to the two key study locations off Coffs Harbour and Sydney (NOAA image courtesy of CSIRO Marine, Hobart).

Pollutant loadings from diffuse sources are driven by rainfall run off which is highly variable, often dominated by large sporadic events. El Niño Southern Oscillation (ENSO) patterns, typically explain as much as 40% of the variance in eastern Australian rainfall (Partridge, 1994). Pollutant loadings from catchments to NSW coastal waters are correspondingly variable.

Few data exist to quantify pollutant loadings from NSW coastal catchments although a number of assessments have been made for nutrients.

Unlike in the Northern Hemisphere, conditions in temperate Australia are characterized by irregular flood and fire regimes that strongly influence catchment hydrology and nutrient inputs (Roy *et al*., 2001). NSW coastal catchments provided highly episodic nutrient loadings to ocean waters mostly via estuaries (**Pritchard** *et al*., 2003). Direct measurements of nutrient exports from coastal catchments are scarce and costly because flows and nutrient concentrations must be measured simultaneously in order to calculate loads, especially during critical high flow events. Nutrient exports are, therefore, often estimated from catchment models which simulate exports according to landuse types.

Comprehensive modelling of NSW coastal catchments has been restricted to broad scale models based on the unit load model Catchment Management Support System (Baginska, **Pritchard** & Krogh, 2003; Baginska & **Pritchard**, 2000 & 1999) and the Long-Term Hydrologic Impact Assessment (L-THIA) model which simulates run-off using the curve number method and derives loads by applying event mean concentrations to the run-off volumes (Lu, Baginska & **Pritchard**, 2004). A dearth of relevant observations emphasises the need to maximize the use of available data and improve estimates of confidence limits (e.g. Baginska, **Pritchard** & Krogh, 2003).

L-THIA modeling by Baginska, Lu, Mawer and **Pritchard** (2004) found increasing nutrient exports associated with rapid development in the NSW coastal zone especially in northern NSW where in some coastal catchments urban areas have doubled in the last two decades. Agriculture/Cropping land uses also have high nutrient emission rates. Overall anthropogenic contributions are shown in Figure 2.2.

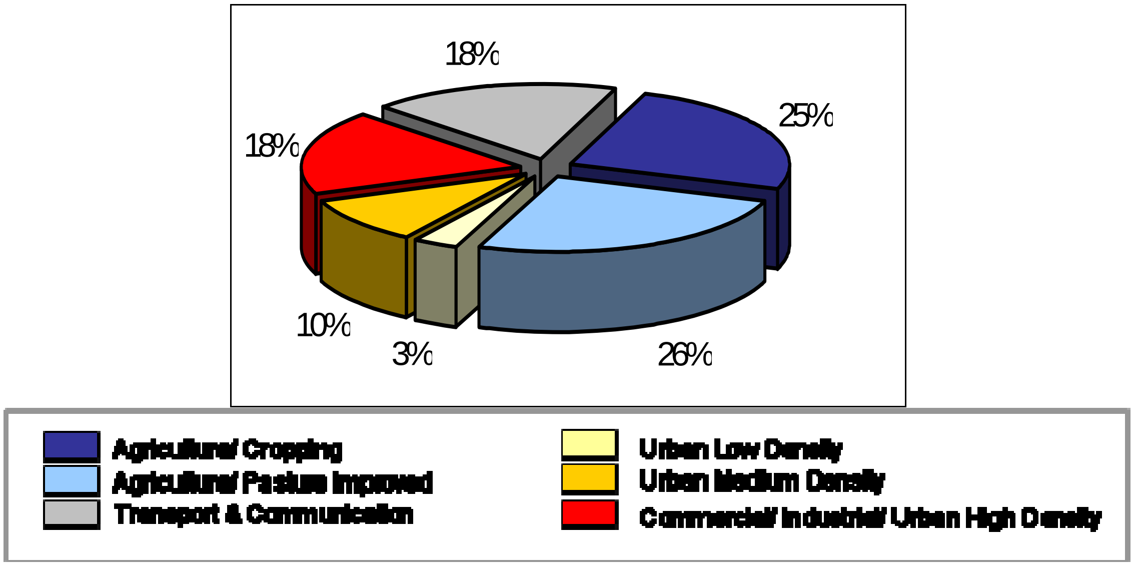


Figure 2.2: Relative proportions of Total Nitrogen exports from diffuse anthropogenic sources in NSW coastal catchments (excluding the Wollongong-Sydney-Newcastle conurbation). Modified from Baginska, Lu, Mawer & **Pritchard** (2004).

The average annual nutrient export potential from NSW coastal catchments is represented in Figure 2.3.

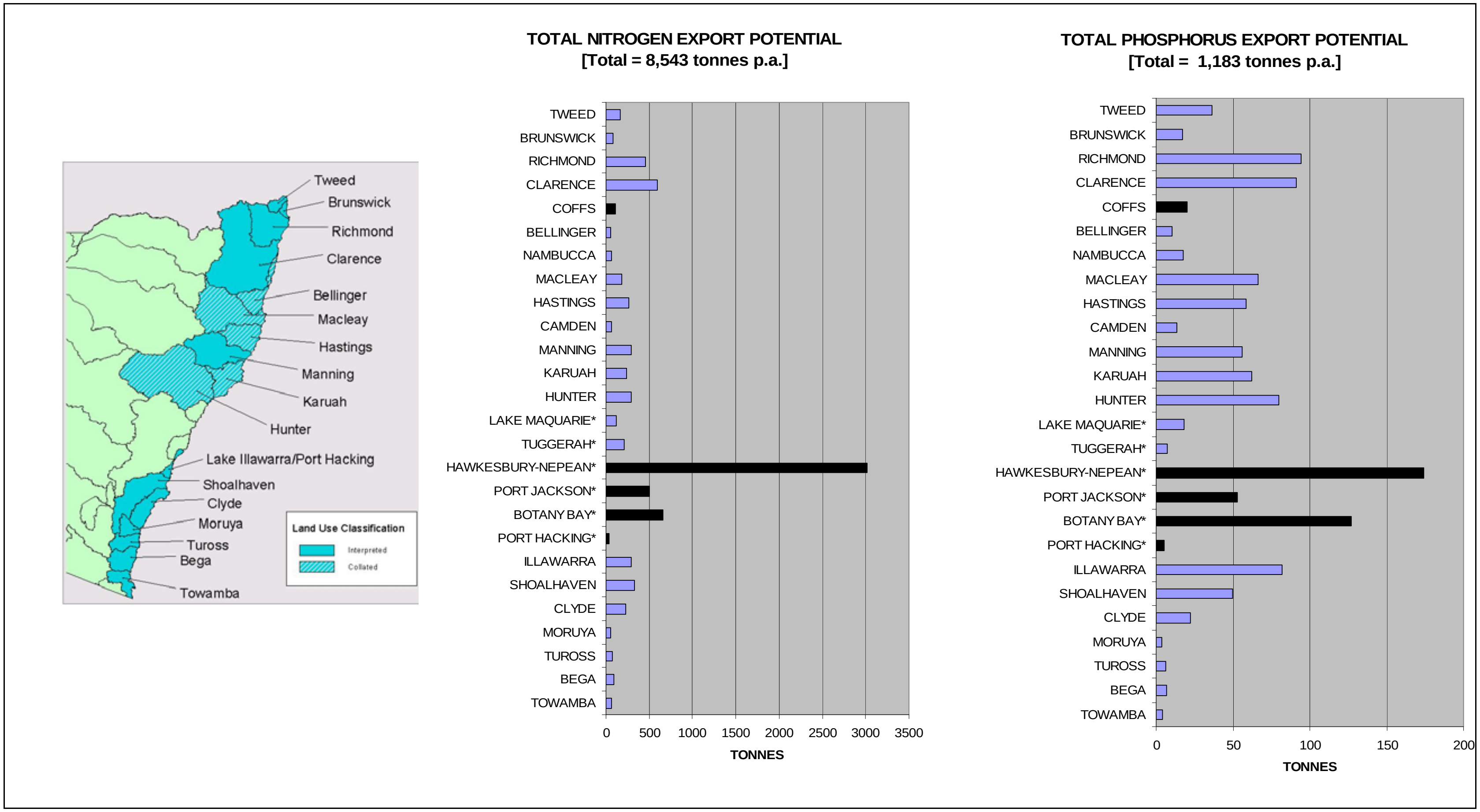


Figure 2.3 Average annual nutrient export potential from NSW coastal catchments based on **Pritchard** *et al.* (2003) for metropolitan catchments (Wollongong-Sydney-Newcastle marked by asterisk) and Baginska, Lu, Mawer & **Pritchard** (2004) for non-metropolitan catchments. Coffs Harbour and Sydney catchments highlighted in black.

In urban areas overflows from the sewerage system during high rainfall conditions can result in a significant contribution of nutrients to estuaries such as the two estuaries closest to the centre of Sydney, Port Jackson and Botany Bay (Sydney Water, 1996).

Catchment modeling, such as that by Baginska, Lu, Mawer and **Pritchard** (2004), merely estimates the nutrient export potential from diffuse sources across coastal catchments without determining the proportion of this potential that may escape the estuary and enter open coastal waters.

Many catchments along the NSW coast have well-developed estuarine systems which act as natural buffers, regulating exchanges between freshwater and ocean systems. For instance, the freshwater section of the Hawkesbury River ends some 80 kilometres upstream from the ocean. There is a steep transition from freshwater to marine conditions over a distance of 30km and this transition appears to be relatively insensitive to flow rate (Wolanski and Collis, 1976). The transport of nutrients from their sources in the catchment to their ultimate sink in the estuary or the ocean can, therefore, be long and convoluted. Sediments in waterways can act as both a source and a sink for nutrients with sorption depending on particle chemistry and size, water temperature, flow (sediment suspension), concentration gradient, redox potential and salinity. Nutrients are also modified within estuaries by biological processes particularly via uptake by vegetation including algae. The net effect of these processes generally results in declining nutrient concentrations with downstream distance from nutrient sources in the catchment. As a result a relatively small proportion of the nutrient load exported from the catchment to the estuary may escape to the ocean except under extreme flood conditions.

Eyre and Pepperill (1999) estimated that the seven major rivers of northern NSW discharge some 12,646 x 10^6 m^3 of freshwater to the shelf annually. These discharges carried some 8,805 tonnes of dissolved nitrogen and 895 tonnes of dissolved phosphorus.

Major discharges from the two large central NSW coastal catchments (Hunter and Hawkesbury /Nepean) were investigated when widespread rainfalls in July/August 1998 broke drought conditions, causing 1 in 2 year floods (Lee & **Pritchard**, 1999). During these events, nutrient concentrations at estuary mouths were 2-5 times greater than those observed during typical dry weather conditions. For over 2 weeks of flooding, saline (ocean water) intrusions were limited to the lower 20km of the Hawkesbury estuary. Observations during this period showed negligible loss of nutrients from the surface fresh (flood) water as it traveled through the estuarine system and aerial photography and SeaWiFs satellite imagery indicated flood plumes extending many kilometres offshore within a coastal boundary layer.

Direct diffuse pollution sources to coastal waters include marine debris and atmospheric deposition.

Few data exist to assess the direct pollutant loading from the atmosphere to NSW coastal waters. In some parts of the world, such as the western Baltic Sea, western Mediterranean and the North Atlantic, atmospheric nitrogen is the most rapidly growing source of new nitrogen in seawater (Pelley, 1998). Activities, which promote these increases, include fossil fuel combustion and ammonia vaporisation from manure and fertilisers. Therefore, expanding urbanisation and agricultural and industrial activities associated with coastal population growth have the potential to make atmospheric deposition an important source of new nitrogen in coastal waters. Data from Ayres *et al*. (1987) suggest atmospheric fluxes of total nitrogen of 4.6 kg/hectare/year based on typical (1981/1982) Sydney rainwater concentrations of 170 μg/L nitrate & 210 μg/L ammonia, average rainfall of 1225mm/yr (assuming negligible organic N in air). Carnovale and Saunders (1987) estimated aerial deposition to Port Phillip Bay (Melbourne) at 2.56 kgN/hectare/yr while a US review (Feth, 1966) indicated a range of 0.6-13 kgN/hectare/yr. These available data may not be representative of NSW coastal waters but indicate potential for significant atmospheric loads.

Marine debris impacts marine wildlife through entanglement, ghost fishing, and ingestion (Gregory, 1999) and is a worldwide problem. A survey in the Greater

Sydney Region indicated the abundance of marine debris within the Greater Sydney Region was comparable to some of the most polluted beaches around the world (Cunningham & Wilson, 2003). The vast majority (89.8%) of debris found was plastic, particularly hard plastic (52.3%) predominantly originating from stormwater or beachgoers. The high proportion of plastics is consistent with overseas studies (e.g. Goldberg, 1995 and Kusui & Noda, 2003).

2.1.2 Point Sources

Loadings to NSW coastal waters from point sources are generally continuous and easily quantified compared to the highly episodic and poorly defined nutrient loadings from diffuse catchment sources described above. Treated sewage effluent accounts for the vast majority of licensed discharges to NSW marine waters, exhibiting limited interannual variability with total annual loadings of >3,000 tonnes total phosphorus, >15,000 tonnes total nitrogen, and >55,000 tonnes total suspended solids.

New South Wales discharges the majority of its treated sewage directly to the ocean with more than thirty ocean outfalls operating between Lennox Head and Eden (Figure 2.4). These discharges are described and quantified in the *NSW Coastal Outfalls Atlas* (Krogh, **Pritchard** & Holden, 2000), which appears on the CD accompanying this chapter and is summarised on the following page. Most NSW outfalls discharge relatively small volumes of secondary or tertiary treated sewage (e.g. Coffs Harbour), but three deepwater outfalls off Sydney discharge large quantities of primary treated sewage. Together Sydney's three deepwater outfalls account for over 80% of the total nitrogen and 90% of the total suspended solids discharged from point sources to NSW coastal waters.

Ocean Outfall Inventory (Appendix 4 DVD)

Martin Krogh, Tim Pritchard & Clive Holden

PURPOSE:

- **summarise and make accessible available information on ocean outfalls in NSW**

METHODS:

Information sources included scientific literature, 'grey' literature (consultant reports), effluent monitoring data, compliance reports, aerial photography and site inspections.

Information included general descriptions of location, sewerage system, known future plans, landscape, receiving environment, biota observed near outfall, outfall configuration, effluent quality and quantity and previous monitoring results.

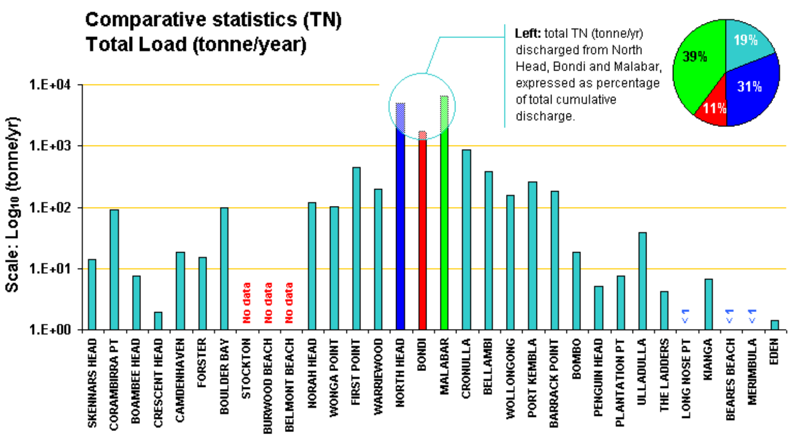
Information presented as:

- outfall-by-outfall summaries
- comparisons of effluent quality and quantity data across all NSW outfalls (see figure)
- summaries of observed environmental impacts (by ecological issue)
- interactive Intranet and CD information systems

RELEVANCE & APPLICATIONS:

The Ocean Outfall Inventory was developed as an information resource and did not attempt to interpret information in a strategic context. It has served as a foundation for:

- ranking ocean outfall performance
- justification of less assessment monitoring where previous studies at other similar outfalls have demonstrated little or no impacts
- review consistency of monitoring requirements across NSW outfalls
- ready access to information to support regulatory advice
- demonstration of an information system with possible broader EPA application

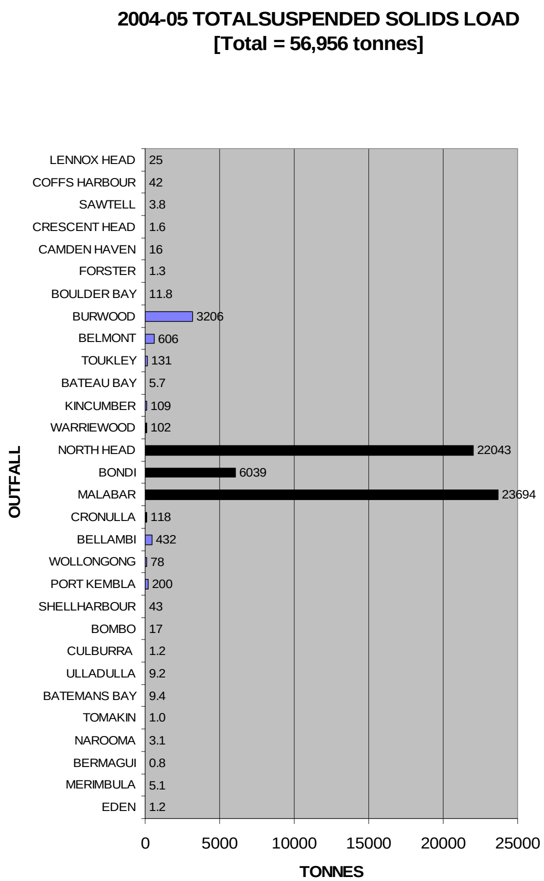


Sydney's deepwater outfalls, which were commissioned during 1990-91, consist of a series of diffuser heads positioned along shore normal outfall systems located 2 to 4 kilometers offshore in water depths of 60m to 80m. Effluent is dispersed by barotropic and baroclinic processes as described by Lee and **Pritchard** (1996) and as observed by **Pritchard** *et al*. (1996b). Nitrogen is present in effluent mostly as ammonia which is readily available to phytoplankton (Parsons *et al*., 1997). Likewise, phosphorus is mostly present in biologically available dissolved forms (70%) (**Pritchard** *et al*., 2003).

NSW ocean outfalls ranged from single pipes located in beach foredunes to multi-port rose head diffusers located 3-4 kilometres offshore (see Figure 2.5). Clearly many early outfall designs failed to optimise outfall performance and demonstrate little or no consideration of sensitive receiving environments and the need to maximise dilution and dispersion. The USEPA model CORMIX was applied to predict the near field plume behaviour of NSW ocean outfalls under a standard set of ambient conditions (Ingleton & Large, 2004) with the following findings:

- Offshore multiport diffuser outfalls were found to be highly efficient (e.g. Bondi, North Head, Malabar, Burwood and to a lesser extent, Boulder Bay and Belmont).
- Some single port shoreline outfalls were moderately efficient (e.g. Tomakin & Norah)
- Other single port shoreline outfalls were very inefficient (e.g. Bellambi, Cronulla, Sawtell, Wonga, Warriewood, First Pt)

It is noteworthy that deepwater outfalls in Sydney performed well while all existing outfalls in the Coffs Harbour region performed poorly. Ingleton & Large (2004) identified considerable scope to improve the efficiency (initial dilution) of many existing shoreline outfalls and reduce the severity of environmental exposure without necessarily resorting to deepwater outfalls. Common problems with these existing outfalls included low discharge velocities and limited three-dimensional mixing due to boundary contact.



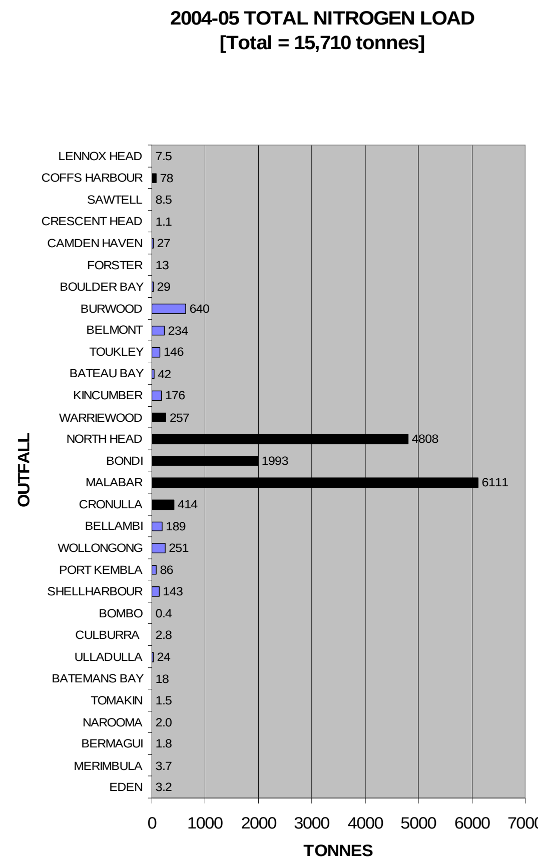


Figure 2.4 Sewage Treatment Plant discharges to New South Wales ocean waters during 2004-05 (DEC data). Coffs Harbour and Sydney outfalls loads highlighted in black. See attached *Ocean Outfall Inventory* (attached CD) for location map.

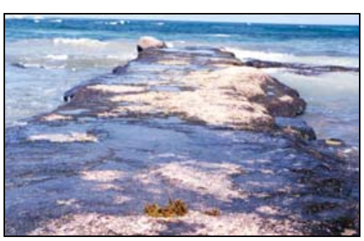
Effluent-on-show	Obvious	Concealed
 Stockton Beach Outfall	 Forster Outfall	 Shellharbour/Barrack Pt Outfall
 Merimbula Outfall	 Batemans Bay/Ladders Outfall	 Culburra/Penguin Head Outfall
 Coffs H./Corambirra Pt Outfall	 Tomakin/Long Nose Pt Outfall	 Lennox/Skennars Head Outfall
 Ulladulla Outfall	 Bateau Bay/Wonga Outfall	 Wollongong/Conniston Outfall
 Bellambi Beach Outfall	 Warriewood Outfall	 Camden Haven Outfall

Figure 2.5 Examples of NSW outfall settings (photos by **Pritchard** and Krogh)

2.1.3 Other Sources

Spills and shipping accidents are direct discharges that can be regarded as a diffuse source or as a series of transient point source discharges. The majority of reported pollution incidents have been minor oil spills in Sydney Harbour and Botany Bay, most from land-based sources (NSW SoE 2006) with few detectable impacts in offshore coastal waters. However, shipping accidents such as the grounding of HMS Nottingham on Lord Howe Island in July 2002 (fuel tanks not damaged in this case) are potentially significant pollutant sources.

The terms 'biological pollution' and 'biological pollutants' have emerged recently with impacts of introduction and invasion of species throughout the world (Boudouresque & Verlaque, 2002). Plants such as the green alga *Caulerpa taxifolia* are well known as invasive species in the Mediterranean (Islam & Tanaka, 2004) and now in New South Wales (NSW Fisheries, 2004). Mainly anecdotal reports indicate that invasive *Caulerpa filiformis* is displacing native species across large tracts of exposed, shallow, subtidal platforms in NSW coastal waters. Introduced toxic dinoflagellates have also been observed in NSW coastal waters both as blooms and in sediments of harbours and estuaries (Ajani, Hallegraeff & **Pritchard**, 2001a). The role of hydrodynamic processes in the spread of these species remains poorly defined or unknown.

2.2 Receiving Environment

The shape and physical characteristics of the coastal margin (*Geomorphic Setting*) both influence and reflect hydrodynamic processes (*Hydrodynamic Setting*). Pollutants (described above) are transported and dispersed by these processes thus affecting the chemical status of coastal waters (*Chemical Setting*). Biota (*Biological Setting*) respond to, and interact with, this dynamic system, which is increasingly impacted at all scales by human activity (*Observed Impacts*).

2.2.1 Geomorphic Setting

NSW's continental shelf is very narrow, varying in width from about 30 km to 50 km (see Figure 1.1). Shelves worldwide display a variety of configurations but can extend up to 1,500km in width (e.g. Siberian shelf in the Arctic Ocean). The NSW continental shelf is narrow compared to most other Australian regions where the shelf width typically varies from about 50 to more than 300km. Worldwide, narrow continental shelves are found mostly at active margins such as off Peru, California and Hawaii. NSW's narrow and steep continental margin is a result of its tectonic history of asymmetric passive margin rifting (Boyd *et al*., 2004). The NSW shelf narrows near Smokey Cape and changes orientation just north of Port Stephens.

Most of the sediments overlying the shelf were deposited during the Holocene transgression some 7000 years ago. Three sedimentary zones have often been identified (eg Roy and Thom 1981): an inner zone to water depths of 60 m, characterised by coarse, clean (<2% mud) and relatively well sorted sands; a mid-shelf zone from 60 to 120 m water depth, characterised by coarse sands with a high mud content (5 to 30% mud); and an outer zone of relic carbonate sediments (<5% mud) at depths greater than 120 m. The surface sediments nearer shore appear to be highly mobile with potential for resuspension (reworking) of the top metre of sediment at water depths of 40 m and of the top 0.5 m of sediment at water depths corresponding to the deepwater outfalls (Schneider *et al*. 1994). Resuspension events (associated with high wave activity and/or strong currents) are expected to occur irregularly and vary in intensity, but may occur within time spans as short as seasons (Schneider *et al*. 1994).

The regional coastline is aligned obliquely to the south-east, inner-shelf, modal wave direction, and hence sediment is transported obliquely on the shoreface with a net northward movement (Goodwin *et al*., 2006). Large sandy beaches are prominent in the north of the State while smaller pocket beaches bounded by rocky headlands tend to dominate in the south.

2.2.2 Hydrodynamic Setting

NSW coastal waters are dynamic with complex current and density stratification, driven by processes, which operate over a wide range of spatial and temporal scales.

Pronounced density stratification is a dominant feature of the water column, principally driven by temperature differences which are especially prominent in spring, summer and early autumn each year (Rendell & **Pritchard**, 1996). A 30 year record of water temperature at a site off Port Hacking (southern Sydney) in 55m of water indicates maximum mean monthly top to bottom temperature difference of about 5ºC with maximum sea surface temperatures occurring in late summer (February - March).

Critical oceanographic processes in the study region include the mainly southward flowing East Australian Current (EAC) and associated eddies (Cresswell and Legeckis, 1986; Roughan & Middelton, 2004), northward propagating coastal trapped waves (Church et al., 1986; Griffin and Middleton, 1991), local wind driven currents and relatively high frequency internal tides and waves (Griffin and Middleton, 1992), local winds (Griffin and Middleton, 1991) and swell waves. Tides are semidiurnal with a microtidal range (mean spring tidal range is approximately 1.2 m) (Harris *et al*. 1991).

These processes operate over a wide range of spatial and temporal scales. For instance, instability along the front between the warm EAC and the cooler Tasman Sea water often leads to the formation of both large (about 150 km diameter) warm core (anticlockwise) eddies and smaller (20 to 50 km) cold core (clockwise) eddies. These eddies may persist off central and southern NSW for periods of days to many weeks during which time they profoundly affect the currents and temperature structure of the water column. Low frequency, inter-annual to multi-decadal variability in EAC transports can be significant as depicted in Figure 2.6.

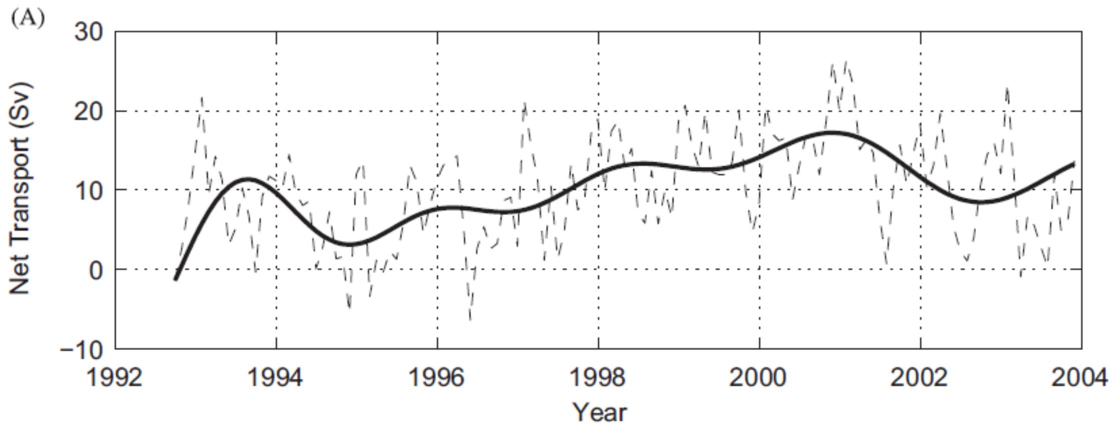


Figure 2.6 Estimated net monthly southward EAC transports (Sverdrup) calculated from model-hindcast results along a zonal transect extending eastwards from Sydney (modified from Holbrook et al. (2011) based on Ridgway et al. (2008)).

Griffin and Middleton (1991) have indicated that approximately 60% to 70% of the 'weather band' (40 hour to 20 day period) current variance is wind driven, with the major contributors being the southern New South Wales and Bass Strait winds, both lagged by intervals corresponding to the propagation speed of the first Coastal Trapped Wave (CTW) mode. Local winds operate over distances of 10 to 100 km and periods of hours to a few days: south-easterly winds favour downwelling while upwelling can be associated with north-easterly winds. Although barotropic tidal currents are weak (except near the entrances of estuaries), internal wave disturbances of various frequencies are able to propagate along the thermocline when the water column is stratified (Griffin and Middleton, 1992). Internal waves of tidal frequency can result in thermocline displacements as large as 20 m (Lee and **Pritchard**, 1996). Higher frequency internal waves with periods in the range of 10 to 30 minutes, wavelengths of the order of 1 km and amplitudes of about 10m have also been observed off Sydney.

These processes are important in determining the dispersion and fate of pollutants as illustrated by Lee & **Pritchard** (1996). Radioisotope tracer studies conducted during the early 1990's (e.g. Table 2.1) investigated the behavior of effluent plumes released from Sydney's deepwater outfalls under a range of oceanographic conditions and provided validation data for near field models used in Chapter 6 (**Pritchard** *et al.*, 1993 & 1996b).

Table 2.1 Observed Plume Behaviour: Malabar Deepwater Outfall

	09/04/91	17/05/91	18/12/91	30/01/92	17-18/06/92
	CONDITIONS AND TRACERS				
Temperature: upper-lower (ºC)	19.5 – 21.0	18.55-18.6	15-20	15-22	19-20
ORS Current (m/s, Direction)	0.15-0.1 N-S (current reversal)	0.1-0.25 S (baratropic)	0.3-0.4S/0.5S-N (baroclinic)	0.2-0.4-0.2 N-N-S / 0.1-0.2-0.1 N-N-S (baroclinic reversal)	0.15-0.45 S / 0.1-0.3 S (baratropic)
STP Flow ML/day)	315-540	385	520	420	330
Tracers	Technetium, Salinity	Technetium, Salinity	Gold-198, Tritium, Salinity	Gold-198, Tritium, Salinity	Gold-198, Tritium, Salinity, Transmissivity
Duration (hrs)	9	9	9.5	18	30
	RESULTS				
Initial Dilution (1:X)	200-400	700-1300	200-300	400-600	1000-1200
Depth of upper limit of labeled field (m)	0-50	0 (surface)	35-40	45-50	35-40
Labeled field thickness (m)	10-40	30-40	20-30	20-30	40
Field Width 1 km downstream (m)	Reversal	2100	1650	900	900

Compiled from **Pritchard** et al. (1993)

Nutrient enrichment phenomena are critical to marine systems whether they be due to pollutants (as described above) or natural processes such as slope water intrusions and upwelling. Generally, western oceanic boundaries such as off the east coast of Australia experience mean wind fields that are not conducive to the persistent upwellings, unlike those seen in the productive waters off Peru, Oregon and NW Africa. However, episodic coastal upwellings occur in NSW coastal waters when favourable weather patterns persist for more than a couple of days and when EAC-shelf interactions promote shoreward slope water intrusions (**Pritchard** *et al*., 2003). Analysis of data from an extensive array of thermistors deployed for 12 months (8/97 to 8/98) in water depths of 50 – 100m from Port Stephens to Jervis Bay indicated that slope water intrusions operated over (alongshore) length scales of hundreds of kilometres, and occurred over time scales of a few days to a few weeks with surprisingly small phase lags across the study region (**Pritchard** *et al*., 1999). Investigative modelling using the Princeton Ocean Model (POM) at a regional scale and in the vicinities of Port Stephens (Oke & Middleton, 2001) and Jervis Bay (Gibbs *et al*., 1997, & 1998), revealed the importance of shelf configuration in the processes that drive slope water intrusions. Narrowing of the shelf near Laurieton accelerated East Australian Current flows (which are constrained to the shelf by vorticity considerations) and thus increased bottom stress (See Figures 1.1 and 2.7 A). This stress tended to drive water in the bottom boundary layer (including 'slope water') towards the coast in much the same way as wind stress drives surface waters to the left of wind direction in the southern hemisphere. Slope water was thus 'uplifted' onto the mid and outer shelf and carried alongshore with the southward flow. Regional climatology data (Ridgeway et al., 2002; Dunn & Ridgeway, 2002) exhibit consistent temperature and nitrate patterns, with cool, nitrate rich water (indicative of slope water) located downstream of Smoky Cape.

However, these modelling exercises indicated that steady EAC activity alone was ineffective in driving slope water onto the inner shelf and up into the euphotic zone because the bottom boundary layer rapidly 'shut down'. When shoreward advection of dense slope water created a horizontal density gradient, vertical shear in the along shelf velocities reduced bottom stress and 'shut down' the boundary layer (according to the thermal wind relation).

The combination of EAC activity on the shelf break (enhancing stratification and bottom stress) and upwelling favourable winds was found to promote significant upwelling in both the Port Stephens and Jervis Bay modelling investigations. Other factors promoting upwelling/uplifting included divergence of EAC flows from the coast (at about 31°S) and baroclinic instabilities, especially cold core eddies which tend to be associated with along-shelf topographic variability such as that seen near Port Stephens and Jervis Bay (see Figure 1.1). Cold core eddies, spun-up inshore of the EAC front, promote localised upwelling ('Ekman Pumping') because bottom stress associated with the clockwise rotation promotes convergence of bottom waters (towards the centre of the eddy) and, consequent upward transport together with divergence at the surface. Slope water intrusions have been observed inshore of an EAC front off Sydney in association with a southward moving cold core eddy (Cresswell, 1974).

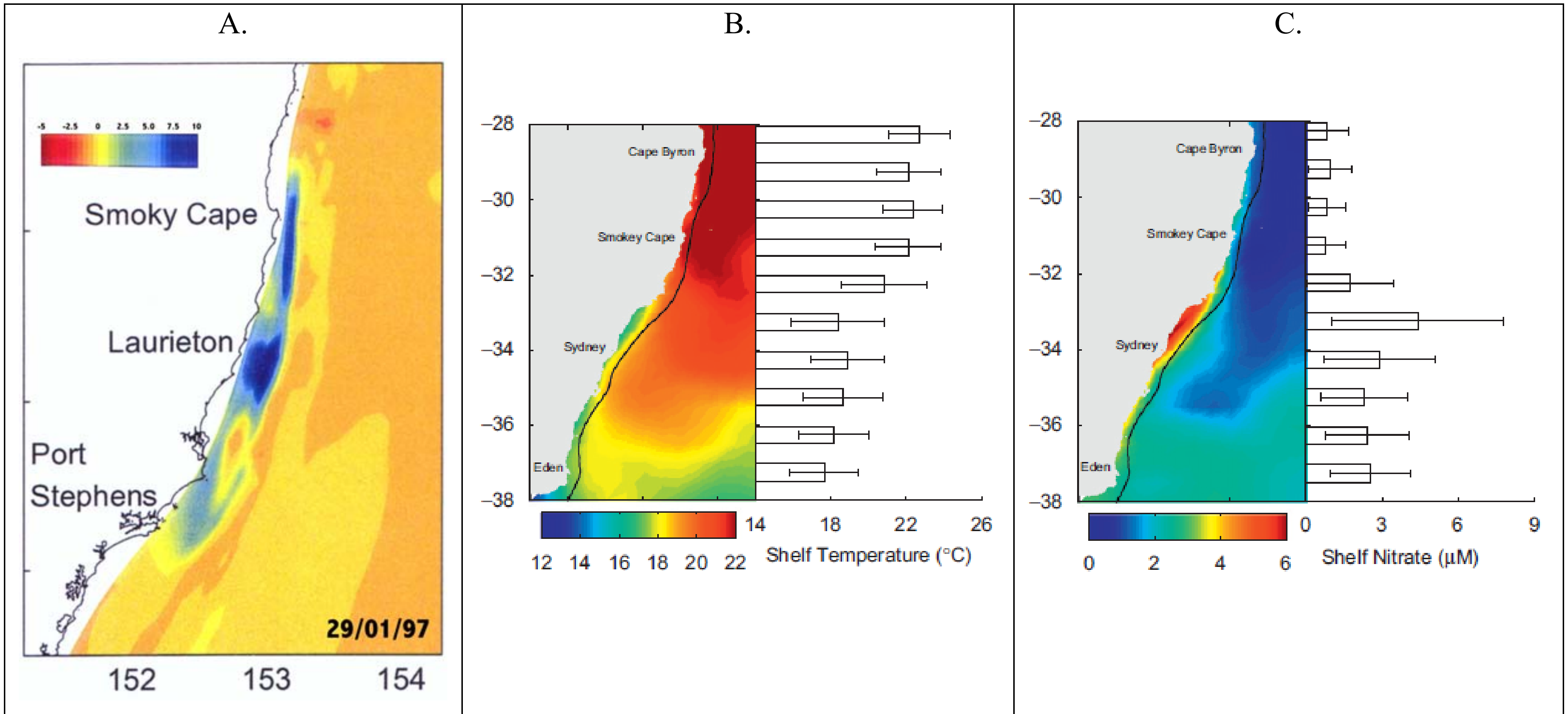


Figure 2.7:

A. Model results showing areas of high bottom stress off Laurieton. Grey scale ranges from -2.5 to 10.0 (m^2s^{-2}) x 10^4 (modified from Oke & Middleton (2001).
B. CARS climatological temperature (modified form Suthers et al., 2011)
C. CARS climatological nitrate concentration (modified form Suthers et al., 2011)

Plots B and C were derived from a quality-controlled depth and seasonal- averaged observations (0–100 m) archived in the CSIRO Atlas of Regional Seas (CARS) as described by Ridgeway et al.(2002) and Dunn & Ridgeway (2002).

Similar topographically induced instabilities and localised nutrient enrichments have been observed elsewhere including on the inshore edge of the Gulf Stream (Anderson, 1992), the Agulhas Current system in the South Indian Ocean (Gill & Schumann, 1979) and off Cape Sable, Nova Scotia (Tee and Smith, 1993). In the example off Cape Sable, upwelled waters were advected alongshore causing nutrient enrichment of coastal water well downstream of the upwelling location.

These driving mechanisms are generally consistent with available thermistor and current data sets (**Pritchard** *et al*., 1999) and NOAA satellite imagery of sea surface temperatures (see Rochford, 1975 & 1984; Cresswell,1994; Tranter *et al*., 1986; Griffin & Middleton, 1992; **Pritchard** *et al*., 2003).

Recent pelagic ecosystem modeling (nitrogen-phytoplankton-zooplankton coupled to an EAC configuration of the Princeton Ocean Model) has described the formation of a deep chlorophyll maximum during downwelling favourable winds and coastally confined phytoplankton blooms during upwelling favourable winds in NSW coastal waters (Baird *et al*., 2006). These simulations revealed the importance of the transport and entrainment of upwelled filaments in determining the plankton distributions in NSW coastal waters.

South eastern Australian waters are a global hot-spot for ocean temperature change. The strength and influence of the EAC has increased along eastern Australia due to ocean warming (Ridgway, 2007) with observed multi-decadal warming at rates between three and four times the global average. Holbrook and Bindoff (1997) observed average warming to 100m depth of 1.5°C century^{-1} off Tasmania from 1955 to 1988, while Ridgway (2007) reported SST warming at 1.5°C century^{-1} based on data from 1944 to 2002. The EAC is predicted to both strengthen and warm significantly under global warming scenarios (Cai et al., 2005). A range of diverse effects are expected from changing weather patterns to shifts in marine species distribution (Hobday et al., 2011).

Closer to shore and at smaller scales, wind and waves are increasingly important drivers of coastal circulation and sediment transport.

Local winds are major drivers of inner shelf currents, they promote vertical mixing of the water column, and contribute to mixing within bays and estuaries (Wolanski, 2007) which increases potential for exchange of particles across bay entrances.

Long term wind data from the Australian Bureau of Meteorology, summarised in Figure 2.8, indicate significant spatial variability across NSW coastal waters thus signaling the imperative for local assessments of wind conditions. However, some patterns are discernable: afternoon mostly summer northeasterly sea breezes at most sites except Williamstown and Nowra (where easterly or southeasterly winds dominate); morning westerlies (ranging from SW-NW) especially during winter; and, southerly and south-easterly wind events.

Maximum internal bay dimensions along the preferred axes for winds indicate fetch for local wind waves (ie wave induced mixing potential) and local wind driven current pathways (advection potential) within bays. Observed preferred directional axes for winds (from Figure 2.8) are summaries below in Table 2.2.

Table 2 .2 Ranking of axes of preferred wind directions by location

	NE-SW	N-S	NW-SE	E-W
Coffs Harbour	1	2	3	4
Pt Macquarie	1	4	3	2
Williamstown	4	3	1	2
Sydney	4	1	2	3
Nowra	4	3	2	1
Bega	1	4	2	3

No consistent statewide pattern of preferred wind axes are apparent in Table 2.2 although the frequency of winds oriented along the NE-SW axis exhibit an apparent latitudinal distribution being dominant at sites in northern and far south NSW but subordinate at sites in central NSW.

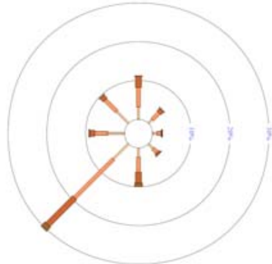
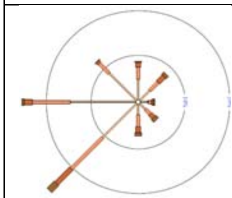
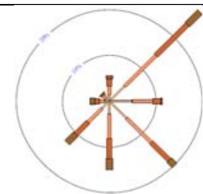
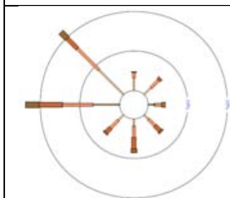
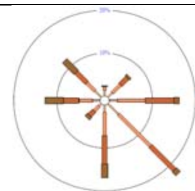
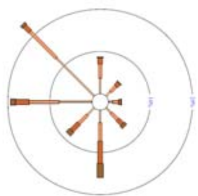
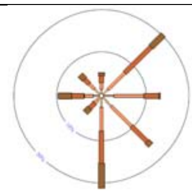
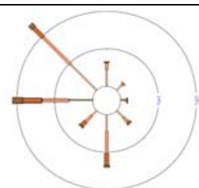
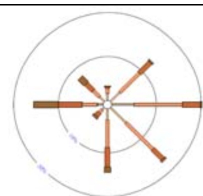
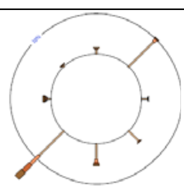
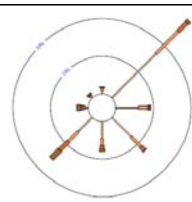
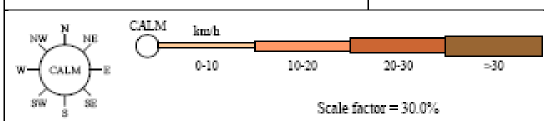
9 am	3 pm	
		COFFS HARBOUR 30.31°S
		PORT MACQUARIE 31.44°S
		WILLIAMSTOWN 32.79°S
		SYDNEY 33.94°S
		NOWRA 34.94°S
		BEGA 36.69°S
		National Climate Centre of the Bureau of Meteorology (2004) webclim@bom.gov.au

Figure 2.8: Average wind roses based on long term observation at 9am & 3pm.

Breaking waves have the potential to increase vertical mixing, re-suspend particles and drive circulation in bays (e.g. Bate Bay, NSW as reported by Large et al., 1994). Furthermore ocean waves are the single most important process affecting the coast (Short and Woodroffe, 2009) thus shaping and orientating geomorphic features that interact with regional flows.

NSW wave data collected at seven locations over periods of up to 28yrs indicate average significant wave heights of ~1.6m, spectral peak periods of ~9.6s and maximum wave heights of ~7.1m as shown in Figure 2.9. Directional data are available from three of these locations for lesser durations, exhibiting predominantly south-south-easterly wave directions.

Central NSW appears to have a higher frequency of storms (wave height > 2.5m) due to mid latitude and east coast cyclones, based on historical records from 1920 to 1980 (Short 1993). This is consistent with maximum wave height data depicted in Figure 2.9. However, in general for significant wave heights <4m there is a similar exceedance distribution for all sites except Batemans Bay (Kulmar et al., 2005) which is reflected by the lower average HSIG in Figure 2.9. Although Kulmar et al. (2005) suggest that it is generally possible to extrapolate between waverider sites there is no evidence to indicate the spatial extent of the exceptional Batemans Bay waverider observations.

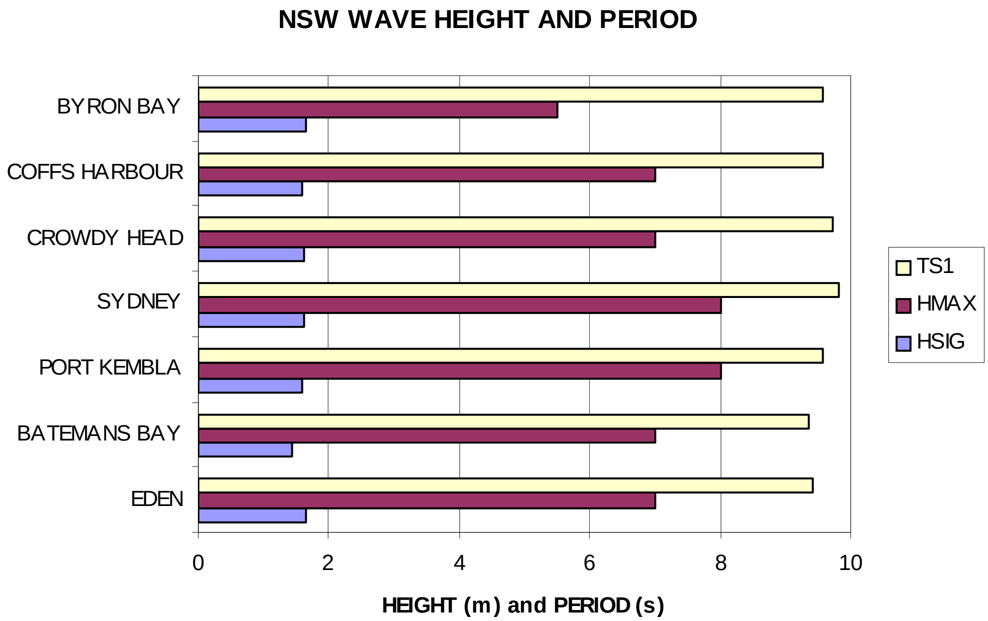
Refraction and diminished energies of dominant south easterly waves can create low wave energy depositional environments on the northern sides of headlands.

Wave induced rip currents return water previously brought shoreward by broken waves and may result in narrow offshore jets of up to 2 m/s, usually dissipating within a distance of one to three times the width of the surf zone (Short and Woodroffe, 2009). Wave induced alongshore feeder currents can be diverted offshore by topographic features such as headlands, reefs and training walls resulting in stronger rips which penetrate further offshore. Under high wave conditions (>3m) megarips can dominate the circulation of embayments when erosional rips increase in spacing and merge with topographic rips. These megarips can reach velocities of 3 m/s and extend 1-2 km offshore as shown in Chapter 8. Rips are a feature of almost all wave dominated embayments although their spacing and intensity depends on wave conditions. Short and Woodroffe (2009) identified 2952 rips across 755 open coast beaches in NSW, with a mean spacing of 246m, of which 677 were topographically controlled.

2.2.3 Chemical Setting

The chemical characteristics of NSW coastal waters are profoundly affected by the physical processes outline above. At any particular time a variety of water masses with different origins and physical and chemical characteristics (eg salinity, temperature, nutrient and trace contaminant levels) may be present. Their position and extent (both horizontal and vertical), the duration they are present, and the extent of mixing are all dependant on a combination of processes described above.

Ridgeway et al.(2002) and Dunn & Ridgeway(2002) describe the nutrient distributions as shown in Figure 2.7 while Rendell and **Pritchard** (1996) and **Pritchard** *et al*. (1999, 2003) described the nutrient characteristics of coastal waters based on previous studies in the shelf waters off Sydney extending back to the 1940s (e.g. Newell 1966, Hahn *et al.* 1977, Rochford 1984, Tranter *et al*. 1986, Cresswell 1994). The emphasis in much of this work was on nitrate and to a lesser extent phosphate. While concentrations vary considerably, the pattern that has emerged is of low levels of nutrients in surface waters, nutrient levels increasing with depth and seasonal cycles in nutrient levels for both surface and deeper waters. The smallest differences between surface and deeper waters tend to occur in late autumn and winter when thermal stratification is absent or at its weakest. During this period, nutrient concentrations in surface waters tend to be at their highest and nutrient concentrations at depth tend to be at their lowest. Nitrate concentrations in surface waters off Sydney are typically less than 1 µg atom/L (14 µg nitrate-N/L) for most of the year. Reactive phosphate concentrations in surface waters are typically less than 0.25 µg atom/L (7.7 µg phosphate-P/L). At depth, concentrations of nitrate greater than 10 µg atom/L occur episodically in association with the intrusion of slope water onto the shelf.



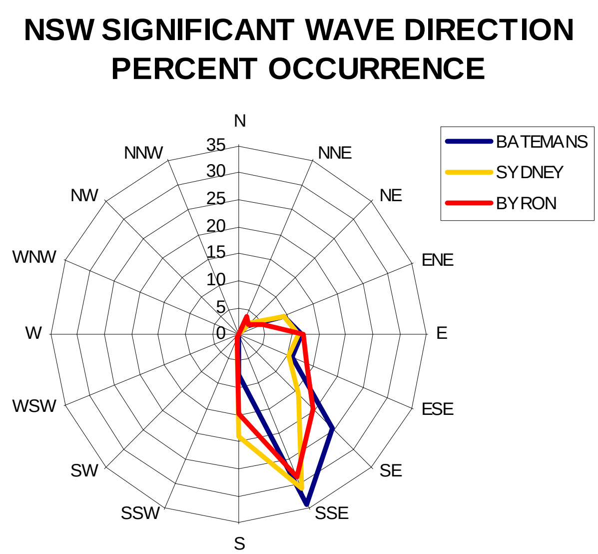


Figure 2.9: NSW waverider buoy data summaries to December 2004 (data derived from Kulmar et al. (2005). Top showing spectral peak period (TS1), maximum wave height (HMAX) and significant wave height (HSIG). Lower showing directional distributions of waves at three locations.

Surface water concentrations of trace metals in New South Wales coastal waters are among the lowest reported in the Southern Hemisphere and are consistent with oceanographic data for the surface waters of the Pacific Ocean (Apte *et al*., 1998).

Contaminant levels observed in marine sediments off NSW represent only minor environmental impact although some estuaries contain highly contaminated sediments (Birch, 2000). This is indicative of how efficiently contaminants are dispersed from the high energy continental margins. However, surficial sediment concentrations of trace metals (Cd, Co, Cu, Fe, Mn, Ni, Pb, Zn) in the fine fraction (<62.5 mu m) of sediments adjacent to the major urban centres of Sydney, Newcastle and Wollongong on the central New South Wales (NSW) continental margin, Australia, are elevated above regional background (Matthai and Birch, 2000). Disposal of dredged harbour spoil off Newcastle and disposal of large volumes of sewage effluent off Sydney were implicated. Contaminated sediments in estuaries such as Sydney Harbour have also been implicated as a source of offshore sediment contamination (Schneider *et al*., 1994).

2.2.4 Biological Setting

New South Wales has rich and diverse biological assemblages, structured to a large extent by the morphological setting, physico-chemical conditions and hydrodynamic processes. Biological processes in turn alter their physico-chemical environment especially through biogeochemical cycles.

Biological settings include rocky shores, sand beach, subtidal rocky reef, coral communities and the water column. Habitat maps have recently become available for NSW coastal waters (Jordan et al., 2010).

Rocky shores have high biodiversity with mostly temperate species and some tropical species mostly in the north of the region. Communities are very patchy in time and space because of variables in the dynamic physical environment, irregular recruitment and complex ecological interactions such as competition and predation (Underwood and Chapman, 1995). Typically, there is an overlapping zonation on rocky shores of foliose and encrusting algae, barnacles, molluscs, polychaetes and other organisms (Zann, 2000).

The distribution of sandy beach fauna is also affected by physical processes with distinct zonation and species diversity and abundances increasing as wave exposure decreases. Sandy shores have a rich meiofauna (nematodes, copepods, mites, gastrotrichs, oligochaetes, polychaetes, nemerteans, tardigrades, rotifers, protozoans and turbellarians) and macrofauna (crabs, hermit crabs, mysid shrimps, isopods, amphipods, insects, polychaete worms, gastropods, bivalves) (Jones and Short, 1995).

Subtidal rocky reef biota are structured by depth presumably influenced by availability of light and levels of turbulence and scouring. Shallow temperate rocky reefs are typically dominated by canopy-forming large brown algae (e.g. Ecklonia, Sargassum, Phyllospora) and a high diversity of sessile colonial animals (e.g. sponges, hydroids, soft corals, bryozoans and ascidians. In deeper waters, reefs are dominated by sponges which at least off Sydney, increase in species diversity with depth (>15 m) (Roberts and Davis, 1996).

There is a strong association between the distribution of coral communities and the persistence of the East Australian Current on the continental shelf (as described above). Rich coral dominated communities are found in northern NSW coastal waters on shallow, sheltered subtidal rocky reefs away from freshwater influences to South-West Rocks (31°S) (Harriett & Banks, 2002). Ninety species of corals have been recorded in the Solitary Islands just north of Coffs Harbour (~30°S) – see Figure 2.10. Hermatypic or reef-building corals are generally the dominant benthic species, but they form a veneer over the existing rocky substratum rather than limestone based reefs (Harriot *et al*., 1994). Coral species diversity is often high with unique associations of tropical species near their southern latitudinal range and subtropical species that are absent or rare in the Great Barrier Reef area. However, turn-over of species is rapid.

Figure 2.10 Coral systems in the Solitary Islands Marine Park near Coffs Harbour

Planktonic communities in NSW coastal waters range from tropical oceanic in the north to temperate oceanic in the south (Zann, 2000). Phytoplankton productivity is limited by nutrient runoff and low levels of nutrient-rich upwellings. Phytoplankton patterns have been observed and investigated through a series of studies at long term monitoring stations in 50m and/or 100m of water off Port Hacking, southern Sydney (e.g. Humphrey, 1960 & 1963; Grant & Kerr, 1970; Jeffrey and Carpenter, 1974; Hallegraeff, 1981; Hallegraeff and Reid, 1986; Ajani, Lee, **Pritchard** and Krogh, 2001b). Early studies distinguished three major phytoplankton categories: a large group of species which were present throughout the year; a group of diatom species, which bloomed following episodic nutrient enrichments; and, a group of warm water species associated with tropical water masses. Recent studies (Ajani, Lee, **Pritchard** and Krogh, 2001b) observed blooms with similar frequency and magnitude to those seen in previous studies but found that the small diatom *Thalassiosira partheneia* generally dominated blooms unlike previous studies which found a variety of taxa (Lee, Ajani, Krogh and **Pritchard,** 2001). Furthermore, the heterotrophic dinoflagellate, *Noctiluca scintillans*, was found at dramatically higher frequency than previously documented. This is consistent with a dramatic increase in the number of visible blooms of *Noctiluca scintillans* as reported by Ajani, Hallegraeff and **Pritchard**, (2001a) and shown in Figure 2.11. Annual variations in abundance of *Noctiluca* were related to episodic uplifting events, which stimulate blooms of the phytoplankton prey of *Noctiluca* during the austral spring and summer (Dela-Cruz, Ajani, Lee, **Pritchard** and Suthers, 2002).

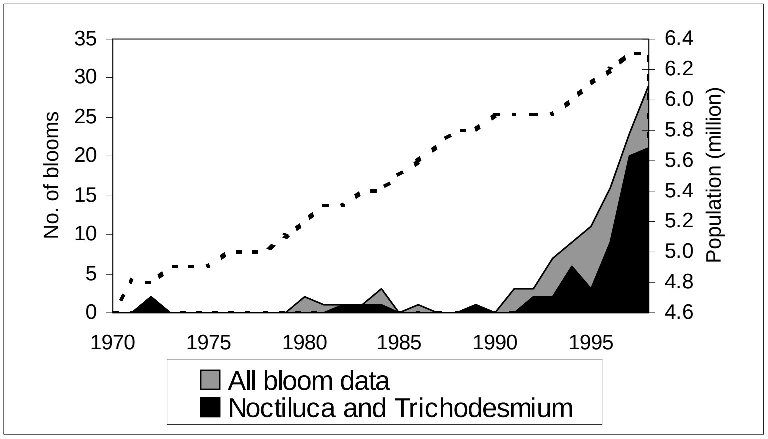


Figure 2.11 Recorded algal blooms in NSW marine and estuarine waters (1970 - 2000) with human population data shown by the dashed line (from Ajani, Hallegraeff and **Pritchard**, 2001a)

Fish stocks are quite small due to low primary productivity and consequently NSW lacks the large demersal fisheries that characterise many northern hemisphere continental shelf systems. Despite this, coastal fish communities are highly diverse ranging from tropical species (e.g. wrasses and damsel fish on northern reefs), to mainly temperate species in the south (e.g. weed whitings, rock cales and Morwongs).

Detailed descriptions of the geomorphic, hydrodynamic, chemical and biological characteristics of the environments that receive treated sewage from NSW outfalls are provided in the interactive NSW Coastal Outfalls Atlas (Krogh, **Pritchard** & Holden, 2000) which appears on the CD that accompanies this chapter

2.3 Observed Pollutant Impacts

Impacts are defined here as the biological consequences of human induced environmental disturbances. It is a major challenge to rigorously discriminate human impacts from natural variability (Green, 1979). Observed pollutant impacts summarised here and provided in more detail on the attached CD (Krogh, **Pritchard** & Holden, 2000) are based on assessments which range from purely descriptive studies to sophisticated experimental designs (Underwood 1994; Clarke & Warwick 1994; Schmitt & Osenberg 1996). Impacts have been summarised by outfall and according to the major biological communities affected (algae, intertidal fauna, subtidal hard substrate fauna, subtidal soft substrate fauna, subtidal algal associated fauna, fish, shellfish, bacteria and viruses) on the accompanying CD while examples from Coffs Harbour and Sydney are provided here as examples of small shoreline outfalls discharging secondary treated effluent and large deepwater outfalls discharging effluent after just primary treatment (respectively).

'Natural' variability has become a moot point given that human induced environmental disturbances now occur at regional and global scales which affect long-term variability. Therefore, the interpretation and extrapolation of time limited impact assessments is also considered below.

2.3.1 Coffs Harbour

Sewage effluent was discharged from the shoreline outfall on Corambirra Point at Coffs Harbour for over 40 years before a new outfall was commissioned in early 2005. The old outfall discharged effluent at ~10 ML/day when it was de-commissioned although discharges from the new outfall will increase to over 20 ML/day by 2021, due to expansion of the sewerage system and closures of two other outfalls (at Willis Creek and Sawtell). The new outfall lies 1.5km off Boambee Beach in ~20 metres of water, immediately south of the Solitary Islands Marine Park (Figure 2.12).

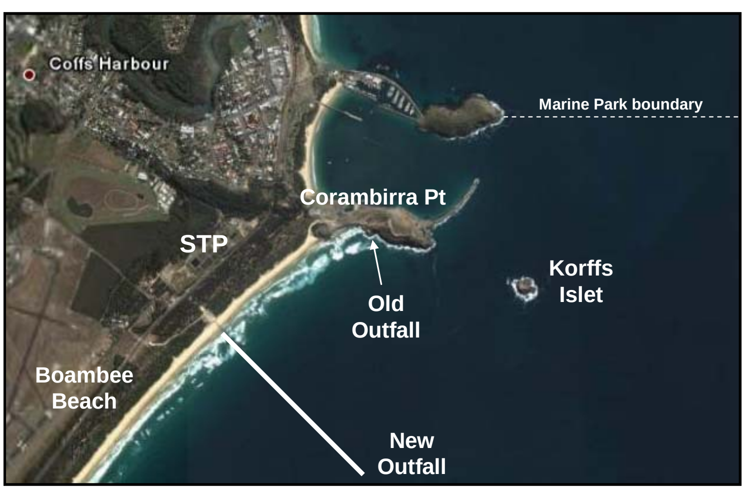


Figure 2.12 Locations of Coffs Harbour's old and new outfalls (2006 TerraMetrics/DigitalGlobe image via Google)

The Corambirra Point outfall was not designed to maximize initial dilutions and minimize boundary contact (see Figure 2.5 above); the dilution was typically 5:1 within 50 m of the outlet and 50:1 within 250 m of the outlet (CHEIS, 2000). Smith (1996) and CHEIS (2000) summarised the findings of a series of quantitative impact assessments that began in May 1987 and ran until 1991:

- the abundance of ephemeral green algae *Ulva lactuca* was elevated at all monitoring sites along Corambirra Point compared to control sites, indicated that effluent impact extended the full length of the Point (~460 m). Increased coverage of *Ulva lactuca* is the most obvious and often quoted impact of sewage outfalls in NSW (Krogh, **Pritchard** & Holden, 2000).
- algal species richness near the outfall was much lower than at the reference locations, sometimes reducing to half that of the reference locations.
- the community structure of animals in the algal holdfasts showed a gradient of change along Corambirra Point including a decrease in abundance of suspension feeders with distance from the outlet and a corresponding increase in omnivorous species, extending over 400m from the outfall.
- concentrations of both nitrogen and phosphorus in *Ulva lactuca* were higher at Corambirra Point compared to control sites, corresponding with elevated *Ulva* abundances
- the density of intertidal bivalves (*L. australis*) was substantially higher at Corambirra Point than at reference locations during most surveys

These impacts were generally consistent with those found at other shoreline outfalls in NSW (see attached CD: Krogh, **Pritchard** & Holden, 2000) and elsewhere although there is considerable variability in the type and scale of impacts due to differences in effluent quality, outfall hydraulic performance and local receiving environment.

2.3.2 Sydney deepwater outfalls

A five year, $24M, multi-disciplinary Environmental Monitoring Program (EMP) measured the environmental performance of Sydney's new deepwater outfalls against a wide range of criteria related to impacts on marine ecosystems and on human utilisation of marine resources (Philip and **Pritchard**, 1996). Findings from component studies of the EMP were reported in a special volume of Marine Pollution Bulletin (Koop & Hutchings 1996) while the overall assessment was reported by **Pritchard** *et al*. (1996a) and **Pritchard** (1997).

The EMP assessed the performance of the deepwater outfalls during the first two years of their operation (August 1991 to August 1993) by comparing conditions before and after the commissioning of deepwater outfalls.

Before the commissioning of deepwater outfalls, discharges at cliff face outfalls often led to poor beach and bathing water quality (Robinson *et al*., 1996), high levels of some contaminants in certain fish (Lincoln-Smith and Mann 1989a & b; McLean *et al*, 1991) and reduced diversity of some biological communities at least in the immediate vicinity of the outfalls (Fairweather, 1990). The gross visual impact of effluent from the former cliff face outfall at North Head is clearly evident in Figure 2.13. Through the 1980s, public opinion had increasingly demanded action to overcome often severe pollution and a decision was taken to divert the effluent of three major sewage treatment plants from the shoreline to offshore deepwater outfalls, using multi-port diffusers in water depths of 60 to 80 metres. The three new outfalls were commissioned during the period from September 1990 to August 1991.

Effluent discharged from the new deepwater outfalls was found to undergo rapid initial dilution, typically within 500 metres of the outfall, before reaching either a level of neutral buoyancy or the ocean surface. Initial dilutions were one to two orders of magnitude greater than those achieved at the former cliff face outfalls and effluent plumes remained trapped below the sea surface for more than 80% of the time (**Pritchard** *et al*., 1993, 1996b, 1997).

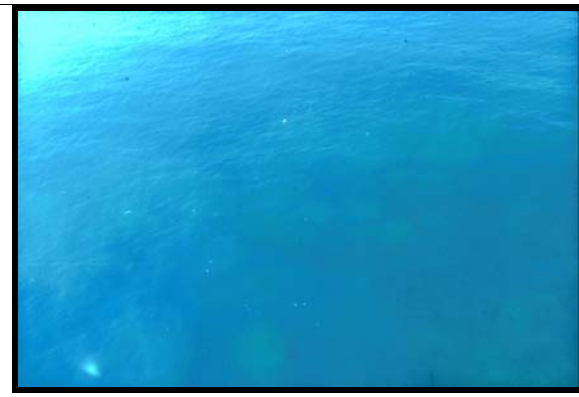
	
Effluent plume emanating from shoreline outfall in 1990 under typical conditions	Effluent plume emanating from deepwater diffuser system in 1992 on a rare occasion when plume surfaced

Figure 2.13 Surface effluent plumes off Sydney (North Head) before and after the diversion to an offshore diffuser system in December 1990. [photo by Pritchard]

Most EMP studies focused on the near vicinity of the outfalls and compared changes at outfall sites (before vs after) with those at distant control (reference) sites. The fate of a range of known effluent constituents was investigated directly through monitoring in the water column (faecal bacteria, nutrients and suspended solids), in deployed oysters and in fish (contaminants), in sediments (contaminants and sediment characteristics) and on beaches (faecal bacteria and sewage grease). Further studies measured the impacts of effluent on marine ecosystems (fish and benthos) and on human utilisation of marine resources (seafood contamination and recreation). The EMP assessment concluded that the new outfalls mitigated most of the environmental problems previously experienced when shoreline outfalls were operating without creating any major new problems in the ocean waters in the short term. During the EMP there were no sustained effects of the outfalls on the overall diversity (number of species) of biological communities found near the deepwater outfalls. However, the outfalls caused both increases and decreases in the abundance of a number of components of the soft bottom, planktonic and demersal fish communities near the outfalls. Modelling of plume behaviour and the studies of biota and sediments indicated that the enhanced dilution and dispersion had resulted in a decreased likelihood of any given organism or area of sediment encountering (and therefore accumulating) high loads of a contaminant, but concomitantly there had been an increased likelihood of more organisms (or sediment) accumulating or being exposed to small amounts of contaminants.

A number of residual environmental issues emerged from EMP studies. Some of these were associated with the deepwater outfalls while others were common to a broad area of NSW coastal waters.

Remaining outfall issues included:

- potential for accumulations of sewage particles and associated contaminants in offshore sediments, especially given the large suspended solids loading (see Figure 2.4 above) and the relocation of the discharge to the mid-shelf which has a greater potential for accumulation (see Geomorphic Setting above);
- unexplained minor changes in abundances of certain bottom dwelling organisms and free swimming fish near outfalls;
- occasional presence of sewage grease on beaches; and
- faecal pathogens in sewage plumes.

Further marine issues raised not specifically attributable to the operation of the deepwater outfalls, included:

- occasional exceedances of National Food Authority Maximum Residue Levels for some trace metals in fish from NSW coastal waters;
- possible nutrient enrichment of coastal waters and its effect on phytoplankton growth (algal blooms); and
- beach and bathing water pollution originating from stormwater sources and the remaining cliff-face outfalls discharging primary treated sewage.

2.3.3 Interpretation and extrapolation of time limited impact assessments

Impact assessment studies including many of the component EMP studies adopt Before and After Control Impact (BACI) designs to isolate outfall impacts on the marine ecosystem from background variability. These studies involved data collection before and after a putative impact at replicated 'control' and 'impact' locations. In this way BACI designs take into account background variability, which is common to both control and impacted sites. In many cases it is reasonable to assume that long-term patterns in the ocean would affect the background variability at outfall and control sites equally. For instance, fish carried with (or attracted to) warm East Australian Current waters are likely to be present in similar numbers at both control and outfall sites if they receive EAC waters at similar times. However, careful consideration needs to be given to both the selection of appropriate 'control' sites and the temporal context of time limited impact assessment.

Unfortunately, spatial variability is generally not known *a priori* if at all, but selection of appropriate 'control' locations can often be informed by an understanding of critical ambient processes. For example, natural sediment transport rates are often markedly different on opposite sides of a headland due to different exposures to waves. In such circumstances, impact assessments to determine the effects of increased sediment load from a new outfall on benthic communities on the headland would need 'control' sites on equivalent positions (w.r.t. wave driven sediment transport) of equivalent headlands especially if directional wave energy changed between 'before' and 'after ' periods. Similar considerations apply to pollutants and biota in the water column. This emphasises the need to develop a predictive understanding of both pollutant transport/behavour and ambient variability.

An understanding of temporal context is also critical if findings from time limited impact assessments are to be extrapolated or generalised to inform broad management decisions or long term strategies. If a long-term pattern changed the nature of the impact by either affecting the distribution (fate) of pollutants or the environmental sensitivity to pollutant impacts, then time limited impact assessment studies could have identified impacts (or lack of impacts), which only occur under rare circumstances (Lee and **Pritchard**, 1996). In addition to this, many impact assessments lack sufficient 'before' data (e.g. Krogh and Robinson, 1996) which further emphasises the need for a temporal context in which to interpret the results.

2.4 Conclusions and information gaps

The interactions of flows with continental shelf bathymetry are wonderfully complex especially in the near shore region. The near shore *coastal boundary layer* which is shaped by patterns of turbulence associated with inner shelf coastal morphology, receives pollutants continuously from point sources and intermittently from diffuse coastal catchment sources.

Case study scenarios for this thesis include: Coffs Harbour, a medium sized coastal town disposing highly treated sewage effluent in shallow water just south of a modest headland on a section of the continental shelf that is regionally dominated by the tropical influences of the East Australian Current stream flow; and, Sydney, Australia's largest city disposing vast quantities of primary treated effluent via deep water diffuser systems located on a section of the shelf regionally dominated by the EAC eddy field.

NSW coastal waters currently support high biodiversity values but are exposed to growing human induced disturbances and pollutant loadings.

Pollutant exports to the ocean from diffuse sources in NSW coastal catchments are poorly quantified due to very limited event based monitoring data and a poor understanding of pollutant assimilation within catchments and estuaries en route to the ocean. Collecting data to fill these information gaps is a formidable task and well beyond the scope of this thesis. However, there is scope to investigate factors that determine the fate of pollutants discharged at or near the land-sea interface. That is, *classify and where possible map coastal boundary layer characteristics that affect pollutant residence times and distributions, exploiting the increasing availability of remote sensed data products*.

As discussed above, sewage discharges account for the vast majority of point source loadings to NSW offshore waters and of these Sydney's deepwater outfalls account for more than 80% of the total nitrogen loadings. Nutrient concentrations in all treated effluent discharged at all NSW sewage outfalls exceed national water quality trigger criteria (ANZECC/AMCANZ, 2000), and the greatest exceedances occur in primary treated effluent discharged from Sydney's deepwater outfalls. Few impact assessments anywhere in NSW have considered water column eutrophication. Even the $24M Sydney Deepwater Outfalls Environmental Monitoring Program failed to adequately address possible nutrient enrichment of coastal waters and its effect on phytoplankton growth (Pritchard, 1997). Information is required to *determine ambient (non outfall) nutrient distributions and patterns, quantify nutrient enrichment patterns due to Sydney's deepwater outfalls and, assess the importance of outfall nutrients in relation to phytoplankton activity.*

In contrast to Sydney's deepwater outfalls, the vast majority of NSW sewage outfalls discharge relatively small pollutant loads at the shoreline after at least secondary levels of treatment. These outfalls were rarely located and designed to optimise initial dilution and avoid contact with sensitive habitats to minimise environmental impacts. With rapid population growth in the NSW coastal zone the development of regional effluent management strategies provide windows of opportunity to optimise ocean discharge, such as in the Coffs Harbour area. However, this requires an understanding of dispersion potential across the local receiving environment. Although many aspects will be site specific, *case studies are required to illustrate key processes and approaches to determine and exploit dispersion potential in relation to outfall location and design for small, coastal sewage treatment systems.*

Although climate variability in Australia has been described in terms of large scale phenomena such as the El Nino Southern Oscillation (Allan 2000) and the Interdecadal Pacific Oscillation (Micevski *et al*., 2006) there is little information on how these and other phenomena are manifest at a site specific level in NSW coastal waters. Small scale process based understanding will be critical to determine the local consequences of global scale climate variability/change scenarios. That is, in the context of this thesis there is a need to *investigate the importance of morphology in controlling the dispersion and fate of pollutants discharged to the NSW coastal waters in order to develop a predictive understanding of pollutant impacts*.

2.5 References

Ajani, P.A., Hallegraeff,G. and **Pritchard,T.R.** (2001a) Historic Overview of Algal Blooms in Marine and Estuarine Waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales, 123, pp. 1-22

Ajani,P., Lee,R., **Pritchard,T.R**. and Krogh,M. (2001b) Phytoplankton patterns at CSIRO's long-term coastal station off Sydney. Journal of Coastal Research, 34, 60-73.

Allan, R.J., 2000. ENSO and climatic variability in the last 150 years. In: Diaz, H.F., Markgraf, V. (Eds.), El Nin˜o and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts. Cambridge University Press, Cambridge, pp. 3–56 (Chapter 1).

Anderson, D.M. (1994) Red Tides, Scientific American 271, 62-68.

ANZECC/ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment & Conservation Council and Agriculture & Resource Management Council of Australia & New Zealand.

Apte S.C., Batley G.E., Szymczak R., Rendell P.S., Lee R., Waite T.D. (1998) Baseline trace metal concentrations in New South Wales coastal waters. Marine and Freshwater Research 49 (3): 203-214 1998

Ayres, C.P., Gillett, R.W. and Cernot, U. (1987) Rainwater Acidity in Sydney, An Addendum, Clean Air, Vol. 21/2, 8p.

Baginska,B., **Pritchard,T.** and Krogh,M. (2003) Roles of land use resolution and unit-area load rates in assessment of diffuse nutrient emissions. Journal of Environmental Management 69, 39-46.

Baginska, B. and **Pritchard,T.R**. (2000) Nutrient Emissions for Manning and Richmond Catchments (NSW). NSW Environment Protection Authority Report prepared for the National Pollutant Inventory Program.

Baginska, B. and **Pritchard,T.R**. (1999) CMSS as a tool for assessment of aggregated catchment emissions - sensitivity testing. NSW Environment Protection Authority.

Baginska, B., Lu,Y. Mawer, D. and **Pritchard, T.R.** (2004) Linking Land Use Decisions to Nutrient Exports. Department of Environment and Conservation. Refereed report, November 2004.

Baird ME, Timko PG, Suthers IM, Middleton JH (2006) Coupled physical–biological modelling study of the East Australian Current with idealised wind forcing. Part I: Biological model intercomparison. Journal of Marine Systems 59 (2006) 249–270

Birch G.F. (2000) Marine pollution in Australia, with special emphasis on central New South Wales estuaries and adjacent continental margin. International Journal of Environment and Pollution 13 (1-6): 573-607.

Boudouresque, C.F. and Verlaque, V.M. (2002) Biological pollution in the Mediterranean Sea: invasive versus introduced macrophytes. Marine Pollution Bulletin 44 (1), 32–38.

Boyd, R., Ruming, K. & Roberts, J. J. (2004) Geomorphology and surficial sediments of the southeast Australian continental margin. Australian Journal of Earth Sciences 51 (5), 743-764.

Cai, W., Shi,G., Cowan,T., Bi,D., Ribbe,J. (2005) The response of the Southern

Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. Geophysical Research Letters,32.

Carnovale, F. and Saunders,J. (1987) The Deposition of Atmospheric Nitrogenous Species to Port Phillip Bay – addendum. SRS Report No. 87/002, Victorian EPA, Melbourne.

CHEIS (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coff Harbour City Council, NSW, Australia.

Church, J.A., Freeland, H.J. and Smith, R.L. (1986) Coastal trapped waves on the east Australian continental shelf Part I: propogation of modes. Journal of Physical Oceanography, 6, 1929-1943.

Clarke, K.M. & Warwick, R.M. (1994) Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. Natural Environment Research Council, UK, 144pp.

Cresswell, G. (1994) Nutrient Enrichment of the Sydney Continental Shelf. Aust.J.Mar.Freshwater Res., 45, pp677-691

Cresswell G.R. (1974) Ocean currents measured concurrently on and off the Sydney area continental shelf, Australian Journal of Marine and Freshwater Research, 25, 427-438.

Cresswell, G.R. and Legechis, R. (1986) Eddies off southeastern Australia. Deep Sea Research, 33, 1527-1562.

Cunningham D.J., Wilson S.P. (2003) Marine debris on beaches of the Greater Sydney Region. Journal of Coastal Research 19 (2): 421-430.

Dela-Cruz, J, Ajani, P, Lee, R, **Pritchard, T** and Suthers, I (2002), Temporal abundance patterns of the red tide dinoflagellate Noctiluca scintillans along the southeast coast of Australia, Marine Ecology Progress Series, 236, 75-88.

Dunn, J.R., Ridgway,K.R. (2002) Mapping ocean properties in regions of complex topography. Deep-Sea Research, I49, 591–604.

Eyre, B. and Pepperell, P. (1999) Budgets for Australian estuarine systems: Sub-tropical Systems. In: Smith, S.V., C.J. Crossland, Australasian Estuarine Systems: Carbon, Nitrogen and Phosphorus Fluxes . LOICZ Reports & Studies No. 12, ii + 182 pp. LOICZ, Texel, The Netherlands

Feth, J.H. (1966) Nitrogen Compounds in Natural Water – A Review, US Geological Service.

Fairweather, P. (1990) Sewage and the biota on seashores: assessment of impact in relation to natural variability. Environmental Monitoring and Assessment, 14, 197-210.

Gibbs, M.T., Middleton, J.H., Marchesiello, P., 1998. Baroclinic response of Sydney shelf waters to local wind and deep ocean forcing. J. Phys. Oceanogr. 28, 178–190.

Gibbs,M.T., Marchesiello, P. and Middleton, J.H., "Nutrient enrichment of Jervis Bay during the massive 1992 coccolithophorid bloom". (1997) Mar.Freshwater Res, 48, 473-8

Gill A.E. and Schumann E.H. (1979) Topographically induced changes in the structure of an inertial coastal jet: application to the Algulhas current, J. Phys. Oceanogr., 9, 975-991.

Goldberg, E.D. (1995) Emerging problems in the coastal zone for the twenty-first century. Marine Pollution Bulletin 31 (4–12), 152–158.

Goodwin, I.D., Stables, M.A. and Olley, J.M. (2006) Wave climate, sand budget and shoreline alignment evolution of the Iluka–Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. Marine Geology 226 (2006) 127– 144.

Grant, B. R. and Kerr, J. D. (1970) Phytoplankton numbers and species at Port Hacking station and their relationship to the physical environment. Australian Journal of Marine and Freshwater Research 21, 35-45.

Green R. H. (1979). Sampling Design and Statistical Methods for Environmental Biologists. Wiley & Sons. New York.

Gregory, M.R. (1999) Plastics and South Pacific Island shores: environmental implications. Ocean and Coastal Management 42, 603–615.

Griffin, D.A. and Middleton, J.H. (1991) Local and Remote wind forcing of New South Wales inner shelf currents and sea level. Journal of Geophysical Research, 21, 304-322.

Griffin, D.A. and Middleton, J.H. (1992) Upwelling and internal tides over the inner New South Wales continental shelf, Journal of Geophysical Research, 97, C9, 14389-14405.

Hahn, S. D., Rochford D. J., Godfrey, J. S., 1977. Long term variability of oceanographic data at the Port Hacking 50-metre station. Aust. J. Mar. Freshwater Res. 28, 57-66.

Hallegraeff, G. M. (1981) Seasonal study of phytoplankton pigments and species at a coastal station off Sydney, Marine Biology 61, 107-118.

Hallegraeff, G. M. and Reid, D. D. (1986) Phytoplankton species successions and their hydrological environment at a coastal station off Sydney. Australian Journal of Marine and Freshwater Research 37, 361-377.

Harriott V.J. & Banks S.A. (2002) Latitudinal variation in coral communities in eastern Australia: a qualitative biophysical model of factors regulating coral reefs. Coral Reefs 21 (1): 83-94

Harriott, V. J., Smith, S. D. A. and Harrison, P. (1994) Patterns of coral community structure of subtropical reefs in the Solitary Islands Marine Reserve, Eastern Australia. Marine Ecology Progress Series 109, 67-76

Harris, P. T., Baker, E. K. and Cole, A. R. (1991) Physical Sedimentology of the Australian Continental Shelf. Ocean Sciences Institute Report No. 51, University of Sydney, Sydney

Hobday, A.J., Young, J.W., Moeseneder, C., Dambacher,J.M. (2011) Defining dynamic pelagic habitats in oceanic waters off eastern Australia. Deep-Sea Research II58(5),734–745.

Holbrook N.J., Goodwin,I.D., McGregor,S., Molina,E., Power,S.B. (2011) ENSO to multi-decadal timescale changes in East Australian Current transports and Fort Denison sea level: oceanic Rossby waves as the connecting mechanism. Deep-Sea Research II58(5), 547–558.

Holbrook, N.J. and Bindoff,N.L. (1997) Interannual and decadal temperature variability in the southwest Pacific Ocean between 1955 and 1988. Journal of Climate10, 1035–1049.

Humphrey, G. F. (1960) The concentration of planktonic pigments in Australian waters, CSIRO Division of Fisheries and Oceanography Technical Paper No. 9.

Humphrey, G. F. (1963) Seasonal variations in plankton pigments in waters off Sydney. Australian Journal of Marine and Freshwater Research 14(1), 24-36.

IMCRA (1998) Interim Marine and Coastal Regionalisation for Australia: an ecosystem based classification for marine and coastal environments, Version 3.3. Environment Australia, Commonwealth Department of the Environment, Canberra.

Ingleton, T and Large D. (2004). NSW Ocean Outfalls: Using Near-field models to investigate hydrodynamic performance. Australian Journal of Water Resources Vol 8, No. 1, 45 – 56

Islam, M.S. & Tanaka, M. (2004) Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. Marine Pollution Bulletin 48 624–649

Jeffrey, S.W. and Carpenter, S. M. (1974) Seasonal succession of phytoplankton at a coastal station off Sydney. Australian Journal of Marine and Freshwater Research 25, 361-369.

Jones, A. R. & Short, A. D. (1995) Sandy beaches. In Coastal Marine Ecology of Temperate Australia, eds. A. J. Underwood and M. G. Chapman, pp. 136-151. UNSW Press, Sydney.

Jordan,A., Davies,P., Ingleton,T., Foulsham,E., Neilson,J. and **Pritchard,T.** (2010) Seabed habitat mapping of the continental shelf of NSW. DECCW 2010/1057, ISBN 978 1 74293 085 5.

Koop, K and Hutchings, P. (1996) Ocean Outfalls – Sustainable Solution? Mar. Pollut. Bull., 33 (7-12), 121-308.

Krogh, M., **Pritchard, T.R.** & Holden, C. (2000) NSW Coastal Outfalls Atlas. Provided in Appendix 4 of this thesis.

Krogh, M. and Robinson, L. (1996) Environmental variables and their association with faecal coliform and faecal streptococci densities at thirteen Sydney beaches. Marine Pollution Bulletin 33(7-12), 239-248.

Kulmar,M., Lord,D., Sanderson,B. (2005) Future Directions for Wave Data Collection in New South Wales. Coasts and Ports: Coastal Living - Living Coast; Australasian Conference 2005; Proceedings. Barton, A.C.T.: Institution of Engineers, Australia, 167-172.

Kusui, T. & Noda, M. (2003) International survey on the distribution of stranded and buried litter on beaches along the Sea of Japan. Marine Pollution Bulletin 47 (1–6), 175–179.

Large, D., Holden, C., Xie, J.,Tate, P. (1994) Bate Bay Pollution Study Volume 2 Physical Oceanography Summary Report. Australian Water Technologies Water Board, Sydney.

Lee,R., Ajani,P., Krogh,M. and **Pritchard,T.R.** (2001) Resolving climatic variance in the context of retrospective phytoplankton pattern investigations off the east coast of Australia. Journal of Coastal Research, 34, 74-86.

Lee, R. S. and **Pritchard, T. R.,** (1999) Extreme Discharges into the Coastal Ocean: A Case Study of August 1998 Flooding on the Hawkesbury and Hunter Rivers. Pacific Coasts and Ports ’99 Proceedings, Perth, W.A. 341-346. Institute of Engineers, Australia.

Lee, R.S. and **Pritchard, T. R.** (1996) How Do Long-term Patterns Affect Time-limited Environmental Monitoring Programmes ? Mar. Pollut. Bull. 33, 260-268.

Lee, R. S. and **Pritchard, T. R.** (1996) “Dispersion of effluent from Sydney’s new deepwater outfalls Part 1: ocean processes”. In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), 430-438. American Geophysical Union, Washington.

Lincoln-Smith and Mann (1989a) Bioaccumulation in nearshore marine organisms. Organochlorine compounds in the red morwong Cheilodactylus fuscus, around Sydney's three major sewage outfalls. State Pollution Control Commission, Sydney

Lincoln-Smith and Mann (1989b) Bioaccumulation in nearshore marine organisms. Organochlorine compounds in the rocky reef animals near Malabar sewage ocean outfall. State Pollution Control Commission, Sydney

Lu,Y, Baginska, B. and **Pritchard, T.R**. (2004) Applying remote sensing to Managing Impacts of Diffuse Sources of Pollution due to landuse change in Tweed catchment, NSW, Australia.13th International Soil Conservation Organisation Conference, Brisbane, July 2004.

McLean, C., Miskiewics, A. and Roberts, E. (1991) Effect of Three Primary Treatment Sewage Outfalls on Metal Concentrations in the Fish Cheilodactylus fiscus Collected Along the Coast of Sydney, Australia. Marine Pollution Bulletin, 22(3), 134-140.

Matthai C., Birch G.F. (2000) Effect of coastal cities on surficial sediments mantling an adjacent high-energy continental margin - central New South Wales, Australia. Marine and Freshwater Research 51 (6): 565-576.

Micevski, T., Franks, S.W. & Kuczera, G. (2006) Multidecadal variability in coastal eastern Australian flood data. Journal of Hydrology (2006) 327, 219– 225.

Middleton, J.H. (1995). The oceanography of Australian seas. In: Zann, L.P. (ed) State of the Marine Environment Report for Australia: The Marine Environment - Technical Annex: 1. Department of the Environment, Sport and Territories, Canberra, ISBN 0 642 17399 0

National Climate Centre of the Bureau of Meteorology (2004) webclim@bom.gov.au

Newell, B. S., 1966. Seasonal changes in the hydrological and biological environments off Port Hacking, Sydney. Aust. J. Mar. Freshwater Res. 17, 77-91.

NSW Fisheries (2004) NSW Control Plan for the noxious marine weed Caulerpa taxifolia in NSW waters NSW Fisheries, February 2004, 1-19

NSW SoE (2006) New South Wales State of the Environment Report. NSW Department of Environment and Conservation.

Oke, P.R., Middleton, J.H., 2001. Nutrient enrichment off Port Stephens: the role of the East Australian Current. Cont. Shelf Res. 21, 587–606.

Parsons, T.R., Takahashi, M. & Hargrave, B., 1997. Biological Oceanographic Processes Second Edition. Pergamon Press.

Partridge, I.J. (ed), 1994. Will it Rain?, Agricultural Production Townsville, State of Queensland, Dept. of Primary Industries.

Pelley, J. (1998) 'Is Coastal Eutrophication Out of Control?' Environmental Science and Technology, October 1998, 462-466.

Philip, N.A. and **Pritchard, T. R.** (1996) Australia's First Deepwater Sewage Outfalls: Design Considerations and Environmental Performance Monitoring. Mar. Pollut. Bull. 33, 132-139.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T. R., Lee, R. S. and Ajani, P. (1999) Anthropogenic and Oceanic Nutrients in NSW's Dynamic Coastal Waters and Their Effect on Phytoplankton Populations. Pacific Coasts and Ports '99 Proceedings. 537-543. Institute of Engineers, Australia.

Pritchard, T.R. , 1997. Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, Vol 24, No.1. March/April 1997.

Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N., 1996a Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental

Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

Pritchard, T. R., Lee, R. S. and Davison, A. (1996b) “Dispersion of effluent from Sydney’s new deepwater outfalls Part 2: Observations of Plume Behaviour: Winter and Summer Examples” In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), pp. 430-438. American Geophysical Union, Washington.

Pritchard, T.R., Lee, R.S. and Davison, A., 1993. Sydney’s Deepwater Outfalls. In situ Observations of Plume Characteristics. In:Proceedings of 1th Australasian Conference in Coastal and Ocean Engineering, Townsville, 23-27 August 1993. Institute of Engineers, Australia.

Rendell, P.S. and **Pritchard, T. R**. (1996) Physicochemical Conditions in Coastal Waters off Sydney, Central NSW, Australia. Mar. Pollut. Bull. 33, 132-139.

Ridgway, K.R. (2007) Long-term trend and decadal variability of the southward penetration of the East Australian Current.Geophysical Research Letters34, L13613. doi:10.1029/2007 GL030393

Ridgway, K.R., Coleman,R.C., Bailey,R.J., Sutton,P. (2008) Decadal variability of East Australian Current transport inferred from repeated high-density XBT transects, a CTD survey and satellite altimetry. Journal of Geophysical Research 113, C08039.doi:10.1029/2007JC004664.

Ridgway, K.R. and Dunn, J.R. (2003). Mesoscale structure of the mean East Australian Current System and its relationship with topography. Prog. Oceanogr. 56, 189–222.

Ridgway, K.R., Dunn, J.R., Wilkin, J.L. (2002) Ocean interpolation by four-dimensional least squares – Application to the waters around Australia. Journal of Atmospheric and Oceanic Technology 19,1357–1375.

Roberts, D. E. and Davis, A. R. (1996) patterns in sponge (Porifera) assemblages on temperate coastal reefs off Sydney, Australia. Journal of Marine and Freshwater Research 47, pp. 897-906.

Robinson, L., Heggie A. and Coade, G. (1996). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 3: Water Quality. Environment Protection Authority. Sydney.

Rochford, D.J. (1984). Nitrates in eastern Australian coastal waters. Aust. J. Mar. Freshw. Res., 35, pp. 385-397.

Rochford, D. J. (1975) Nutrient enrichment of East Australian coastal waters. II Laurieton upwelling. Aust. J. Mar. Freshwater Res. 26, 233-243.

Roughan, M., Middleton, J.H., 2004. On the East Australia Current: variability, encroachment, and upwelling. J. Geophys. Res. 109, C07003.

Roy, P.S., and Thom, B.G. (1981) Late Quaternary marine deposition in New South Wales and southern Queensland: an evolutionary model. Journal of the Geological Society of Australia, 28, 471-489.

Roy, P. S., Williams, R. J., Jones, A. R., Yassini, I., Gibbs, P. J., Coates, B., West, R. J., Scanes, P. R., Hudson, J. P. & Nichol, S. (2001) Structure and Function of South-east Australian Estuaries Estuarine, Coastal and Shelf Science, 53, 351–384

Schneider P.M., Davey, S.B. and Lock, N (1994) Offshore sydney sediment contaminants – their distribution & associations. AWT Ensight March 1994.

Schmitt, R.J. & Osenberg, C.W. 1996. Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats. Academic Press, San Diego, 401pp.

Short, A. (1993) Beaches of the New South Wales Coast: a guide to their nature, characteristics, surf and safety. Australian Beach Safety and Management Program. ISBN 0 646 15055 3.

Short,A.D. and Woodroffe,C.D (2009) The Coast of Australia, Cambridge University Press, pp288.

Smith, S.D.A. (1996) The Effects of Domestic Sewage Effluent on Marine Communities at Coffs Harbour, New South Wales, Australia. Marine Pollution Bulletin, Vol. 33, Nos 7-12, pp. 309-316,

Suthers, I.M., Everett,J.D., Roughan,M., Young, J.W., Oke, P.R., Condie,S.A., Hartog,J.R., Hobday, A.J., Thompson, P.A., Ridgway, K., Baird, M.E., Hassler, C.S., Brassington, G.B., Byrne, M., Holbrook, N.J. Malcolm, H.A. (2011) The strengthening East Australian Current, its eddies and biological effects — an introduction and overview. Deep-Sea Research II 58, 538–546.

Sydney Water, 1996. Environmental Indicators Monitoring Report & Special Objectives Statement. Sydney Water Annual Environment Report Auxiliary volume. Sydney Water Corp.

Tee K.T. and Smith P.C. (1993) Topographic upwelling off southwest Nova Scotia, J. Phys. Oceanogr., 23, 1703-26.

Tranter, D.J., Carpenter,D.J. and Leech,G.S. (1986) The coastal enrichment effect of the East Australian Current eddy field, Deep Sea Research, 33 (11/12), 1705-1728.

Underwood, A.J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. Ecological Applications, 4, 3-15.

Underwood, A. J. & Chapman, M. G. (1995) Rocky shores. In Coastal Marine Ecology of Temperate Australia, eds. A. J. Underwood and M. G. Chapman, pp. 55-82. UNSW Press, Sydney.

Wolanski (2007). Estuarine Ecohydrology, pp 17-39

Wolanski, E., and Collis, P. (1976) Aspects of aquatic ecology of the Hawkesbury River, 1 Hydrodynamical processes, Aust. J. Mar. Freshwater Res., 27, pp565-582.

Zann, L.P. (2000) The Eastern Australian Region: a Dynamic Tropical/Temperate Biotone. Marine Pollution Bulletin Vol. 41, Nos. 1-6, pp. 188-203.

3. OBSERVATIONS, DATA ANALYSIS AND MODELLING

In order to address information gaps outlined in the previous chapter it was necessary to collect new data, collate and re-analyse existing data, and develop predictive understanding through modelling. This chapter describes sampling methods, instrument specifications, analytical methods, sources of existing data, catchment, dispersion and hydrodynamic models, quality assurance and data validation. As such this chapter complements the core chapters that follow in this thesis, especially those based on journal papers which are necessarily concise.

3.1 Oceanographic Observations

3.1.1 Vessels

The NSW Environment Protection Authority (EPA) (now Department of Environment and Climate Change - DECC) research vessel *Glaucus* (Figure 3.1) was used for monthly Port Hacking sampling at the Commonwealth Science and Industrial Research Organisation (CSIRO) monitoring stations and for Conductivity/Temperature/Depth (CTD) and Acoustic Doppler Current Profiling (ADCP). The EPA (DECC) research vessel *Aquila* (Figure 3.5 & 3.6) was used for CTD and ADCP current meter profiling and for tracking drogues at Coffs Harbour. Moored current meters were deployed and recovered from chartered vessels at Coffs Harbour.

Figure 3.1 The 8.5m twin hulled *RV Glaucus* used for routine Port Hacking sampling, Nisken, CTD and ADCP profiling.

3.1.2 Currents

Flow characteristics of regional currents and the coastal boundary effects were observed using a range of Acoustic Doppler Current Profiling (ADCP) current meters.

Four RDI Broadband Workhorse ADCPs were deployed during the Coffs Harbour study. Commercial trawl resistant bottom mounting with pod recovery and conventional concrete mountings (Figure 3.2) were used for ADCP moorings.

Off Coffs Harbour, two shallow water units (1200KHz) were positioned close inshore at sites A and B, and two deep water units (300KHz) were deployed at offshore sites C and D. GPS site coordinates are given in Table 3-1 and locations are shown in Figure 3.3.

All instruments were deployed on 6 September 2000. Those at sites A, B and D were recovered on 28 November 2000 and that at site C, shortly after, on 30 November 2000. Current meters at sites B, C and D operated continuously for the full deployment period. Current data from site A ceased towards the end of October due to excessive marine growth around the transducer head. Water temperature data, however, continued to be recorded at site A until the instrument was recovered on 28 November 2000.

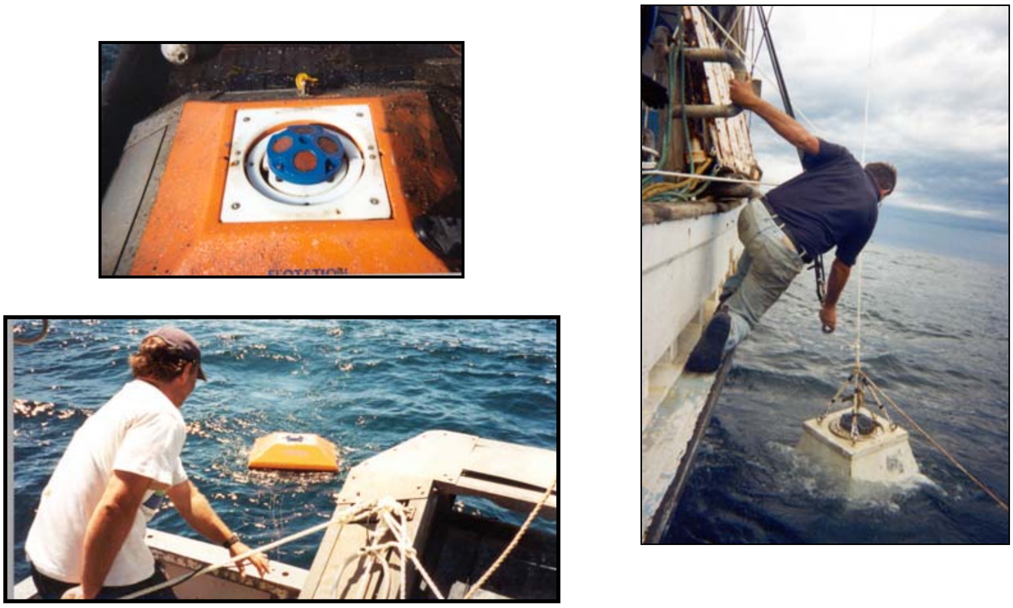


Figure 3.2 Trawl resistant bottom mounting with gimble cradle for ADCP (top left) and recovery of floatation pod and mounting (bottom left); and, concrete mounting with gimbaled ADCP cradle (right).

The profiling range of the ADCP is limited by the transducer design, the acoustic attenuation properties of sea water and the proximity of the sea surface. Range limitations occur at both ends of the profile, often causing a loss of data at crucial interfaces. Ringing (persistent transducer oscillations after each ping) prevents reliable current measurements within 0.5m (1200 KHz ADCP) and 1.75m (300 KHz ADCP) of the transducer; this is the 'blanking depth'. The hard signal reflection at the sea surface produces a sharp echo response that can contaminate data in the upper 6% of the water column. For the purpose of determining the 'last good bin', the sea surface range was taken to be the distance between the transducer head and the sea surface at low tide (determined using the ADCP echo intensity strength).

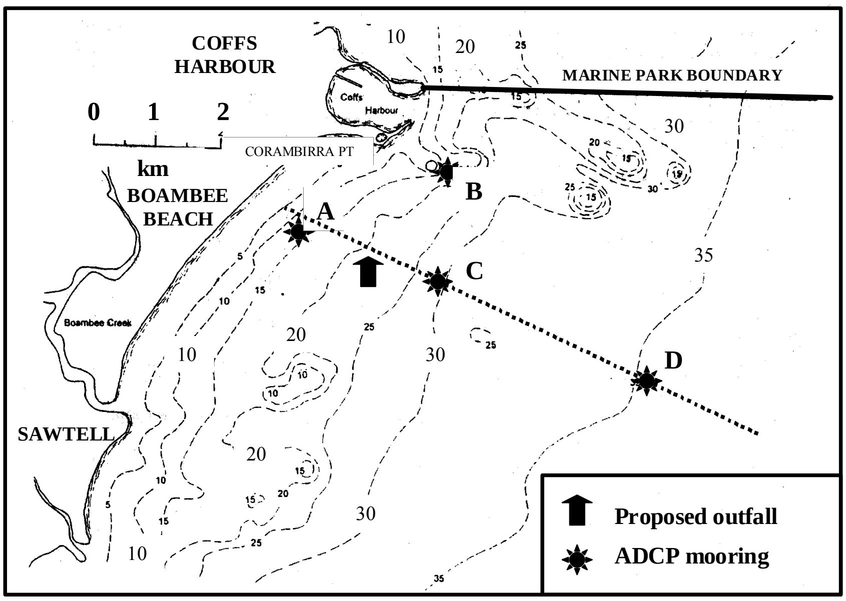


Figure 3.3 ADCP current meter locations at Coffs Harbour.

Table 3-1 Coffs Harbour ADCP locations, specifications and settings

SITE	Latitude S	Longitude E	Head Depth (m)	Blanking Depth (m)	Frequency (KHz)	No. Bins (after QA)
A	30° 19.555′	153° 08.062′	13	0.5	1200	11
B	30° 19.033′	153° 09.540′	21	0.5	1200	17
C	30° 20.445′	153° 09.646′	28	1.75	300	22
D	30° 21.055′	153° 10.774′	35	1.75	300	33

Setting	Value
Time Local	time = Eastern Australian Time (EST) + 1 hour
Burst sampling interval	Every 30 minutes
Data Out	Current speed and direction, correlation magnitude, echo intensity, percentage-good data and water temperature.
Ping rate	2 Hz (0.5 cps)
Depth cell size	1 meter
Centre of first bin, measured from the transducer head	1200 KHz: approx. 1 m 300 KHz : approx 2.25m
Magnetic variation	12.4 degrees East (*applied during post processing*)

Setting	Site A 1200KHz	Site B 1200 KHz	Site C 300 KHz	Site D 300 KHz
Pings per ensemble	240	480	240	240
Number of depth cells	15	24	33	44
Depth of transducer head above sea floor (m)	1.0	0.5	0.5	0.5
Random error estimation (σ) in cm/s *	0.9	0.6	3.5	3.5

* The random error for the horizontal current velocity (σ) is given by σ (m/s) = $(1.6 \times 10^2)/(fDN^{½})$ where *f* is the ADCP frequency (kHz), D is the depth cell thickness and N is the number of pings per ensemble.

A soft and hard iron compass calibration was conducted on all four current meters prior to deployment. With one exception, all instruments were calibrated to within ± 1 degree. Repeated calibration of the ADCP deployed at site C failed to improve upon the starting accuracy of ± 2.7 degrees. This prompted a software message, advising that the unit be returned to RDI for factory calibration. [However, after the deployment, the instrument was re-calibrated without any difficulty to ± 0.8 degrees. The reason for the apparent fix is unknown. One explanation is that the battery pack may not have been properly degaussed by the supplier].

The RDI Broadband ADCP applies four levels of internal data screening based on the *beam correlation* (auto correlation between pings), *percent-good* (a range of RDI acceptance criteria) and *vertical error velocity* (difference between simultaneous vertical velocity estimates from adjacent beams) and *fish detection* (inconsistencies in target echo intensity across the 4 beams). All screening measures except *fish detection* are logged. Acceptance checks were performed on data from each site at Coffs Harbour; for example, Figure 3.4 provides sample time-series (20 days) plots of the beam correlation, percent-good and vertical error velocity data for the top three (least accurate) depth bins from Site A.

ADCP data captured for the Coffs Harbour study following quality assurance screening is summarised in Table 3.2.

Table 3.2 Coffs Harbour data capture summary

Site	First ensemble	Last ensemble	Start	End	Last Good Bin
A	17	2323	18:00 6-Sep	19:00 24-Oct	10
B	16	4043	17:30 6-Sep	14:30 29-Nov	17
C	13	4136	16:00 6-Sep	13:30 1-Dec	22
D	8	4030	13:30 6-Sep	8:30 29-Nov	30

ADCP and wind data from Coffs Harbour were input to a visual assessment tool produced with assistance from Oceanographic Field Services and can be viewed on the attached compact disc.

In addition to the fixed ADCP deployments described above, current profile transects were run at Coffs Harbour using a 300 KHz RD Instruments ADCP (Figure 3.5). Depth bins were set at 1m and 20 pings per ensemble recorded every ~3 seconds. Most transects were ~7km in length, ranging from water depths of 10m to 50m.

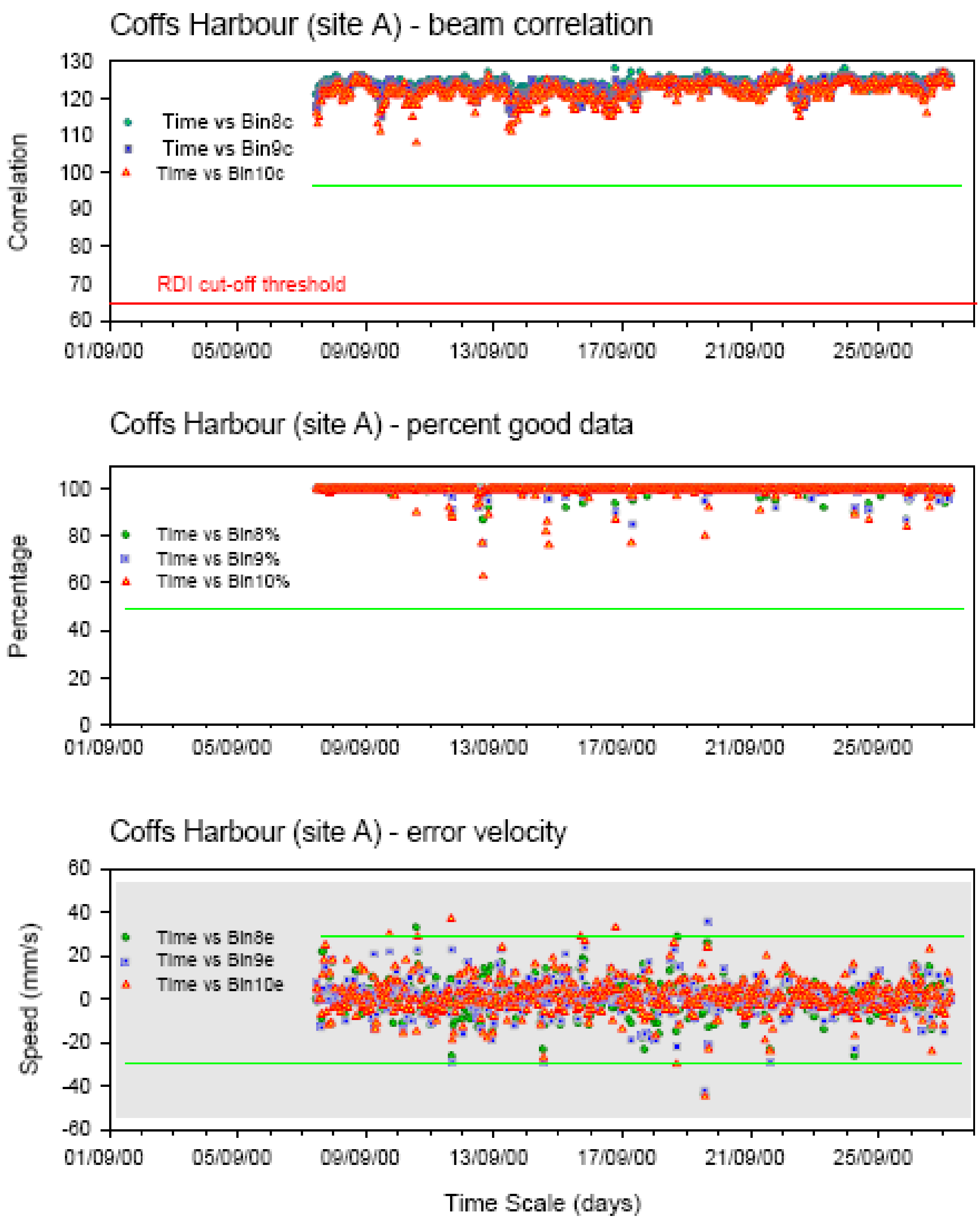


Figure 3.4 *Beam correlation*, *percent good* and *vertical error velocity* for the top three bins at site A. The gray panel shown in the vertical error velocity plot marks the region enclosed by ± 6 times the standard error. Green lines mark the 50% cut-off threshold.

Figure 3.5 RDI 300KHz profiling ADCP (left), deployment (right), and operation (centre).

3.1.3 Trackable Drifters

Headland wake effects were investigated during limited deployments of trackable drifters (drogues) in near surface waters.

Four Innotech Coastal Lagrangian Drifters (passive drifter buoys) were released at increasing distances along the proposed Coffs Harbour outfall alignment to investigate current shear and possible re-circulation cells in the vicinity of the proposed outfall. These limited duration drifter deployments did not coincide with re-circulation in the lee of Corambirra Point but nevertheless were useful for qualitative verification of numerical model simulations.

The drifter buoys used the Differential Global Positioning System and downloaded position fixes via mobile phone communication systems. Deployments lasted about 2 to 3 hours on three separate days (7/9/00, 28/11/00 & 30/11/00). These drifter tracks indicate moderate southward stream flow offshore with shorter and/or more erratic paths inshore of the 30m isobath as shown in Figure 3.6.

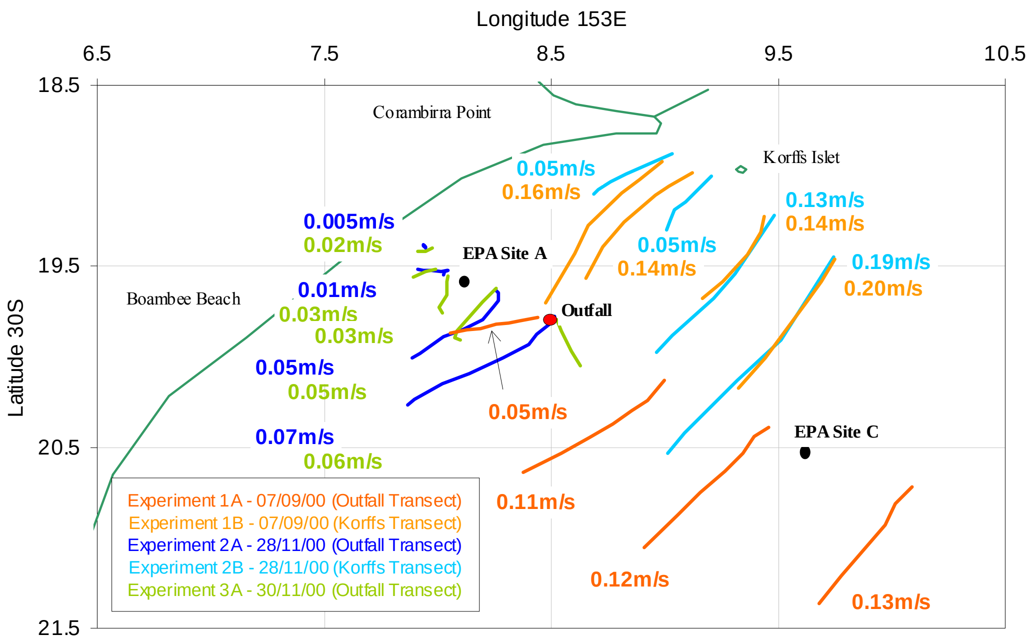


Figure 3.6 Paths traveled by passive drifters released on 5 occasions.

3.1.4 Winds

Wind observations were required to determine the wind driven component of flow fields, to assess potential bias during the investigation period, and for numerical model simulations.

The Bureau of Meteorology provided average wind speed and direction for the last five years at 30 minute intervals from a weather station at Coffs Harbour airport, located immediately inshore from Boambee Beach.

The distribution of winds during the four month sampling period was compared with long term distributions of winds (Figure 3.7) to assess the degree to which the study period represented long term average conditions. In the absence of long term current data and given the strong correlation between local winds and currents (Chapter 8), bias in wind data is indicative of bias in observed currents (w.r.t long term average).

The Coffs Harbour study sampling period included a greater proportion of wind driven southward currents than would normally be expected – Figure 3.7. Indeed long-term wind data suggested a tendency for wind driven currents to be northward (53%) at least as often as southward currents in the study region as indicated by Table 3.3.

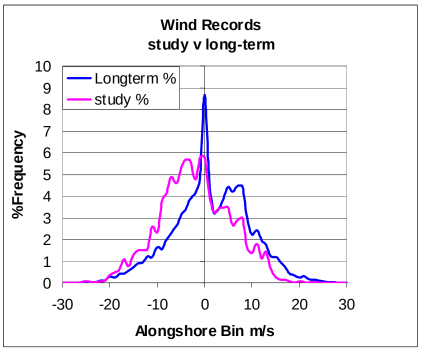


Figure 3.7: Southward (negative) alongshore winds distributions for our study period (Sept-Nov 2000 in red) and long-term local wind monitoring (1996-2000 in blue).

Table 3.3: Percentile along-shore wind velocities (northward>0 ; southward<0)

Alongshore component	**Study period**	**1996-2000**
20%ile	-8.5	-5.5
50%ile	-2.5	0.5
80%ile	4	7.8

3.1.5 CTD and Nutrients

Conductivity Temperature Depth (CTD) profiles were taken at the ends of ADCP transect lines off Coffs Harbour (in Figure 3.3. and described above) and during regular monitoring off Port Hacking in southern Sydney at sites shown in Table 3.4 and Figure 3.8.

Table 3.4: Port Hacking sampling locations

SITE	Latitude (deg S)	Longitude (deg E)	Water Depth (m)	CTD (Y/N)	NISKIN sample depths (m)
PH01	34º 04.92′	151º 10.82′	25	Y	N/A
PH02 (PH50)*	34º 05.66′	151º 11.60′	55-60	Y	50, 40, 30, 20, 10, 0
PH04 (PH100)*	34º 07.05′	151º 13.13′	105-108	Y	100, 75, 50, 25, 10, 0
PH05	34º 08.89′	151º 15.40′	125	Y	N/A

* long term CSIRO monitoring stations

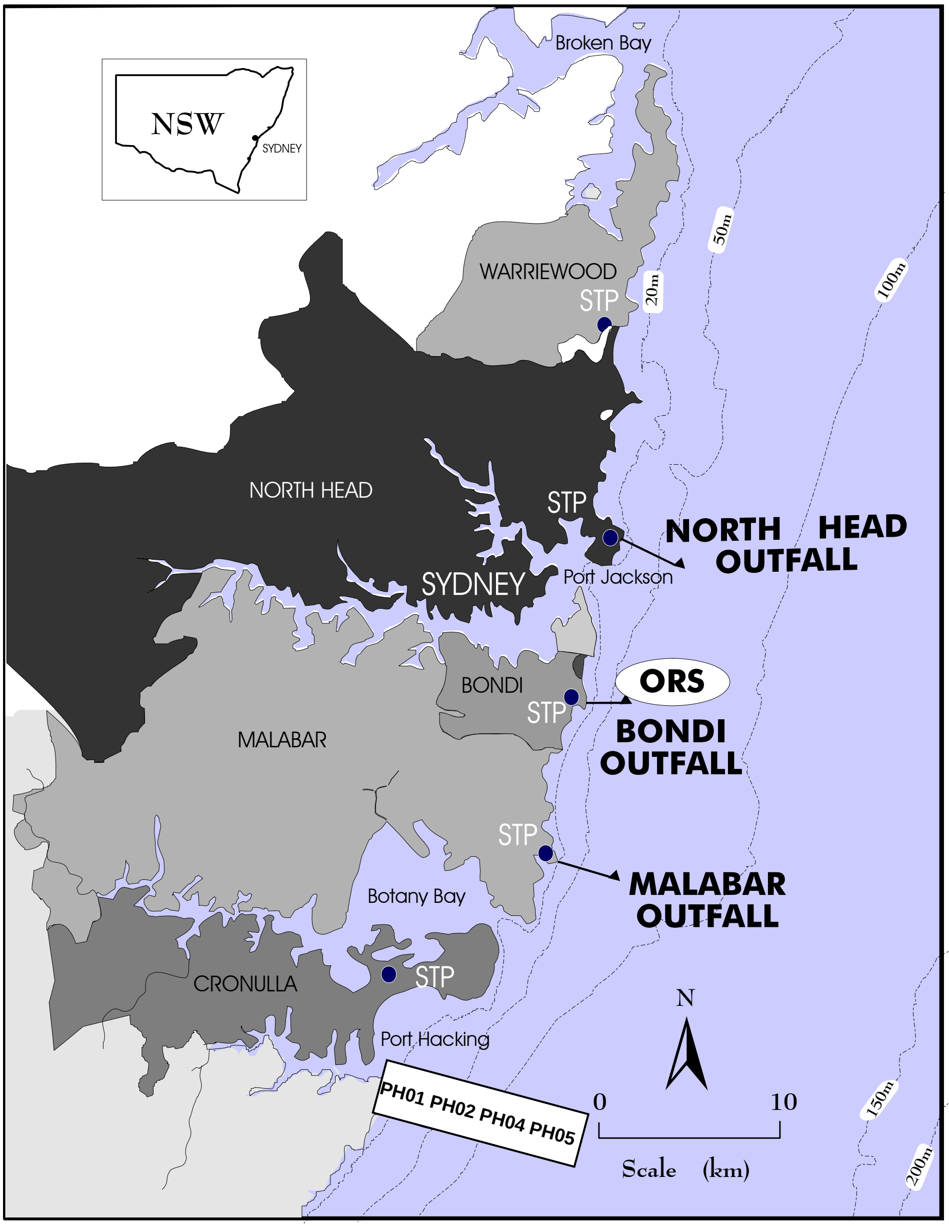


Figure 3.8 Locations of the Sydney Ocean Reference Station and four sampling locations along the Port Hacking transect including long term CSIRO stations at PH02 (CSIRO PH50) and PH04 (CSIRO PH100). Sydney's major ocean outfalls are also shown together with the sewerage catchments that they serve.

A profiling SEABIRD SBE25 Sealogger CTD probe was used: the probe logged at 8Hz with respective conductivity, temperature and pressure accuracy (resolution) of 0.0003 (0.00004S/m), 0.004 (0.0003)°C and 1.25 (0.75)m. The instrument was also configured with a Chelsea Instruments Fluorometer (0.01mg/L), Seabird dissolved oxygen and pH sensor, and a Seatech 25 cm pathlength Transmissometer. A constant flow was ensured across temperature, conductivity, and dissolved oxygen sensors by an in-line pump that delivered a constant flow regardless of the instruments profiling speed. All in-line sensors were routinely soaked in distilled water while the pH sensors was soaked in pH 4 buffer solution and the fluorometer lens was protected by a cap between deployments. Seasoft software was used for initial data processing (pressure reversals, wild point editing, thermal expansion of the conductivity cell) and profile data were then averaged over 1m bins.

Monthly CTD profiles have been sampled at PH01, PH02 (PH50), PH04 (PH100) and PH05 since 1997.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has maintained mainly physico-chemical data offshore from Port Hacking (PH50 and PH100) since the 1940's (Humphrey, 1963). Ambient nutrient concentrations were obtained for the surface and at 10 m depth intervals to 50 m at CSIRO PH50 (PH02 in Figure 3.8) in water depths of 55-60 m and at CSIRO PH100 (0,10,25,50,75,100m). Nutrient data used in this thesis were limited to those from periods of more consistent chemical analyses prior to the commissioning of Sydney's deepwater outfalls: nitrate (NO3-N) from 1965 to September 1990 and phosphate (PO4-P) from 1957 to September 1990. Prior to 1990, similar quantities of effluent were discharged via shoreline outfalls at North Head, Bondi and Malabar resulting in surface plumes but extensive monitoring prior to the commissioning of deepwater outfalls suggested little or no impact at PH50 (Pritchard *et al*., 1996a). Therefore, these pre-commissioning data from CSIRO Port Hacking monitoring stations are assumed to approximate ambient nutrient conditions prior to the diversion of effluent offshore through the deepwater outfalls.

Analytical methods have been described elsewhere by Major *et al*. (1972) and Airey and Sanders (1987). Sampling frequencies varied from approximately weekly (~47 $year^{-1}$) before 1985 to about monthly (~10 $year^{-1}$) after 1985. The change in sampling frequency was not expected to bias nutrient distributions with respect to variability associated with El Niño Southern Oscillation because the period of reduced sampling included similar periods of cold (La Nina) and warm (El Niño) (Lee *et al*., 2001).

Figure 3.9 Niskin (left) and CTD (right) vertical profile system (centre)

The author together with staff from the NSW Office of Environment and Heritage have monitored hydrographic parameters at Port Hacking since the mid 1990's, under contract to CSIRO using equipment including that shown in Figure 3.9.

The author was instrumental in securing these sites as a National Reference Transect during the establishment of the Australian Integrated Marine Observing System.

3.1.6 Sydney Ocean Reference Station

The Sydney Ocean Reference Station (ORS) located in 65 m of water, ~3km due east of Ben Buckler Head, Bondi at 33° 53.685' S, 151° 18.972' E and is operated by Sydney Water Corporation.

The ORS is an instrumented buoy configured with two R.M. Young wind speed and direction sensors, a Datawell heave sensor (for measuring wave height and period), two InterOcean S4 electromagnetic current meters (at 17m and 53m below the surface) and a string of 14 Aanderaa thermistors (nominally 3m apart, to provide ocean stratification data) plus two semi-conductor thermistors located in the hull of the buoy (Figure 3.10). Data are collected from the wave sensor every second and at 30sec intervals from the other instruments. Five-minute block averages of wind, current and temperature data were obtained for this thesis (Chapter 6) with most analysis focused on the thirteen year period from November 1990 to November 2003.

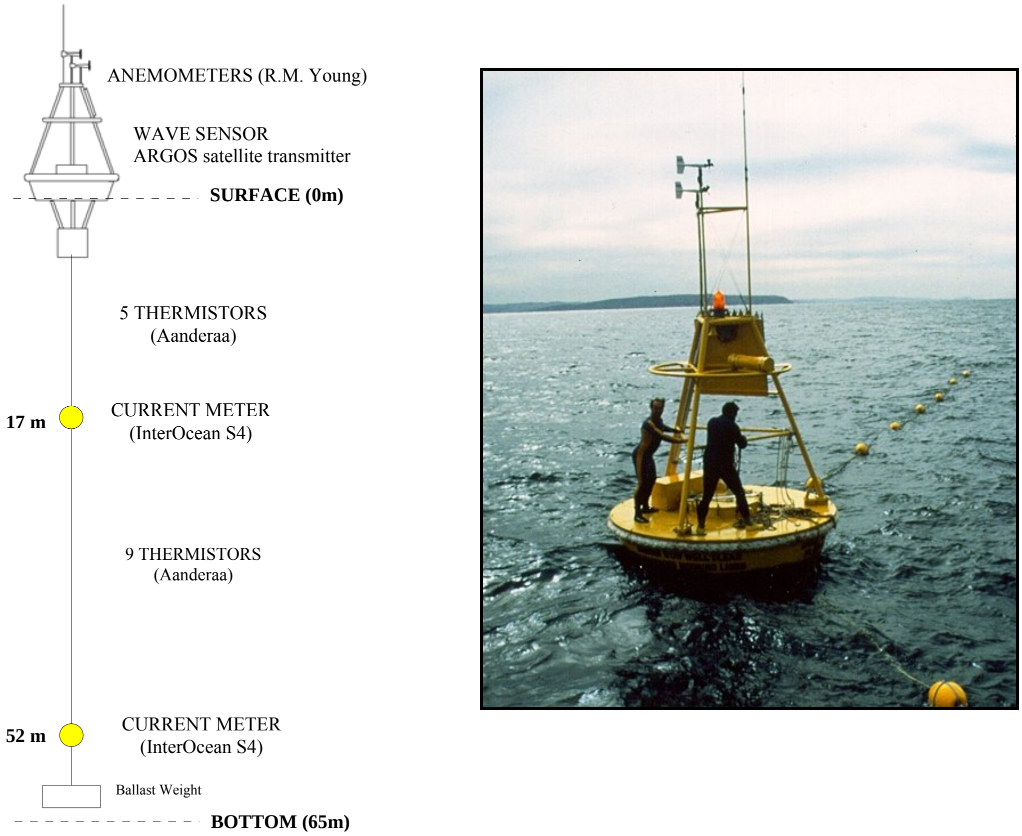


Figure 3.10 Ocean Reference Station configuration (photo courtesy Sydney Water Corporation)

Validation of ORS data

In 2003, concerns about diminishing continuity of ORS data and questions about recent quality assurance prompted an evaluation of the contemporary ORS data.

Technological advances have surpassed the original ORS instrument configuration but the ORS data set remains a unique long term time series of oceanographic conditions off Sydney. Knowledge of the directional stability (accuracy) of the ORS current measurements is critical, especially when investigating intra-annual variability as in Chapter 6. The validity of observations from the ORS was tested by deploying a 300 kHz acoustic Doppler current profiler (ADCP) about 500m south of the ORS in about 66 m water depth, between 8 August 2003 and 28 January 2005 in partnership with Clive Holden and Sydney Water Corporation (Figure 3.11). The purpose of this study was to compare simultaneous data sets to determine the consistency and relative accuracy of the present ORS current meter records.

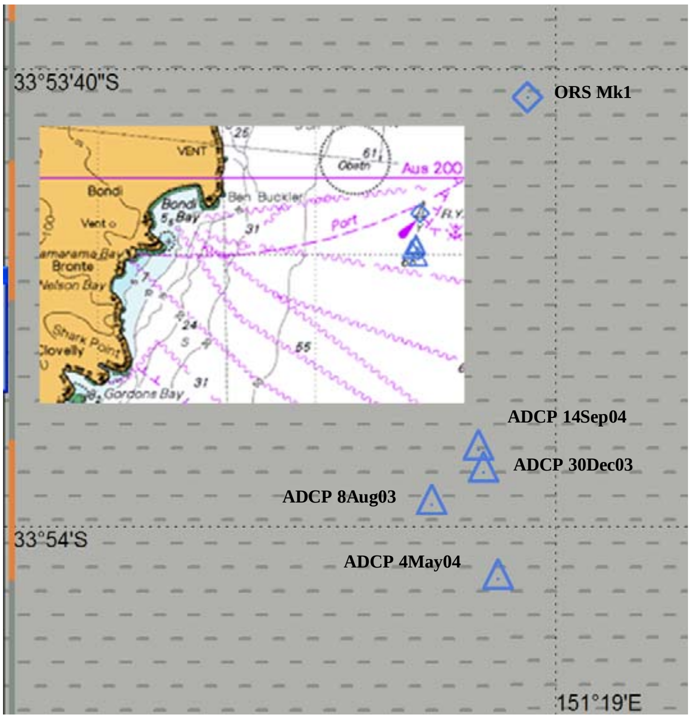


Figure 3.11. Mooring locations for the ADCP deployments for August 2003 to January 2005 in relation to the Ocean Reference Station (ORS Mk1).

ADCP hard and soft iron compass calibrations were conducted to ensure that the ADCP had a directional accuracy of better than ±1 degree (magnetic) on deployment (& re-deployments). No internal timing errors were found in any of the raw data files.

The ORS current meter data were corrected for local magnetic variation (+ 13 deg) to facilitate direct comparison with the processed ADCP files.

The ADCP data captured for the ORS validation study following quality assurance screening, is detailed in Table 3.5, while data coverage for ADCP and top (TS4) and bottom (BS4) ORS current meters is shown in Figure 3.12. Progressive vector displacement plots (Figures 3.13 & 3.14) are highly sensitive for visual discrimination of directional differences between current meter records because even small consistent offsets result in large cumulative differences.

Table 3.5 Sydney ADCP data capture summary

No	First good ensemble	Start time (EST)	Last good ensemble	End time (EST)	Last good bin	Depth above bottom (m)
1	37	8Aug03 10:00	33658	3Dec03 03:45	55	57.75
2	31	30Dec03 05:30	36337	4May04 07:00	54	56,75
3	11	04May04 11:30	38267	14Sep04 07:30	47 ŧ	49.75
4	6	14Sep04 12:15	39107	28Jan05 06:40	57	59.75

ŧ. *This is the minimum last good bin taken over the record as a whole. However, good data occur in all bins up to bin 55 early in the record, before the first major current event.*

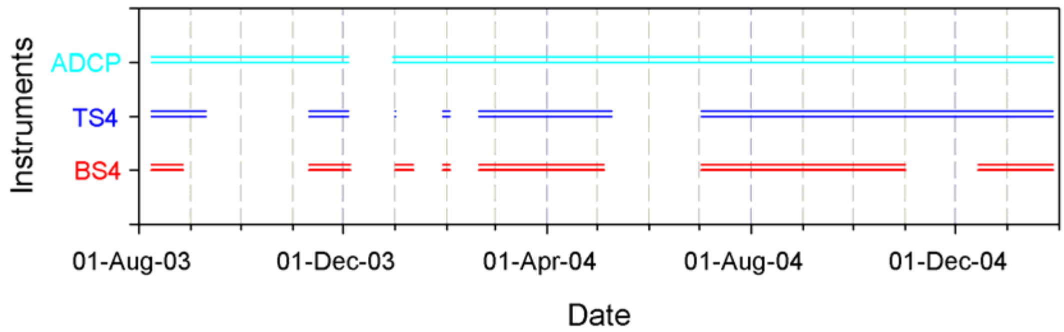


Figure 3.12 Timeline of ADCP and ORS current data.

Comparison between ADCP and ORS data revealed:

(1) Broad agreement between ADCP (2003-2005) and historic ORS (1991 - 2002) data. The principal current direction recorded by the ADCP between August 2003 to January 2005 was about 20/200 deg (true) at 17 m (Figure 3.13). This is identical to the long-term mean determined from ORS upper current meters between 1991 to 2002 (presented in Chapter 6). In addition, the ADCP showed an average transport of 12.7 km/day and 3.1 km/day at 17m and 52m respectively, broadly consistent with the long-term ORS estimates of 12 km/day and 2.4 km/day at the equivalent depths (Chapter 6). In this regard the ADCP results are broadly consistent with historic records.

(2) Inconsistencies in the recent ORS data (2003-2005). Successive ORS plots for August 2003 to January 2005 highlighted several inconsistencies in the ORS data. The most obvious of these was that the data characteristics altered almost every time the ORS was serviced (e.g. Figure 3.14). This suggests that the fault lies with the current meters, possibly because the

(3) Significant differences in comparable ADCP and ORS current velocity. Table 3.6 lists the ORS and ADCP estimates of mean current speed and direction at 17m and 52 m for three periods in 2004, ranging from 6 weeks to four months. Values for the upper current meter records show that the ADCP estimate of the mean current alignment is about 200 deg, which is consistent with that determined from the ORS historic records. In contrast the recent ORS data estimate the current alignment to be between 163 deg and 204 deg - a range of 40 degrees. A similar case is presented for the lower current meter records, with the ADCP estimating the mean current orientation to be between 194 and 210 degrees, while the ORS estimates cover a wider range of between 153 to 182 degrees.

These findings indicate that historical records are generally consistent with rigorous contemporary ADCP observations but that at least recent ORS current observations should be regarded with a degree of skepticism. Chapter 6 (including Pritchard *et al*., 2005) restricted its analysis to the ORS data collected prior to November 2003. During and following this study, the regulator (NSW Environment Protection Authority) expressed concerns regarding the continuity and quality of data presently being obtained by the ORS and requested that the operator of the ORS (Sydney Water Corporation - SWC) address this problem. SWC have since developed a new ORS configuration and quality assurance system including a bottom mounted ADCP, which is returning quality assured data with vastly improved continuity. This experience is now contributing to the development of other moorings for the NSW node of the national Integrated Marine Observing System.

Table 3.6. Comparison on mean current speed and direction between the ADCP and ORS.

Period	Top (17m depth)				Bottom (52m depth)			
	ADCP		Top S4		ADCP		Bottom S4	
	Mean Speed (m/s)	Mean Direction (deg. T)	Mean Speed (m/s)	Mean Direction (deg. T)	Mean Speed (m/s)	Mean Direction (deg. T)	Mean Speed (m/s)	Mean Direction (deg. T)
2 Mar – 2 May 2004	0.15	202	0.13	188	0.01	194	0.01	157
2 Jun – 30 Sep 2004	0.19	197	0.30	163	0.07	199	0.10	182
14 Dec 2004 – 28 Jan 2005	0.24	198	0.19	204	0.02	210	0.06	153

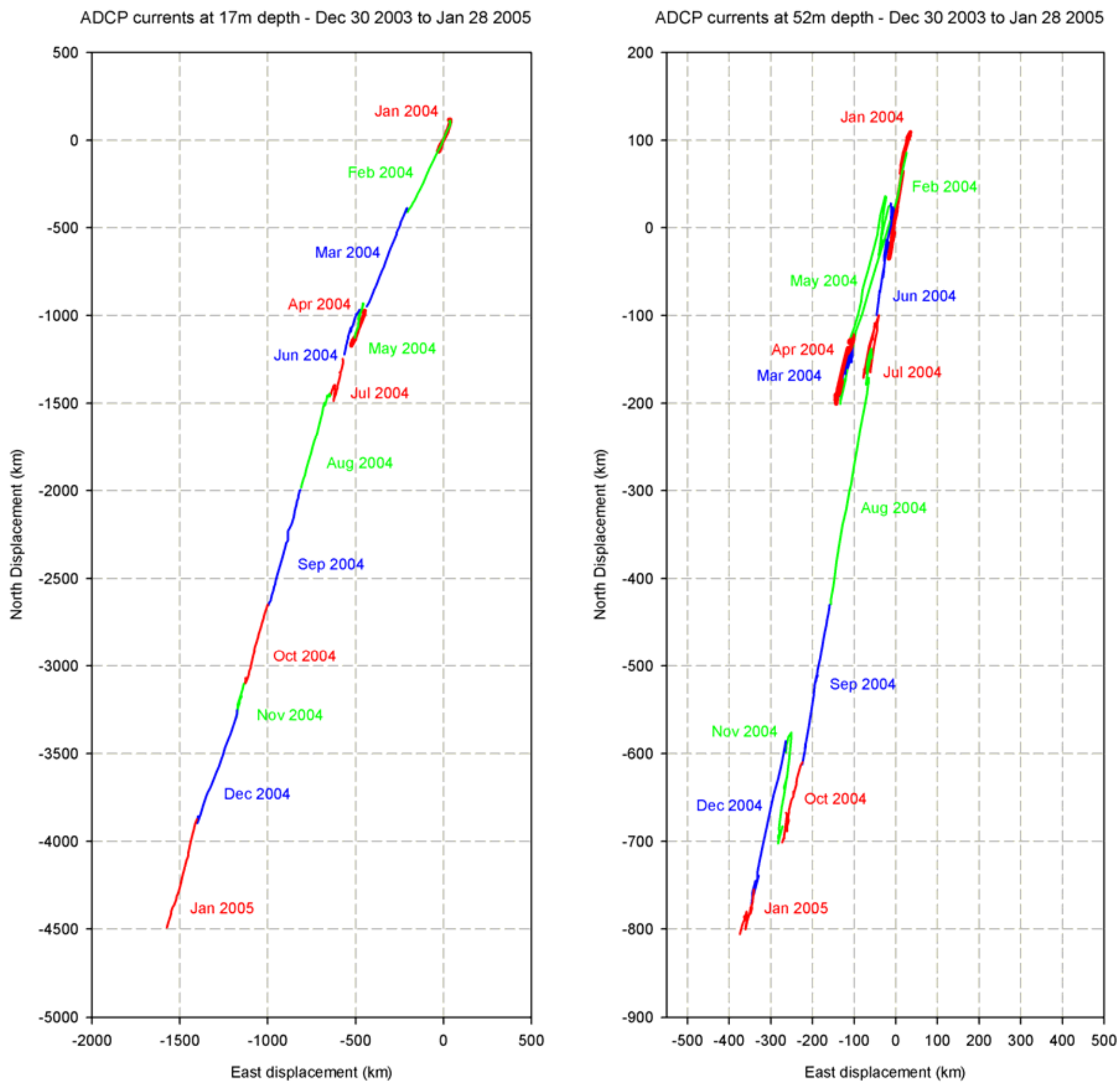
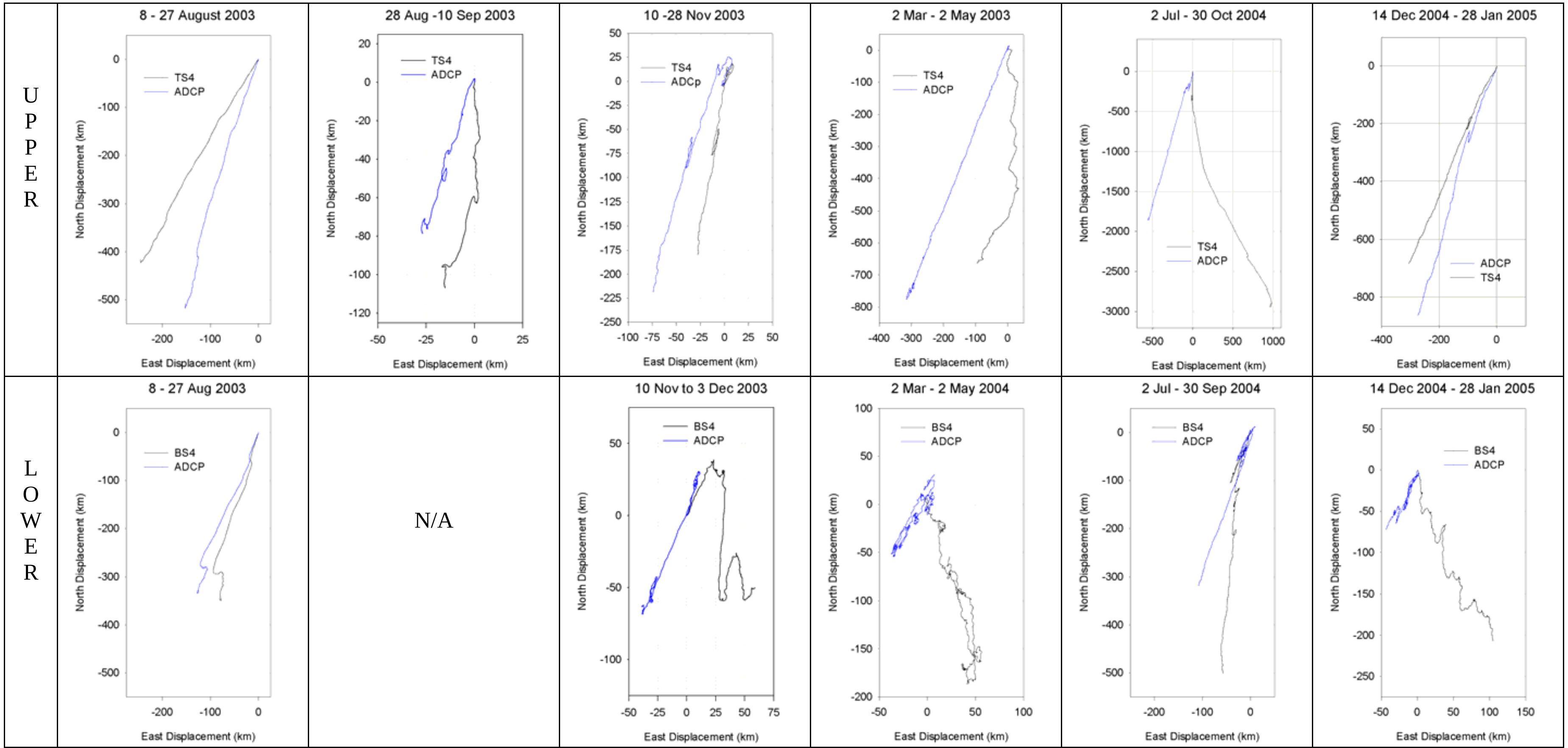


Figure 3.13 Progressive vector displacements for ADCP bins 12 (52m depth) and 47 (17m depth) for 30 December 2003 to 28 January 2005.



Consistent magnitude Differences in direction	Comparable magnitude Directional offset (failed upper S4 replaced by lower S4)	S4s, especially lower S4, often problematic – perhaps offset error (a known issue with electromagnetic current meters, Jones 1980) or 3rd quadrant conversion error (InterOcean S4 Current Meter User's Manual, 1987) or transcription errors. To some extent, the natural differences between the Nov-Dec 03 52 m records may have been exaggerated by the series of alongshore reversals but even so results are clearly problematic.

Figure 3.14 Visual comparison of progressive vector displacements for coincident ORS (S4 current meters) and ADCP time series data

Time Series Analysis

Variance preserving spectra of current and wind time series were produced, using the method of Emery and Thomson (2001), to assess dominant energy frequencies and to infer forcing mechanisms. MATLAB routines were used for each depth layer (bin) of ADCP data using a lag window of 256 hours. Variance preserving spectra were selected for graphical presentation because equal areas under the curve represents equal energy.

3.2 Modelling and Bathymetry

3.2.1 Bathymetry

The majority of NSW bathymetric data has been collected by two agencies: the Royal Australian Navy Hydrographic Service (RAN) and, the former Australian Division of National Mapping in the Department of Natural Resources (1:250,000).

3.2.2 Coffs Harbour hydrodynamic modeling – 3DD

The 3-dimensional baroclinic model 3DD was used for Coffs Harbour flow simulations. 3DD is based on established momentum and mass conservation equations as described by Black (1987); it provides an explicit finite difference (Eulerian) solution of the momentum and continuity equations for velocity and sea level, through a series of vertical layers that are hydrodynamically linked by a vertical eddy viscosity. The physical representations of various terms in the momentum equation are: local acceleration; inertia; Coriolis; pressure gradient resulting from sea level variation; pressure gradient resulting from atmospheric pressure (which was not included in the small scale Coffs Harbour simulation); horizontal eddy viscosity, wind stress, and bed friction.

The model 3DD has been successfully applied and verified in a diverse range of situations (Black 1987, 1989; Black & Gay 1991; Black et al. 1993; Middleton & Black 1994; Young et al. 1994; Black et al. 2005) and the model has been previously applied to investigate the parameters responsible for eddy formation behind islands and reefs (Black & Gay 1987; Black 1989; Hume et al. 2000; Black et al. 2005).

For the Coffs Harbour simulations in this thesis a body force was applied based on ADCP observations to simulate large-scale pressure gradients. The body force is a surrogate for a calculated sea gradient, obtained by inverting the vertically-averaged momentum equation and solving using measurements of currents, sea levels and winds. The body force is,

$$Fy = g\frac{\partial \varsigma}{\partial y} = \left[-\frac{\partial V}{\partial t} + \frac{Wy}{\rho h} - \frac{gV(U^2 + V^2)^{1/2}}{C^2 h} - fU \right]$$

where ς is sea level, U and V are velocities in x and y directions, W_x and W_y are the wind stress components, C is Chezy's C, f the Coriolis parameter and h the depth.

Specific details of model parameterisation and boundary conditions for Coffs Harbour simulations are provided in Chapter 8.

3.2.3 Coffs Harbour dispersion modelling – CORMIX

The CORMIX mixing zone model was used to simulate effluent plume behaviour (effluent dilution and plume extent/position) for a range of discharge scenarios across coastal boundary layer features. CORMIX is well suited as a tool for evaluation of discharge design options (Jirka and Akar, 1991; Jirka and Doneker,1991).

CORMIX is a robust composite flow and mixing zone prediction model developed by the School of Environmental Science and Engineering at Cornell University, New York (www.steens.ese.ogi.edu). It is a USEPA recommended analysis tool for industrial, municipal, thermal and other point source discharges to receiving waters.

The model provides a prediction for both near-field and far-field plume behaviour and design recommendations to improve outfall hydrodynamic performance.

Subsystem CORMIX2 (Jirka and Doneker,1991) was used to examine dilutions achieved by the entire diffuser while Subsystem CORMIX1 (Jirka and Akar, 1991) was used to examine merging of adjacent port plumes using single diffuser port simuations. Model scenarios were conducted using northward and southward flowing (along-shore axis 22.5 - 202.5 degrees; see Figure 3.15) currents at 20th, 50th and 80th percentile ambient velocities. Velocities were calculated from ADCP data collected at three locations along a shore normal transect along the alignment of a proposed outfall site. Discharge flow rates included Average Dry Weather Flow (ADWF of 20.7ML/day) and high flow Wet Weather (130ML/day) conditions (from CHEIS, 2000).

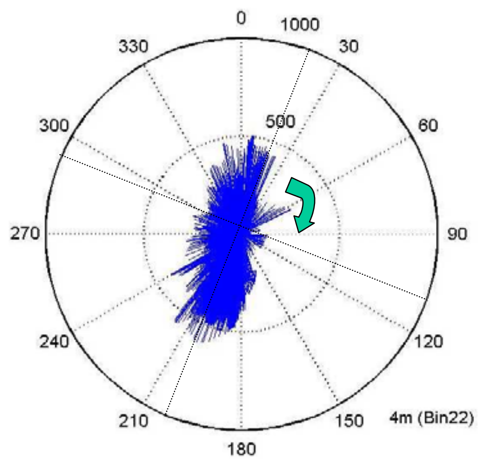


Figure 3.15 Currents observed at ADCP Site C indicate the predominant axis of flow was along shore, parallel to isobaths and coastline (022°).

3.2.4 Sydney outfalls near field modeling – JETLAG

The near-field model JETLAG (Lee and Cheung, 1990) was used, together with Ocean Reference Station data and Sewage Treatment Plant effluent data to provide a long term time series of initial effluent dilutions, plume thickness, and plume centre line depth for Sydney's deepwater outfalls off North Head, Bondi and Malabar (see Figure 3.8 above). This model was selected because it has been subjected to extensive verification for application to Sydney's deepwater outfalls (Pritchard et al., 1993, 1996b) and because JETLAG facilitates the compilation of a time series of plume characteristics immediately after initial momentum and buoyancy driven dilution.

The formulation of JETLAG tracks the evolution of the average properties of plume elements at various time steps by conservation of horizontal and vertical momentum, conservation of mass accounting for entrainment, and conservation of tracer mass. Sensitivity testing and comparisons with data obtained from plume tracing experiments conducted off Malabar indicated that JETLAG provided a good representation of plume behaviour (Cathers and Peirson, 1991).

Hourly average JETLAG model results were obtained for periods when both STP and ORS data were available during the period from January 1991 to December 1998 (54856 records or 78% coverage). The Water Research Laboratory (Manly Vale, NSW) generated the time series of model results under directions specified by the author.

Although this long-term time series can be expected to capture most of the possible variability (extremes) in plume behaviour, there is the potential for the distribution of plume characteristics to be biased by longer term variability associated with teleconnections such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation. This was investigated by comparing cold and warm ENSO episodes (NOAA, 2000) within the model simulation period. The seven year simulation period was associated with a ~17% bias to El Niño conditions; that is, the modelled period included an excess of El Niño conditions equivalent of nearly 400 (of 2290) days of moderate El Niño conditions.

3.3 Remote Sensing and other Spatial Data

3.3.1 Ocean colour – SeaWiFS

Data from the **Sea**-viewing-**Wi**de **F**ield of view **S**ensor (SeaWiFS) were extensively used: in Chapter 5 to link hydrodynamic features to primary productivity and ecosystems assessments; and, in Chapter 4 for coarse scale classification of the coastal boundary layer. SeaWiFS was launched in 1997 as the operational successor to the Coastal Zone Colour Scanner and was one of the first of a new generation of ocean colour satellites. Much of the processing, quality control and initial analysis of SeaWiFS data was undertaken using SeaDAS software (freely available from http://seadas.gsfc.nasa.gov).

Ocean colour (or reflectance) is the ratio of water leaving radiance to downwelling irradiance. Water leaving radiance depends on backscatter (change in direction of a photon) and absorption (the loss of a photon) in the water column as well as the downwelling irradiance. Not surprisingly, water absorbs strongly in the red and scatters strongly in the blue giving it a blue colour. Backscattering is of the order of 0.1% to 2% in the sea with dominant forward scattering. Backscatter and absorption are used to define the optical properties of the water column and are wavelength dependant. SeaWiFS provides 8 band spectral data: 402-422, 433-453, 480-500, 500-520, 545-565, 660-680, 750-780, 845-880 nm. The absorbing and scattering constituents of seawater include both dissolved and particulate material including the water itself, plankton, coloured dissolved organic material (CDOM), and other suspended particulate such as algal detritus and suspended sediment. Other particles and characteristics can have a minor effect on optical properties including bacteria, viruses and bubbles.

Incident irradiance is typically attenuated in an exponential manner described by the downwelling diffuse attenuation coefficient - either spectrally with $K_d(\lambda)$ or broadband (400 nm - 700 nm) with K_d (PAR).

$$E_d(z) = E_d(0)\, e^{-K_d\, z} \qquad \textit{optical depth}\ \zeta = K_d\ z$$

The euphotic (well lit) zone is defined as being the layer within which E_d(PAR) falls to within 1% of the subsurface value. ~ 90 % of water leaving radiance, or the satellite signal, emerges from the first optical depth or $1/K_d$.

SeaWiFS is one of a series of ocean colour scanners. Other scanners used today for biological oceanography include the Medium resolution imaging spectrophotometer (MERIS), and Moderate resolution imaging spectrophotometer (MODIS) which provide a spatial resolution of between 750-2000 m. The data collected by SeaWiFS and these scanners are highly correlated (in strong agreement) with each other and with *in situ* measurements of chlorophyll a and with other pigments, such as yellow substances derived from terrestrial run-off. SeaWiFS presently provides complete global coverage of the oceans every 2 days, MODIS allows global coverage every 1-2 days and MERIS every 3 days.

Ocean colour validation data are extremely sparse in NSW coastal waters. However, NSW Environment Protection Authority (including this author) collected weekly samples at two sites off Port Hacking (CSIRO PH50 and PH100 shown in Figure 3.8) at the surface and from a depth of 10m during the period from September 1997 to March 1998.

HPLC (Spectrophotometry) laboratory determinations of chlorophyll concentrations from discrete water samples were compared with arithmetic means of chlorophyll concentrations estimated from up to eight SeaWiFS pixels (1km x 1km) surrounding the sampling site (Figure 3.16). Estimates were rarely available for all 8 pixels because SeaWifs estimates of chlorophyll concentrations were often either not available or flagged as non-optimal (due to confounding factors like stray light, missing atmospheric data and sun glint), especially at the inshore site (PH50).

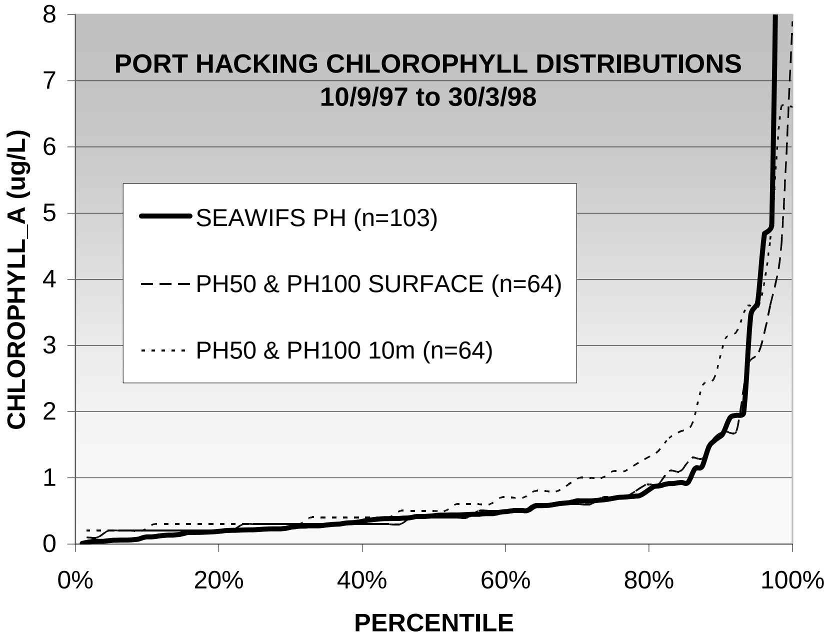


Figure 3.16: Percentile distributions based on SeaWiFS estimates and combined *in situ* observations at PH50 and PH100 (surface and 10m depths) (NSW EPA data)

Based on Figure 3.16, SeaWiFS provides reasonable estimates of the median and 80th percentiles but overestimates the upper 5-10% of the chlorophyll distribution for surface waters. Correlations between contemporary SeaWiFS and in situ determinations were generally better at the offshore site (PH100) than at the inshore site (PH50) (R^2 ranged from 0.48 to 0.79) which could be expected given the high proportion of sub-optimal or absent SeaWiFS estimates at PH50.

3.3.2 Sea surface temperature - AVHRR

Data from the Advanced Very High Resolution Radiometers (AVHRR) aboard the US National Oceanographic and Atmospheric Administration (NOAA) series of satellites were used throughout this thesis to provide a regional perspective especially in relation to East Australian Current activity, slope water intrusions and mesoscale coastal boundary layer features.

AVHRR scanners deliver 4-5 channels (depending on model) including visible and sea surface temperature (SST) images at spatial resolutions comparable to most satellite borne ocean scanner data (Hastings and Emery, 1992). Sea surface temperatures (SST) are estimated across ~1km pixels with an accuracy of 0.1°C. Successive satellites have resulted in a time series of AVHRR data back to 1986.

Satellite data used in this thesis were received and processed (corrected for atmospheric, radiation pressure, etc) by the CSIRO Marine Laboratories.

3.2.3 BlueLink ReANalysis (BRAN) hindcast

Mesoscale flow fields such as those from BRAN reveal dynamic, large scale, coastal boundary layer features. BRAN provides 4km resolution, daily experimental estimates of flow fields dating back to 1992, freely available from CSIRO for research purposes (http://www.marine.csiro.au/ofam1/).

The Bluelink ReANalysis is a multi-year model integration with data assimilation (Oke *et al*., 2005). The Bluelink model is a global ocean general circulation model that is eddy-resolving in the Australian region. Observations that are assimilated into BRAN include satellite altimetry, sea surface temperature and *in situ* temperature and salinity data from Argo, Expendable Bathythermograph (XBT), Tropical Atmosphere Ocean (TAO) project and other sources.

3.2.4 CARS Atlas

Mapped seasonal ocean water properties were used to characterise persistent, large scale, coastal boundary layer features.

CARS is a digital atlas of seasonal ocean water properties, mapping temperature, salinity, oxygen, nitrate, silicate and phosphate in the **C**oastal **A**nd **R**egional **S**eas around Australia. The atlas is derived from two major datasets, interpolated onto standard depths: the US Nation Oceanographic Data Center World Ocean Atlas 1998 hydrographic data, and the CSIRO archive of Australian hydrographic data. The mapping algorithm was a sophisticated weighted least-squares quadratic smoother which was applied in horizontal and vertical coordinates, with bathymetry-influenced weighting as described by Dunn and Ridgway (2002) and Ridgway *et al*. (2002). CARS provides information on a 0.5º by 0.5º grid.

3.4 Pollutant Load Estimates

3.4.1 Diffuse Catchment Sources

Run-off and pollutant exports from coastal catchments are critical inputs to the coastal boundary layer.

The paucity of data for calibration and simulation limit the use of sophisticated models in most Australian catchments. Simple unit load models such as the Catchment Management Support System (CMSS) were initially investigated and new applications of bootstrap techniques were applied to reduce subjectivity and to improve estimates of confidence limits (Baginska, **Pritchard** and Krogh, 2003). However, the ***Long-Term Hydrologic Impact Assessment (L-THIA) model*** (Lim et al., 1999) was ultimately selected because it is a spatially distributed model that provides greater scope to simulate the effects of climate variance. This facilitates better specification and evaluation of catchment landuse/management scenarios and provides for assessment of climatic variability (e.g. Baginska, Lu, and **Pritchard,** 2005).

L-THIA has medium data requirements and uses well established concepts to simulate runoff volumes. The basic input for the model consists of soil, precipitation and land use data as described by Baginska, Lu, Mawer & **Pritchard** (2004) (Figure 3.17).

Runoff volumes are predicted using the Curve Number (CN) method which uses commonly available information such as soil type, cover and hydrologic conditions to estimate runoff (USDA, 1986). The method has been applied to a wide range of catchments and climatic conditions for estimation of runoff volumes in ungauged areas in the United States (Browne, 1999, Knisel, 1980).

Contemporary 6-band Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data were used to determine 14 generic land use classes which were verified using IKONOS imagery and aerial photography. Daily rainfall was extracted from the Bureau of Meteorology records of rainfall gauging stations across NSW coastal catchments for the period 1990 –2002 and interpolated across the modeling domain using a Thiessen polygon method. Hydrologic soil groups were assigned based on a range of soil properties such as runoff potential, drainage, hydraulic conductivity, soil depth, texture, infiltration, transmission.

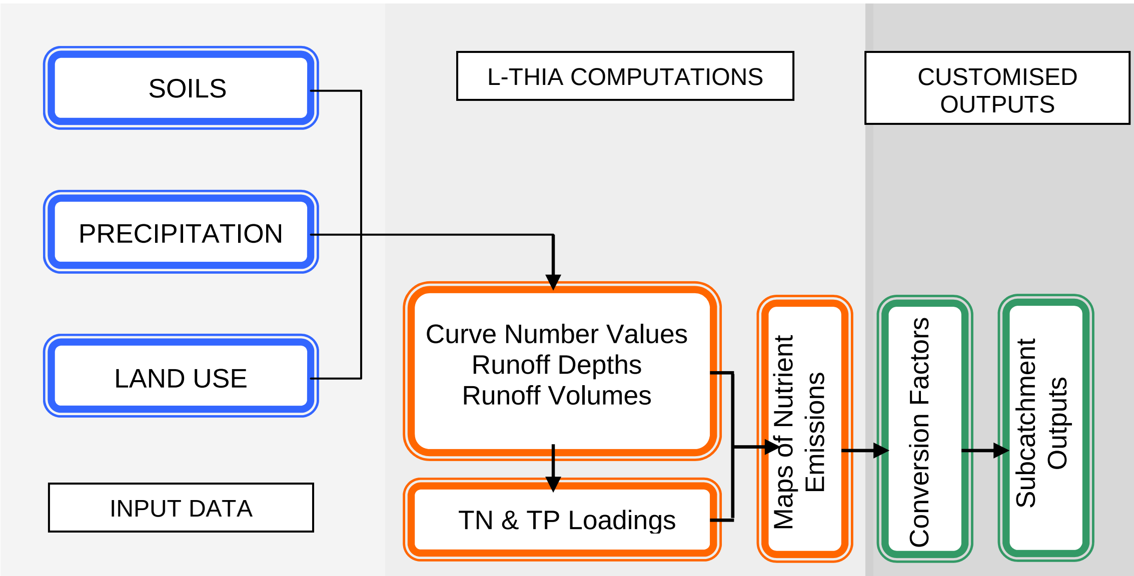


Figure 3.17 L-THIA Model Structure

3.4.2 Point Sources

All sewage effluent discharged to the ocean from NSW sewage treatment plants requires significant dilution in the coastal boundary layer in order to meet criteria set out in national water quality guidelines (ANZECC/ARMCANZ, 2000). Some treatment plants provide high levels of treatment while others, such as Sydney's deepwater outfalls, rely more heavily on outfall design to rapidly dilute and disperse pollutants to 'acceptable levels'.

Loads and concentrations of pollutant discharged to ocean from NSW sewage treatment plants are publicly available through mandatory reporting specified in licenses granted by the NSW Environment Protection Authority under the POEO Act. Point source discharge data are also available through the National Pollutant Inventory (http://www.npi.gov.au/).

Impacts associated with existing NSW ocean outfalls were assessed through a review of a plethora of studies published in scientific journals and technical reports ('grey literature') – see attached compact disc containing the NSW Coastal Outfalls Atlas.

3.5 References

Airey, D. and Sanders, G. (1987) Automated analysis of nutrients in seawater, CSIRO marine Laboratories Report 166.

ANZECC/ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment & Conservation Council and Agriculture & Resource Management Council of Australia & New Zealand.

Baginska, B. Lu, Y and **Pritchard, T.** (2005) Modelling nutrient loads to better manage impacts of urbanization in Tweed catchment, New South Wales, Australia. Proceedings of International Congress on Modelling and Simulation Advances and Applications for Management and Decision Making, 2346-2352.

Baginska, B., Lu,Y. Mawer, D. and **Pritchard, T.R.** (2004) Linking Land Use Decisions to Nutrient Exports. Department of Environment and Conservation. Refereed report, November 2004.

Baginska,B., **Pritchard,T**. and Krogh,M. (2003) Roles of land use resolution and unit-area load rates in assessment of diffuse nutrient emissions. Journal of Environmental Management 69, 39-46.

Black, K. P. (1987) A numerical sediment transport model for application to natural estuaries, harbours and rivers. In: Noye, J. ed. Numerical modelling applications to marine systems. North Holland, Elsevier, 77–105.

Black, K. P. (1989) Numerical simulation of steady and unsteady meso-scale eddies. Proceedings of the 9th Australasian Conference on Coastal and Ocean Engineering, Adelaide, 204–208.

Black, K. P. and Gay, S. L. (1987) Eddy formation in unsteady flows. Journal of Geophysical Research 92, 9514–9522.

Black, K. P. and Gay, S. L. (1991) Reef-scale numerical hydrodynamic modelling developed to investigate crown-of-thorns starfish outbreaks. In: Bradbury, R. ed. Acanthaster and the coral reef: a theoretical perspective. Springer-Verlag. , 120–150.

Black, K. P., Hatton, D. and Rosenberg, M. (1993) Locally and externally-driven dynamics of a large semienclosed bay in southern Australia. Journal of Coastal Research 9(2), 509–538.

Black, K., Oldman, J. and Hume, T. (2005) Dynamics of a 3-dimensional, baroclinic, headland eddy. New Zealand Journal of Marine and Freshwater Research 39 (1), 91-120.

Browne, F.X. (1999) 'Stormwater management' in Standard Handbook of Environmental Engineering R.A. Corbitt (ed.), McGraw-Hill, pp.7.1-7.127.

Cathers, B. and Peirson, W. L., (1991). Verification of Plume Models Applied to Deepwater Outfalls. In Lee, J. H. W. and Cheung, Y. K. (Eds) Environmental Hydraulics, Proceedings of International Symposium on Environmental Hydrology, Hong Kong, 16-18, December 1991, pp. 261-266.

CHEIS (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coff Harbour City Council, NSW, Australia.

Dunn J.R., and Ridgway, K.R. (2002) Mapping ocean properties in regions of complex topography, Deep Sea Research I : Oceanographic Research, 49 (3) pp. 591-604.

Emery, W. J. & Thomson, R. E., (2001). Data Analysis Methods in Physical Oceanography. Second Ed. Elsevier. ISBN 0-444-50756-6.

Hastings, D.A. and Emery, W.J. (1992) The Advanced Very High Resolution Radiometer (AVHRR): A Brief Reference Guide. Photogrammetric Engineering and Remote Sensing, 58 (8), 1183-1188.

Hume, T. M., Oldman, J. W. and Black, K. P. (2000) Sediment facies and pathways of sand transport about a large deep water headland, Cape Rodney, New Zealand. New Zealand Journal of Marine and Freshwater Research 34: 695–717.

Humphrey, G. F. (1963) Seasonal variations in plankton pigments in waters off Sydney. Australian Journal of Marine and Freshwater Research 14(1), 24-36.

InterOcean S4 Current Meter User's Manual, 1987. InterOcean Systems Inc., San Diego, CA.

Jirka, G.H. and Akar, P.J. (1991) Hydrodynamic Classification of Submerged Multiport Diffusers Discharges, Journal of Hydraulic Engineering, ASCE, 117, No.9, 1113-1128, 1991.

Jirka, G.H. and Doneker, R.L. (1991) Hydrodynamic Classification of Submerged Single Port Discharges, Journal of Hydraulic Engineering, ASCE, 117, No.9, 1095-1112, 1991

Jones, I.S.F., 1980: Electromagnetic Current Meters. In Air-Sea Interaction. Edited by F. Dobson, L. Hasse and R Davis. Plenum Publishing Corporation, N.Y.

Knisel, W.G.(ed.) (1980) A field-scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems. US Department of Agriculture. Conservation Research Report No. 26, pp.640. Washington DC.

Lee, R.S., Ajani, P.A., **Pritchard, T.R.**, and Black, K.P., (2001). Resolving climatic variance in the context of retropective phytoplankton investigations off the east coast of Australia, Journal Coastal Res., 34, 74-86.

Lee, L. H. W. & Cheung, Y. K., (1990). Generalised Lagrangian model for buoyant jets in a current. Proc. ASCE, J. Env.Engineering, 116(6), 1085-1106.

Lim, K.J., Engel, B.A. , Kim, Y., Bhaduri, B. and J. Harbor, (1999). Development of the Long Term Hydrologic Impact Assessment (LTHIA) WWW systems. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds) "2001 Sustaining the Global Farm", 1018-1023.

Major G. A., Dal Pont G., Kyle J., and Newell (1972). Laboratory Techniques in Marine Chemistry - A Manual, CSIRO Division of Fisheries and Oceanography, Report 51, Sydney, 60p.

Middleton, J. F. and Black, K. P. (1994) The low frequency circulation in and around Bass Strait: a numerical study. Continental Shelf Research 14(13/14), 1495–1521.

NOAA (2000) Southern Oscillation Index (SOI), U.S. Department of Commerce, National Oceanic & Atmospheric Administration, NOAA Research, http://www.esrl.noaa.gov/psd/data/correlation/soi.data .

Oke, P. R., A. Schiller, D. A. Griffin, G. B. Brassington (2005). Ensemble data assimilation for an eddy-resolving ocean model. Quarterly Journal of the Royal Meteorological Society, 131, 3301-3311.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T., Rendell, P., Scanes, P. and Philip, N. (1996a) Assessment of the Deepwater Outfalls. Vol 1. EMP Final Report Series. Environment Protection Authority, Sydney, 194p.

Pritchard, T. R., Lee, R. S. and Davison, A. (1996b) "Dispersion of effluent from Sydney's new deepwater outfalls Part 2: Observations of Plume Behaviour: Winter and Summer Examples" In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), pp. 430-438. American Geophysical Union, Washington.

Pritchard, T.R., Lee, R.S. and Davison, A., 1993. Sydney's Deepwater Outfalls. In situ Observations of Plume Characteristics. In:Proceedings of 1th Australasian Conference in Coastal and Ocean Engineering, Townsville, 23-27 August 1993. Institure of Engineers, Australia.

Ridgway K.R., Dunn, J.R. and Wilkin, J.L. (2002) Ocean interpolation by four-dimensional least squares -Application to the waters around Australia, J. Atmos. Ocean. Tech., Vol 19, No 9, 1357-1375.

USDA (1986) Urban Hydrology For Small Watersheds – TR-55.

Young, I. R., Black, K. P., Heron, M. L. (1994) Circulation in the ribbon reef region of the Great Barrier Reef. Continental Shelf Research 14(2/3), 117–142.

4 THE COASTAL BOUNDARY LAYER: CLASSIFICATION AND CHARACTERISTICS IN NSW

4.1 Introduction

This chapter introduces the Coastal Boundary Layer (CBL) and draws from Chapter 2 and other sources to provide a framework to characterise the interactions of flow, local bathymetry and coastline irregularities in relation to the dispersion of pollution in New South Wales (NSW) coastal waters.

Past failures to consider the morphological settings of pollutant discharges to NSW coastal waters have resulted in gross inefficiencies of pollutant discharge systems and potential environmental impacts, as will be discussed further in Chapter 9. Classification of NSW coastal boundary layer effects provides a simple process based framework to guide and focus assessments of potential pollutant impacts.

Concise summaries of each element of the CBL classification are provided with schematic conceptual models and selected examples from NSW. Although the coastal boundary layer classification and characterisations presented here are based on available data from NSW coastal waters, the framework serves as a basis for general application elsewhere, and as a foundation for further refinement in NSW.

4.2 Coastal Boundary Layer

The coastal boundary layer is the turbulent interface between the coastline and open water where regional currents and ocean waves are profoundly affected by changes in the orientation and variable morphology of the coastline and continental shelf.

The CBL is analogous to the Planetary or Atmospheric Boundary Layer (PBL) albeit in the horizontal plane rather than the vertical plane. The CBL results from the interaction between regional currents and coastal bathymetry while the PBL results from interactions between regional winds and the planetary surface (Stull, 1997). Both are characterised by high levels of turbulence, strong gradients and rapid mixing with extreme variability and heterogeneity. Above the PBL (in the free atmosphere) and outside the CBL (in the deep ocean) flows are typically geostrophic, with comparatively low levels of turbulence, except at the boundaries of different water masses. The physical characteristics of both the CBL and the PBL are important in dispersion of pollutants and transport of biological and anthropogenic materials (e.g. sewage discharges in the CBL and photo chemical smog and dust in the PBL).

As early as 1972 Gabriel Csanady used the term 'coastal boundary layer' to describe a zone of dynamic features that were peculiar to near shore waters of the Great Lakes (Csanady, 1972). Following on from this work a COastal BOundary Layer Transect (COBOLT) experiment was designed to study the dynamic complexity of the coastal waters up to 12km off the southern coast of Long Island, New York (May, 1979). The COBOLT study focused on internal tidal oscillations that were trapped to the shore in "that band of water adjacent to the coast where ocean currents adjust to the presence of a boundary"; this zone was thought to be "roughly 10km wide". However, since this work only occasional reference has been made to the coastal boundary layer (eg King and Wolanski,1990; Thorrold & McKinnon, 1991; and, Zaker et al., 2007) and no systematic CBL classification relevant to NSW coastal waters is evident in the scientific literature. Likewise, no systematic hydrodynamically relevant morphological classification exists for coastal NSW.

In the ocean, advection (mean transport) generally decreases with proximity to the coast due to bottom friction, highly variable nearshore bathymetry and the roughness of the coastline slowing alongshore flows. Relationships such as the Law of the Wall (von Kármán, 1930) have been used to characterise frictional boundary effects whereby the average shore parallel velocity of a turbulent flow ideally displays a logarithmic decline towards the coast/wall, with the slope of log-linear segments (of log distance vs velocity) representing scales of coast/wall roughness which exert frictional forces on the flow (analogous to the roughness lengths of seafloor bedforms reported by Lefebvre *et al*., 2010). Unfortunately, an approach like this is unlikely to be successfully applied to the NSW coastal boundary layer because depths are small compared to horizontal length scales and velocity observations along cross shelf transects are too sparse to use this approach to characterise NSW coastal roughness lengths.

The solid boundary against the coast also inhibits cross shelf flows but may promote baroclinic flows such as upwelling dynamics as will be explored in Chapter 5 (and **Pritchard** and Koop, 2005). Turbulence, shear zones and frontal features develop near the coast due to interactions with inner shelf bathymetry, irregular coastlines and estuarine outflows. It is hypothesized that residence times of pollutants introduced to this coastal boundary layer are long relative to offshore regional flows due to retarded flows, turbulent re-circulation and zones of convergence: this will be tested in Chapter 8 where headland wake effects are investigated, near Coffs Harbour, on the northern NSW coast.

Oceanographic processes are modified on the shelf by discharges from coastal catchments and oscillatory disturbances are accentuated by vorticity effects making the coastal boundary layer extraordinarily dynamic and variable. As the water depth decreases the relative importance of wind stress and bottom boundary stress increases. These coastal boundary layer processes affect the dispersion and fate of pollutants and influence the distributions of biota that may be exposed to pollutants, as will be illustrated in Chapters 6 and 9.

Bottom boundary layer effects are more intense on the shelf because bottom water flows are much stronger than in the deep ocean: bottom boundary stress produces similar effects to wind stress at the surface, as illustrated off Port Stephens NSW by Oke and Middleton (1999). Fluctuations of sea levels are also much greater on the continental shelf where flows are constrained by the coast and the shallow shelf: extreme sea level set-up can occur along the cost in response to atmospheric storms (Nielson and Hanslow, 1991); and, coastal trapped waves which are constrained to the sloping shelf by vorticity considerations result in sea level excursions that propagate along the shelf (Church et al., 1986). Salinity gradients are extreme in inner shelf waters following the influx of freshwater from coastal catchments (Lee and **Pritchard**, 1999): this can have a substantial impact on the density field on the shelf and create its own circulation. For NSW this is typically episodic in response to major floods from coastal catchments, as described in

Chapter 2. The suspended material associated with these extreme coastal discharges provide a dramatic tracer of this CBL feature.

A coastal boundary layer classification structure is proposed for NSW in Table 4.1 which recognises that coastal boundary layer effects operate over a broad range of temporal and spatial scales as discussed in Chapter 2 and illustrated schematically in Figure 4.1.

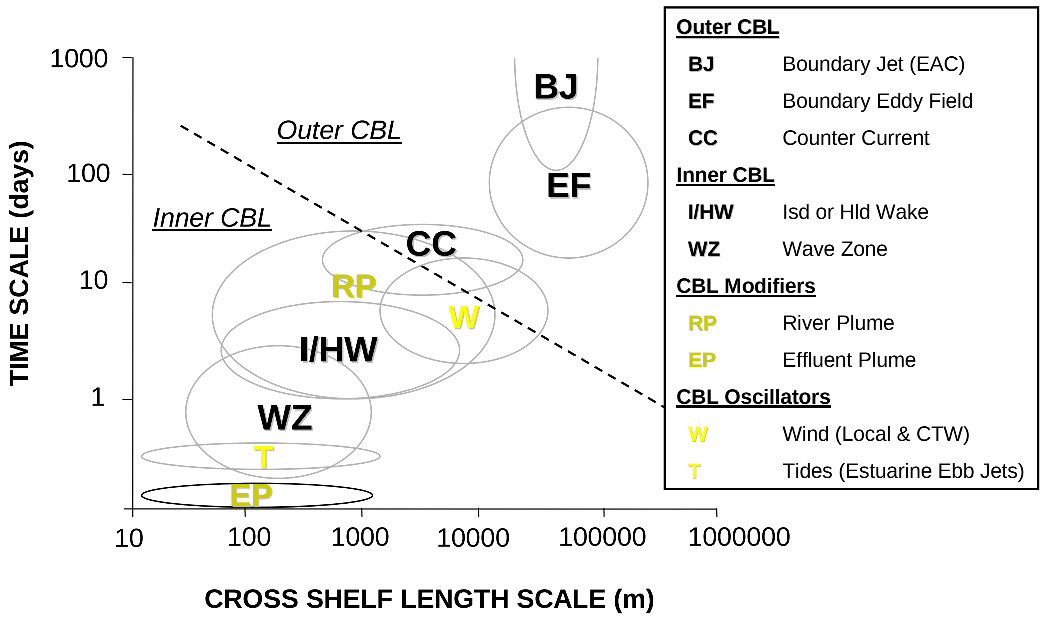


Figure 4.1 Schematic representation of the temporal and spatial scales of coastal boundary layer effects in NSW offshore waters. CBL Modifiers introduce density gradients (and are major pollutant vectors) while CBL Oscillators introduce vorticity. Ellipses represent indicative ranges of cross-shelf extents and dominant temporal expression (energy) based on data presented in this thesis, including referenced material (see Figures 4.3 to 4.11 for specific examples) and remote sensed imagery discussed in **Pritchard** & Koop (2005).

Two categories of coastal boundary layer types are proposed: outer and inner (Figure 4.2). *Outer CBL* types find expression over large spatial and temporal scales including the East Australian Current (EAC), counter currents, upwelling related to variable shelf morphologies, while *Inner CBL* types operate at smaller scales closer to shore influenced by local coastal morphology. *Outer CBL* processes generally drive the outer boundary conditions for *Inner CBL* phenomena.

Table 4.1 Coastal Boundary Layer (CBL) Classification Structure for New South Wales

<table>
<tr><th>CBL Types</th><th>CBL Modifiers</th><th>CBL Oscillators</th></tr>
<tr>
<td>At the largest scale in the Outer CBL, the East Australian Current (EAC) is a poleward boundary jet which diverges from the coast off central NSW to form an eddy field. Separation and recirculation of the EAC within the Tasman Abyssal basin are constrained by bathymetry (Ridgway and Dunn, 2003), the EAC interacts with the continental shelf to produce consistent upwelling zones (Oke and Middleton, 2000), sustained periods of strong counter currents on its inside edge (Roughan et al., 2003) and mesoscale eddies.
At smaller scales in the Inner CBL regional flows interact with the irregular coastline and near shore bathymetry to form turbulent flows around islands, headlands and bays. The shoaling and breaking of surface waves can also transport large volumes of water and sediment alongshore resulting in a wave dominated zone.

<u>Outer CBL</u>
▪ BOUNDARY JET (EAST AUSTRALIAN CURRENT) – BJ - Figure 4.3
▪ BOUNDARY EDDY FIELD – EF - Figure 4.4
▪ COUNTER CURRENT – CC - Figure 4.5
<u>Inner CBL</u>
▪ ISLAND AND HEADLAND WAKES - I/HW - Figure 4.6
▪ WAVE ZONE - WZ - Figure 4.7</td>
<td>Coastal catchment run-off and wastewater discharges result in identifiable plumes that contribute ‘fresh’ water and various dissolved and particulate loads of natural and anthropogenic material. These plumes carry momentum, modify the density structure of the Inner CBL, and promote density driven dynamics often across extreme density gradients. Their temporal expression distinguishes CBL Modifiers in NSW CBLs. River and stormwater plumes are highly episodic Modifiers, especially in southern NSW, whereas effluent plumes are continual CBL Modifiers.

▪ RIVER PLUMES – RP - Figure 4.8
▪ EFFLUENT PLUMES – EP - Figure 4.9</td>
<td>Various dynamic features introduce vorticity to the CBL including wind induced long period waves that are trapped on the continental shelf by vorticity considerations, and tidal ebb jets that result from tidal exchanges between estuaries and open water.
CBL Oscillators can be distinguished by their frequency band in the energy spectrum. Not surprisingly Wind Oscillators are expressed in the energetic weather band (days to weeks), including the remotely generated coastal trapped waves, as described in Chapter 2. Tidal Oscillators are relatively weak mostly semi-diurnal signals in NSW coastal waters due to the micro-tidal regime and the lack of significant tidal phase differences along the NSW open coastline. However, tidal exchanges with estuaries can be significant.

▪ WIND especially COASTAL TRAPPED WAVES - W/CTW - Figure 4.10
▪ TIDAL especially EBB JETS - T / EJ - Figure 4.11</td>
</tr>
<tr><th colspan="3">CBL Convergence/Accumulation Zones</th></tr>
<tr><td colspan="3">From time to time natural accumulation zones form in the ocean, usually along fronts which separate water bodies with different physical characteristics. Fronts are fundamental features of the CBL and have the potential to concentrate both pollutant particles and the marine biota that become exposed to these pollutants.

▪ NSW CBL FRONTAL FEATURES – Figure 4.12</td></tr>
</table>

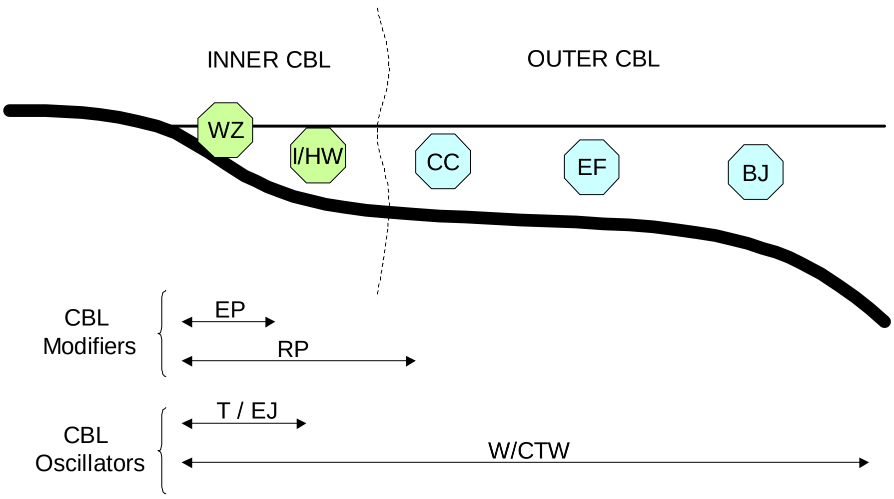


Figure 4.2 Idealised cross-shelf zonation of NSW CBL effects. Acronym listings are provided in Figure 4.1 and described below.

This chapter provides an overview of CBL types, modifiers (inputs resulting in density perturbations), oscillators (features contributing vorticity), and convergence zones (fronts of accumulation) with examples drawn wherever possible from NSW coastal waters.

4.2.1 CBL Types in NSW

Each of the *Outer CBL* and *Inner CBL* types are illustrated below (Figures 4.3 to 4.7) with schematic conceptual models and simple examples observed of New South Wales, sourced from earlier Chapters and referenced literature as indicated.

Many studies have attempted to quantify the broad scale transport/retention of particles (mostly larvae) between coastal and offshore environments. For example, Condie et al. (2011), simulated particle dispersion and transport across cells of the order of 0.2° x 0.2°; they found limited local retention rates of less than 3% after a dispersal time of 28 days presumably due to major current systems over the outer shelf and upper-slope. However, these types of analysis fail to take in to account *Inner CBL* phenomena such as the wake effects of headlands and retention within embayments.

Outer CBL types include a plethora of effects driven by the East Australian Current (EAC). The general EAC characteristics and variability of the EAC have been described by Mata et al. (2000) and Ridgway & Dunn (2003) while a special edition of Deep Sea Research carrying the title “The East Australian Current – its eddies and impacts” compiles more recent research findings. Upwelling processes, including those involving EAC dynamics, have been summarised by Roughan et al. (2002), and are explored further in Chapters 5 and 6.

Both the main flow of the EAC, and the eddy field downstream of the separation zone are highly variable across a range of scales including seasonal, interannual, El Ninõ –Southern Oscillation (ENSO), decadal and multi-decadal variability (Ridgway et al., 2008; Ridgway and Godfrey,1997; Holbrook et al., 2011). The strength of the poleward extension of the EAC has an approximately 10–15 year oscillation (Hill et al., 2008). Large (about 150 km diameter) warm core (anticlockwise) eddies and smaller (20 to 50 km) cold core (clockwise) eddies may persist off central and southern NSW for periods of days to many weeks during which time they profoundly affect the currents and temperature structure of the water column. Other important CBL features are less well understood, for example: “We do not understand the relationship of the EAC and/or eddies with the northward, coastal counter-current(s), which is likely of great importance to understanding the effects of climate change, connectivity and even northward sediment transport” (Suthers et al, 2011). There is evidence of northward counter currents from Gabo Island (near the Victoria-NSW border) to the EAC separation point (mid-NSW), associated with EAC eddies, coastal trapped waves, coastal winds and EAC separation (Roughan et al., 2011; Huyer et al., 1988)

Inner CBL types, especially Island and Headland Wakes (I/HW), will be described at length in relation to coastal morphology and potential pollutant impacts in Chapters 8 and 9. The focus on *Inner CBL* types is driven by the preponderance of pollutant discharges and detected impacts in NSW coastal waters often at spatial scales of tens or hundreds of metres. The need for the focus on turbulent flows across irregular coastlines is accentuated by the fact that, to date, there has been no hydrodynamically relevant morphological classification of bays, headlands and islands for NSW coastal waters.

The Wave Zone (WZ) and its relationship to various beach morphologies is not considered in detail here because existing classifications have previously been well developed, described and applied to NSW beaches (e.g. Short, 1993).

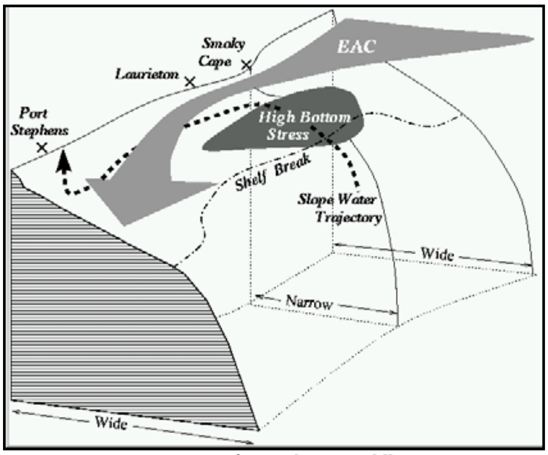
OUTER CBL TYPE: BOUNDARY JET (EAST AUSTRALIN CURRENT)

The East Australian Current (EAC) is a major western boundary current flowing from the southern Coral Sea in a jet centered over the northern NSW continental slope. It is typically ~30 km wide and ~200 m deep with an annual southward transport ranging from about 20 to 30 Sv, reaching speeds of up to 4 knots (2 ms^{-1}) (Mata et al., 2000; Ridgway & Dunn, 2003).

Indicative cross shelf spatial scale: 30-50km

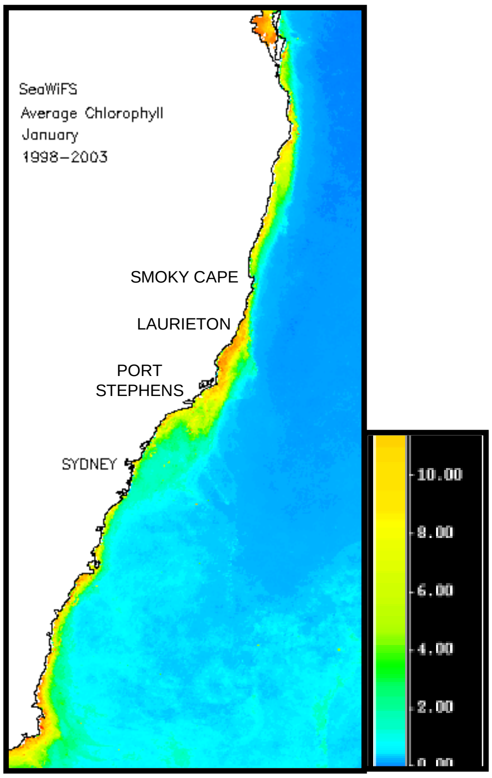
Indicative temporal scale: >100 days

A



from Oke & Middleton, 1998, 2000

B



JAN 98-03

Figure 4.3 Boundary jet with uplifting of slope water resulting from the interaction of the EAC with continental shelf topography.

A: Enhanced bottom stress due to acceleration of the East Australian Current through the narrowing continental shelf off Smokey Cape and Laurieton draws nutrient rich slope waters into shallower coastal regions. Slope water is carried along the shelf to Port Stephens, where divergence associated with change in the orientation of the shelf/coastline contributes to upwelling (from Oke and Middleton, 2000).

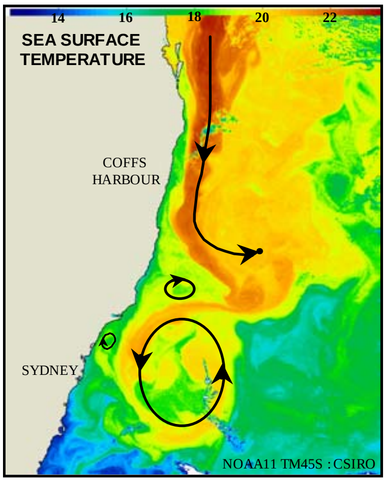
B: Long term ocean colour data illustrate upwelling zones on the inside edge of the EAC jet expressed as high chlorophyll: note that chlorophyll distribution is highly influenced by changes in coastline orientation (DECC SeaWiFS data summary by Davies and **Pritchard** - unpublished).

OUTER CBL TYPE: BOUNDARY EDDY FIELD (EF)

Complex eddies migrate southward in response to the interaction of turbulent EAC dynamics with the changing orientation and morphology of the continental shelf.

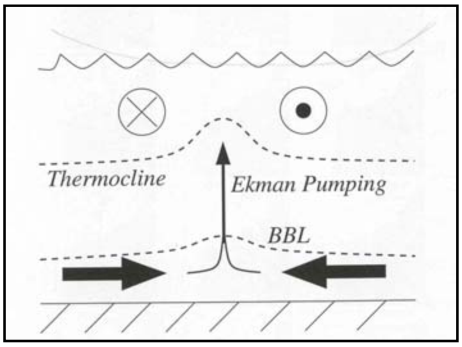
Indicative cross shelf spatial scale: 20-300km *Indicative temporal scale*: 20 - 300 days

A



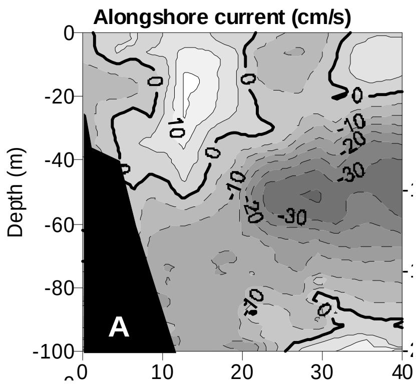
B

Cold core eddy dynamics



(from Oke & Middleton, 1999)

C



D

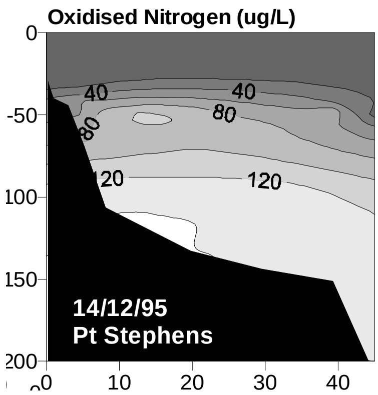


Figure 4.4 Mesoscale Eddy field

A: Sea Surface Temperature (SST) image with inferred surface currents depicting EAC jet diverging from the shelf and the spawned an eddy field: 29th September 1991 NOAA11 TM45S (SST data source: CSIRO);

B: cyclonic (cold core) eddy schematic: bottom stress in shallow shelf waters results in formation of a convergent bottom boundary layer (BBL) so mass balance considerations require upwelling at the centre of the eddy (from Oke and Middleton, 1999);

C: ADCP alongshore currents showing cyclonic eddy dynamics; and,

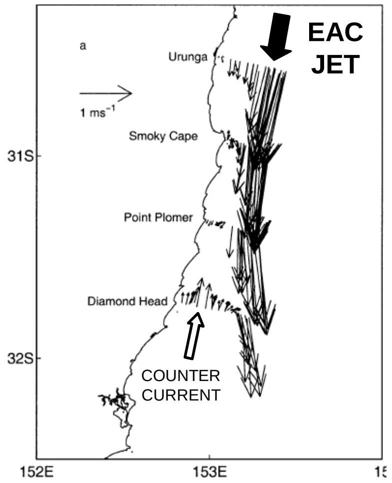
D: contoured discrete nutrient data along a cross shelf transect off Port Stephens depicting nutrient rich upwelling (C and D from Lee *et al.*, 2007).

OUTER CBL TYPE: COUNTER CURRENTS (CC)

Northward counter currents can form on the landward side of the EAC.

Indicative cross shelf spatial scale: 1-20kms *Indicative temporal scale*: 7–30 days (sparse data/understanding)

A



B

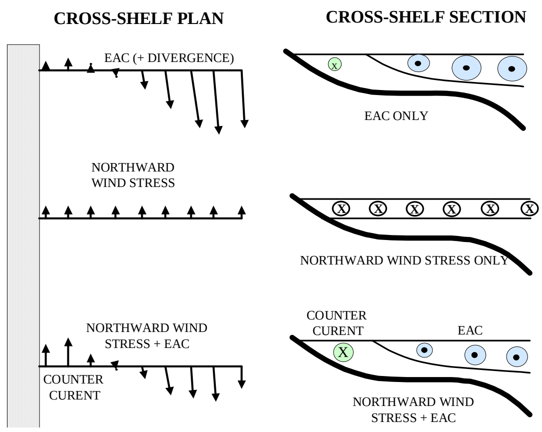


Figure 4.5 East Australian Current stream flow and counter currents.

A: Near surface currents obtained from ADCP measurements during November 1998 (Roughan et al., 2003) depicting southward EAC jet following isobaths, accelerating where the shelf narrows south of Smoky Cape, and ultimately separating from the shelf where the shelf orientation shifts to the southwest. At Smoky Cape the core of the jet was approximately 20 km offshore with a southward velocity of ~1.6 ms^{-1}, reducing to ~0.8 m s^{-1} at 10 km off the coast. Downstream of the EAC separation point off Diamond Head, a northward countercurrent formed about 20km wide inshore of the main jet. The counter current is required by conservation of mass in response to divergence (anticlockwise rotation) of EAC from the shelf: a weak counter current was drawn northward on the inside edge of the EAC (up to 0.3 ms^{-1} at 10 km from the coast). The divergence at the shelf break also generated upward vertical velocities of up to 0.003 ms^{-1} at the shelf break. Figure modified from Roughan et al. (2003).

B. While large scale divergence is the dominant driver for counter currents (see A), southerly (northward) winds can enhance these northward flows. The schematic shows the relative dominance of local wind driven currents in shallow inner shelf waters compared to deeper offshore waters, which are dominated by the inertial energy of the southward flowing EAC.

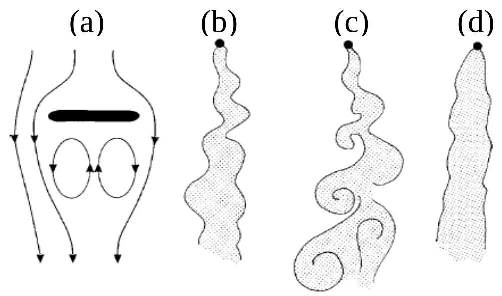
[⊗ = northward; ⊙ = southward]

INNER CBL TYPE : ISLAND & HEADLAND WAKE ZONE (I/HW)

Wakes form when flow separation occurs as currents impinge on bathymetric or coastal obstacles; that is, when inertial forces of the stream flow dominate over frictional forces, which tend to drag particles along the obstacle, resulting in a range of turbulent flow patterns such as eddies.

Indicative spatial scale: 100m – 8km   *Indicative temporal scale*: 1 - 10 days

A



B

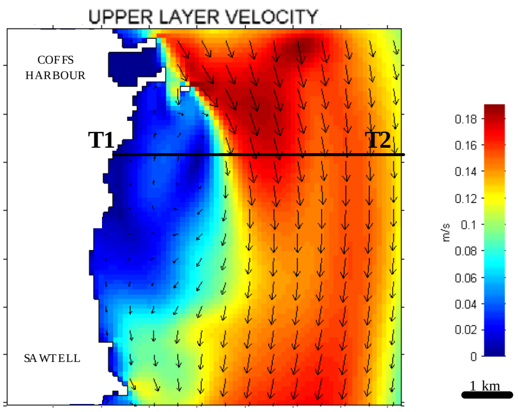


Figure 4.6 Island and headland wakes

A: Schematic shallow water island wakes corresponding to increasing dominance of inertial forces (separating flow from the obstacle) over frictional forces (dragging flow around the obstacle):
(a) vortex pair forms with central return flow;
(b) turbulent wake exhibits wave disturbances;
(c) meanders develop instabilities and roll to form a von Karmon vortex street;
(d) fully turbulent (three dimensional) wake.
Modified from Wolanski (2007). Many studies have attempted to characterise wakes in terms of these modal instabilities often relating them to a critical Reynolds number (e.g. Wolanski, 1988; Tomczak, 1988; Denniss and Middleton, 1995). However, some more recent studies suggest that the transition to unsteady flows in coastal waters occurs through non-modal growth excited by the stochastic variability (turbulence) in the incident flow (Aiken et al., 2003) suggesting that wake characteristics may be pre-conditioned by morphological irregularities.

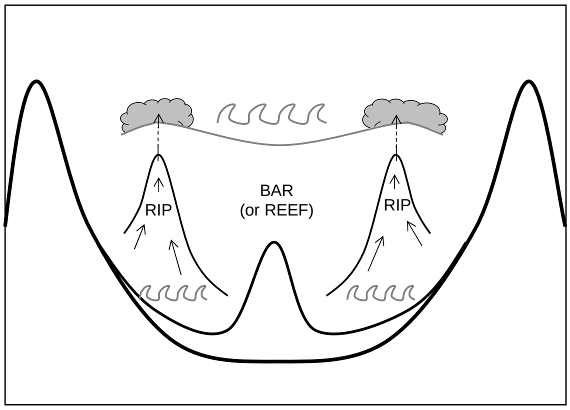
B: Re-circulation cell associated with a headland wake south of Coffs Harbour, New South Wales, Australia (**Pritchard** et al., 2007).

INNER CBL TYPE: WAVE ZONE (WZ)

Wave zones are driven by breaking waves which set up transient rip current (return flow) circulation cells which are pre-conditioned by near shore morphology.

Indicative cross shelf spatial scale: 20m-1km   *Indicative temporal scale*: hours to days

A



B

Figure 4.7 Wave Zone

A. Schematic of wave induced flows adapted from Short (1993) based on Intermediate Bar and Rip Beach.

B. Aerial photograph of Long Reef to Dee Why (Sydney northern beaches) under high wave conditions illustrating distinct sediment laden plume, similar in appearance to plumes of stormwater and primary treated sewage effluent. Under such conditions wave induced flows can dominate circulation at beach and bay scales. (photo by T.**Pritchard**)

4.2.2 CBL Modifiers in NSW

Coastal catchments transport terrestrial material to the oceans (*River Plumes*) and anthropogenic activities generate a variety of waste streams that are discharged at the coast (*Effluent Plumes*). These loads modify the physical, chemical and biological characteristics of the coastal boundary layer, although here only the physical characteristics are considered.

Identified *CBL Modifiers* are illustrated below (Figures 4.8 to 4.9) with schematic conceptual models and simple examples observed in New South Wales, as sourced from earlier Chapters and referenced literature.

The physical characteristics of idealised *River Plumes* (Figure 4.8) are fundamentally the result of three major processes (Fong and Geyer, 2002): (1) non-linear acceleration due to the balance between buoyancy forces and inertia which controls the degree to which the plume penetrates and spreads into coastal waters; (2) shear at the boundaries of the plume which determines the extent of mixing of plume waters with ambient coastal waters; and, (3) geostrophy which causes anticlockwise rotation in the southern hemisphere, where the Coriolis force is balanced by the cross-shore pressure gradient. In this way idealised river plumes can form a ‘bulge’ off the river mouth and a ‘coastal current’ (northward in NSW); the coastal current is trapped to the coast with a width equal to a few times the Internal Rossby Radius* (Kourafalou et al., 1996). A steady state can be achieved with an ambient, alongshore current (García Berdeal et al., 2002).

While river plume features depicted in Figure 4.8 A-C are consistent with some observation in NSW coastal waters, other factors often modify this idealised expression of river plumes, especially the effects of ambient currents, local winds, and density stratification of receiving waters.

* The internal (baroclinic) Rossby radius of deformation is the ratio between the phase speeds of the long internal waves to the Coriolis parameter. Basically, it is the horizontal scale at which rotation effects become as important as buoyancy effects.

Ambient regional dynamics and coastal topography often dictate the along shelf extent of river plumes in NSW. The southward East Australia Current dominates regional flows on the continental shelf especially in northern NSW where the EAC jet dominates, and this flows in an opposing direction to that in which a Kelvin wave would propagate. Therefore, in contrast to the idealized situation in Figure 4.8, major river plumes can extend southward from river mouths such as during the major flood in 2001 (MODIS data archive for 5 February 2001) which was the first major flood of the Clarence River since 1996. In theory a steady state can arise with a constant background ambient current (Kourafalou et al., 1996) although ambient coastal currents and river discharges are rarely constant in NSW, especially within the turbulent EAC eddy field. The highly variable nature of Australian river flows, as evident from NSW river flow hydrographs (OEH/MHL data), result in few major river plumes. As a result there has been limited opportunity to study river plumes in NSW coastal waters (Lee and **Pritchard** 1999). Studies overseas have investigated variations of river plume behaviour under a range of conditions. For example, investigations focused on the Columbia River on the Washington coast (USA) found rapid response (on the time scale of hours) of a river plume generated by a sequence of wind reversals and ambient currents that opposed the direction of propagation of Kelvin waves (García Berdeal et al., 2002). This baroclinic instability was thought to be responsible for the formation of detached eddies or ‘freshwater pools’.

Upwelling dynamics can increase stratification and promote offshore transport of surface waters including buoyant river plumes, while downwelling favourable conditions tend to confine river plumes to the coast and increase their vertical extent. Spreading of the plume under upwelling conditions (and/or local offshore winds) lead to a larger surface area being exposed to boundary turbulence (wind stress at the surface and current shear at other boundaries) and simulations have demonstrated increased mixing as a consequence of these conditions (e.g. Fong and Geyer, 2002; Kourafalou et al., 1996). Roughan et al. (2002) and **Pritchard** et al. (2003) described conditions that favoured upwelling in NSW coastal waters including sustained northeasterly winds and EAC activity on the shelf, while Lee et al. (2007) showed that some locations were predisposed to upwelling due to changes in the orientation of the coast/shelf.

In contrast to *River Plumes*, the behavior of *Effluent Plumes* has been well described in NSW for a variety of surface and submerged discharges (e.g. **Pritchard** et al., 2001; **Pritchard** et al., 1996; **Pritchard**, 1997; Ingleton and Large , 2004), while theoretical and conceptual models of plume behavior have been summarized by Jirka et al. (1996) and others (e.g. Tate and Middelton, 2000).

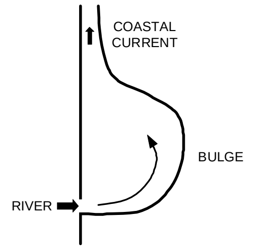
CBL MODIFIERS: RIVER PLUMES

Turbid, low density, river plumes result from outpourings from coastal catchments.

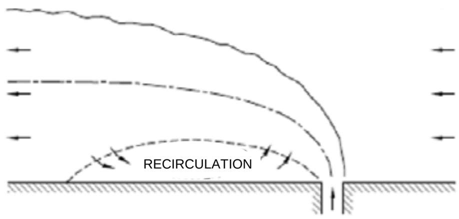
Indicative cross shelf spatial scale:
100m-30km

Indicative temporal scale:
days-weeks

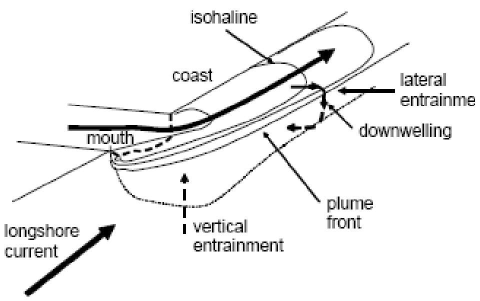
A. Momentum dominated (plan)



B. Buoyancy dominated (plan)



C. Buoyancy dominated mixing (3-D)



D. MODIS image

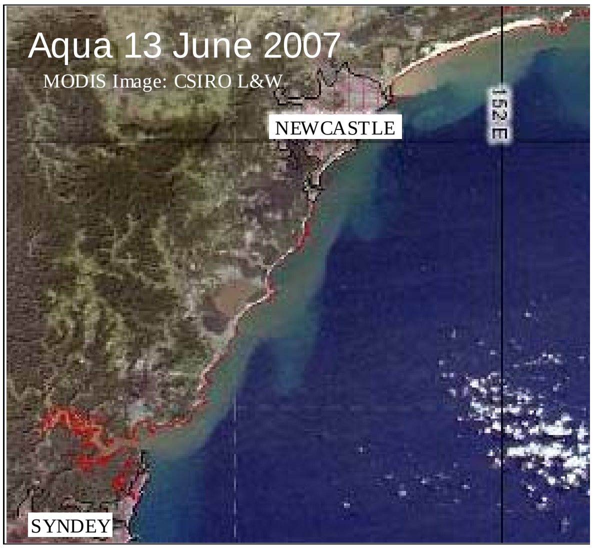


Figure 4.8 Cross shelf dynamics introduce vorticity to the CBL. Inertia and buoyancy determine the penetration and spread of river plumes into surface coastal waters.

A. Schematic of momentum dominated river plume where geostrophy causes anticlockwise rotation resulting in the formation of a bulge.
B. Schematic of buoyancy dominated river plume similar to effluent plume described below. River plume trajectory is dominated by the ambient current when ambient flows are strong (schematic based on Fong and Geyer, 2002).
C. Schematic of buoyancy dominated mixing (from Wolanski, 2007)
D. MODIS image for 13 June 2007 showing turbid river plume waters following a high rainfall event (image courtesy CSIRO Land and Water.)

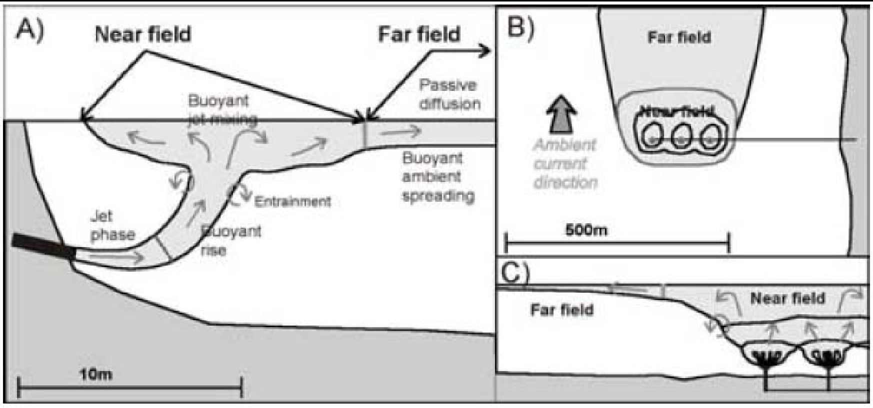
Modified from Jirka et al. (1996) and Fong and Geyer (2002).

CBL MODIFIER: EFFLUENT PLUMES

Effluent plumes result from discharges of buoyant (e.g. treated sewage) or negatively buoyant (e.g. desalination effluent) with mixing enhanced by high exit velocities (momentum dominated mixing).

Indicative cross shelf spatial scale: 20m-2km

Indicative temporal scale: initial (near field) mixing within minutes (continual discharges)



Modified from Ingleton and Large (2004)

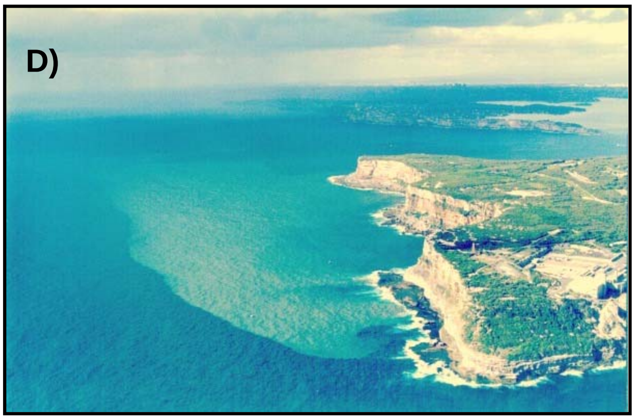


photo courtesy NSW EPA

Figure 4.9 Shoreline outfalls (depicted in A & D) achieve low initial dilution & maintain prominent fronts at the upstream boundary of the plume. In contrast well designed deepwater outfalls (B and C) typically achieve high dilutions due to greater exit velocities and greater scope for entrainment of ambient waters during buoyant rise of plume waters.

A. Cross-sectional view of a plume arising from a single port shoreline discharge.

B. Plan view of a plume arising from a multi-port gas-burner diffuser type outfall.

C. Cross-sectional view of plume arising from a multi-port diffuser type outfall.

D. Aerial photograph of effluent plume resulting from the former shoreline discharge of primary treated sewage effluent at North Head, Sydney (Photo DECCW).

4.2.3 CBL Oscillators in NSW

Winds and tides can introduce harmonic disturbances to the coastal boundary layer in the form of *Coastal Trapped Waves* and *Ebb Jets*, as described in Figures 4.10 and 4.11.

Freeland et al. (1986) and Church et al. (1986) first verified the existence of coastal trapped waves and explained their dynamics in Eastern Australia as part of the Australian Coastal Experiment which was conducted between September 1983 and March 1984. Major weather systems produce wind driven currents which can carry angular momentum across the sloping continental shelf. As depth varies across the shelf, vorticity considerations explain the formation of oscillations which propagate along the shelf as Coastal Trapped Waves.

Ebb Jets result from the tidal exchanges of water between estuaries and offshore coastal areas. Wolanski (2007) describes general entrance and return (re-entrainment) hydrodynamics associated with ebb jets.

Other CBL oscillations include high frequency internal waves which have been observed in NSW coastal waters such as at the Sydney Ocean Reference Station (**Pritchard** et al., 2005) and in the data streams from the NSW moorings of the Integrated Marine Observing System (IMOS) (http://imos.org.au/oceanportal.html). These may be baroclinic responses to tidal forces at the shelf break, changes in atmospheric pressure, lateral movement of oceanic fronts, and shear instabilities, and thus may also introduce vorticity to the coastal boundary layer; their potential effects on pollutants in the coastal boundary layer are discussed by **Pritchard** et al. (2005). For example, buoyant plumes rising through internal wave fields may differ significantly in height of rise and dilution compared to plume behaviour under mean stratification.

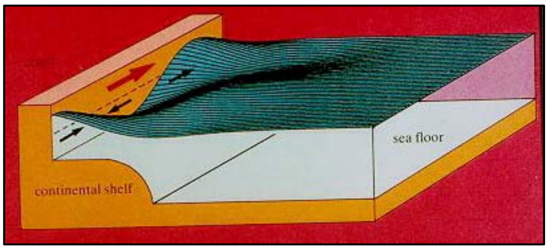
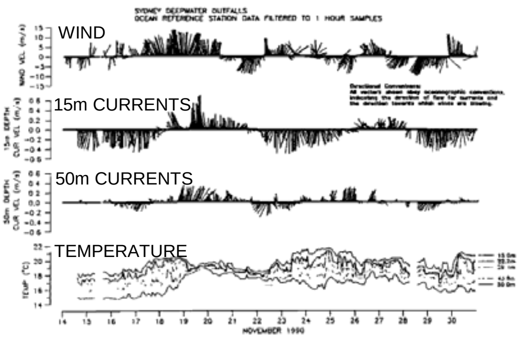
CBL OSCILLATOR: COASTAL TRAPPED WAVES (CTW)	
Coastal trapped waves are wind-forced long shelf waves which propagate northward along the NSW continental shelf. Approximately 60% to 70% of the 'weather band' (40 hour to 20 day period) current variance is wind driven, with the major contributors being the southern New South Wales and Bass Strait winds, both lagged by intervals corresponding to the propagation speed of the first Coastal Trapped Wave (CTW) mode (Griffin and Middleton, 1991). *Indicative cross shelf spatial scale*: 15 – 45km (shelf width)	 *Indicative temporal scale*: 7-20 days (weatherband)
A..  Source: CSIRO	B.  Modified from Lee and **Pritchard** (1996)

Figure 4.10 Coastal trapped wave characteristics.

A. Schematic representation of the passage a northward propagating coastal trapped wave showing characteristic current reversal. Vorticity considerations (conservation of angular momentum) affect the movement of water across the sloping continental shelf waves resulting in CTWs. The wave is trapped against the coast, but unlike a Kelvin wave its profile does not fall off monotonically from the coast out to sea but shows a second region of large amplitudes over the shelf edge.

B. Wind, current meter and temperature data observed at the Ocean Reference Station off Sydney showing weather band variability associated with the passage of coastal trapped waves, which resulted in cross shore oscillation of shear zones (Lee and **Pritchard**, 1996).

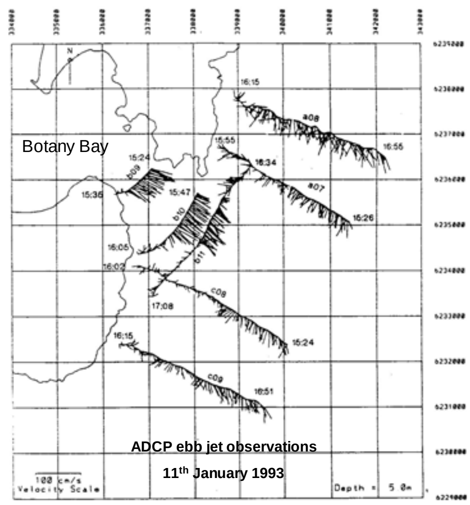
CBL OSCILLATOR: EBB JETS (EJ)

Ebb jets are seaward flows from estuaries or tidal rivers during the lowering tidal phase; their extent, magnitude, and complexity of ebb jets is influenced by the estuarine tidal prism, configuration of the estuary mouth, and dynamics of ambient coastal waters.

Indicative cross shelf spatial scale:
20m – 1km

Indicative temporal scale:
6hrs (semi diurnal tide in NSW)

A.



B.

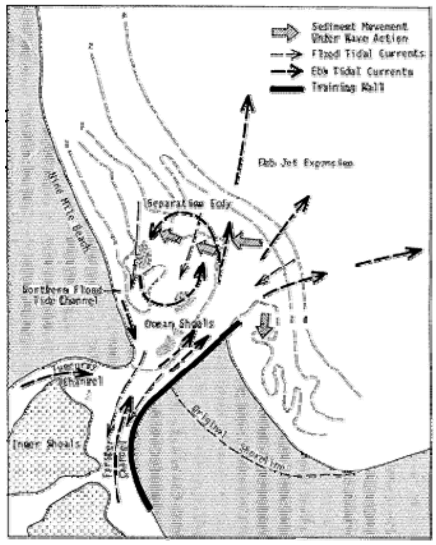


Figure 4.11 Ebb Tide Jets.

A. Large scale ebb jet: Acoustic Doppler Current Profiler observations at Botany Bay - ebb flow initially occurred at depth, strengthening and becoming more uniform with depth before forming a narrow jet on the northern side of the entrance. Strongest currents (~0.6m/s) were observed at the surface while weak re-circulation cells formed to the north and south of the entrance. The ebb jet was ~10m thick and extended ~4km offshore. (from Cox et al., 1993). In wide estuaries, the Coriolis force steers seaward flows to the left hand side of the estuary entrance in the southern hemisphere (Dyer, 1997), creating a tidally-averaged, net in flow on one side and a net outflow on the other side. Note that if the coastal currents are small and the estuary mouth is large, the plume does not form a jet at falling tide; instead it forms a radially symmetric plume which is similar in form to the flood tidal currents thus limiting net exchange (Wolanski, 2007).

B. Complex hydraulic features of a typical trained coastal entrance at Forster-Tuncurry on the NSW mid north coast. Breakwaters and training walls can significantly modify the hydraulic behaviour and sedimentation processes both within the estuaries and along their adjacent coastlines (from NSW, 1990).

4.2.4 CBL Fronts and Convergence (Accumulation) Zones in NSW

Accumulation usually occurs when convergent flows bring particles, such as pollutants and plankton, together. If particles are sufficiently buoyant, they will remain at the surface when two water bodies converge while the convergent water descends usually in the downwelling arm of a three dimensional circulation cell. Positively buoyant particles (e.g. buoyant pollutants and plankton) accumulate to the extent that abundances of plankton may be 10 to 1000 times greater in these zone of convergence than in surrounding waters (Kingsford, 1995). Accumulations of natural and anthropogenic material may be sufficiently dense to be visible in their own right or they may affect the surface tension of the water to such an extent (for example, through the surfactant properties of their breakdown products) that they are visible as lines in the ocean, as evident in Figure 4.12.

Zones of accumulation may be driven by many phenomena including winds, propagation of surface and internal waves, and density gradients. Wind effects can lead to the establishment of three dimensional *Langmuir Cells* which result in surface convergence along lines (along *windrows*) which run parallel to the direction of the wind (Figure 4.12C). Likewise, the passage of internal waves which originate on the shelf break (**Pritchard** et al., 2005), may set up similar three dimensional circulation cells but for internal waves the lines of surface level convergence run perpendicular to the direction of propagation.

Convergent accumulation zones may also occur when breaking surface waves create a water set-up which is opposed by local winds (Figure 4.12D).

Inner CBL fronts typically occur as nonlinear features and represent a dynamic equilibrium brought about by a balance between two or more forces. For example, gradients of water characteristics like salinity are often an order of magnitude greater across effluent or stormwater plume fronts than within or outside the plumes. Current shear between the two different water masses can establish a zone of convergence such as that which occurs at the mouths of many estuaries (Figure 4.12B). Visible organic and floating debris accumulates along these front together with biota such as seabirds and their prey.

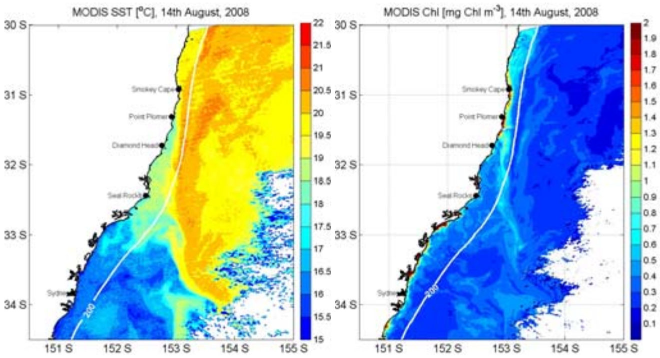
Local topography may make particular areas more prone to convergence through the establishment of re-circulation zones in the lee of promontories.

Large scale *Outer CBL* fronts occur most frequently on the inner edge of the EAC as is evident in ocean colour imagery presented in Figure 4.12A and Chapter 5. Shallow waters inshore of the EAC are well mixed by surface wind stress, waves and bottom frictional stress (as seen off Coffs Harbour in Chapter 8 for nearshore waters <40m), in contrast to mid-shelf waters which are typically stratified and often dominated by the EAC and its eddies (as seen off Sydney in Chapter 6 for water at >65m). This vertical mixing of these inner shelf waters with integration of cool bottom waters results in well-mixed waters which are significantly cooler than EAC which is of tropical origin. Therefore, a horizontal density gradient occurs between these nearshore waters and the EAC. Likewise, the waters underlying the EAC are significantly cooler that the EAC and generally cooler than the well-mixed inner shelf waters. The temperature of inner shelf waters typically corresponds to the temperature found somewhere in the centre of the thermocline. Because the probability of achieving neutral buoyancy is greatest where vertical density gradients are strongest, pollutant and plankton particles tend to accumulate near the thermocline (or more accurately the pycnocline) which is also in close proximity to cool nutrient rich bottom waters. A pathway of neutral density exists along this thermocline which outcrops as the surface expression of the front. Surface accumulations are frequently evident along EAC fronts in ocean colour imagery as filaments of high chlorophyll as shown in Figure 4.12A; this will be explored further in Chapter 5.

CBL CONVERGENCE/ACCUMULATION ZONES

<u>Accumulation zones</u> result from convergent processes along fronts which may be driven and sustained by density gradients, wind and wave forcing and current shear operating.

Indicative cross shelf spatial scale:	*Indicative temporal scale*:
Hundreds of kilometers to tens of meters	Weeks to hours



A: DENSITY – EAC: Sea Surface Temperature (left) and chlorophyll estimates, derived from MODIS data for 14th August 2008 (courtesy CSIRO). Accumulation and high productivity clearly delineated along the inner edge of the EAC. The density gradient supports a geostrophic jet along the front, which can cause eddies to form and break off. Like all other fronts it is also linked with a convergence of the surface current.
Images provided by Dr Mark Baird (2008).

B: DENSITY - ESTUARIES: Current shear between the different water masses can establish a zone of convergence such as that which occurs at the mouths of many estuaries.
For example, fontal accumulations of *Noctiluca scintillans* occur at the mouth of the Hawkesbury River (Broken Bay, 1997). Photo courtesy of Beachwatch, NSW EPA.

C: LOCAL WIND: Wind can lead to the establishment on *Langmuir Cells* and lines called *windrows* which run parallel to the direction of the wind. Frontal processes (local convergence) accumulated *Noctiluca scintillans* off Manly near Sydney, NSW, during 1997. This accumulation was then fragmented by the onshore wind into bright red streaks directed shoreward (windrows). Photo from **Pritchard** and Koop (2005)

D: SURFACE WAVES: Breaking waves create a water set-up that generates a seaward surface current that is opposite to the shoreward wind (Wolanski, 2007). These opposite effects meet at the convergence point where they form a slick line parallel to the shore.
Photo T.**Pritchard**: Warriewood, NSW on 23/04/91 under high wave conditions (NSW)

Figure 4.12 Selected examples of NSW CBL frontal features: A (Density EAC), B (Density Estuaries), C (Local Wind) & D(Surface Waves)

4.3 Exploration and Application of the NSW CBL Classification

The following chapters of this thesis explore the interactions of flows with coastal bathymetry in the context of this CBL classification for the purpose of pollutant impact assessments. Coastal boundary layer effects that control the dilution, dispersion and fates of pollutants are explored at various scales within the *Outer* and *Inner CBL*.

The utility of remote sensing techniques to reveal mostly *Outer CBL* processes and to inform broad scale marine ecosystem assessments is investigated in Chapter 5. Analyses of these spatial data sets are complemented by interrogation of temporal (time series) data from Sydney coastal waters in Chapter 6. This Sydney case study in Chapter 6, explores scales of mostly *Outer CBL* variability and investigates environmental impacts, especially those related to discharges from NSW's largest sewage treatment plants. In particular, investigations attempt to address the question: how do ocean outfalls affect nutrient phytoplankton relationships in coastal waters of New South Wales, Australia? These *Outer CBL* studies also furnish an understanding of the dynamic processes that drive the outer boundary conditions for *Inner CBL* phenomena.

In Chapter 7 the focus shifts to the *Inner CBL* where the effects of coastal roughness and orientation – headlands and bays – are investigated in relation to their potential to limit dispersion and trap pollutants. A new morphological classification is developed and applied to NSW headlands and bays and island as a basis to screen nearshore morphological settings for potential pollutant 'trapping'.

Headland Wake effects are the focus of investigation in the second case study conducted off Coffs Harbour on the NSW mid north coast (Chapter 8), where a regional sewage management strategy required a relocation of the discharge of treated effluent to the ocean.

These and other case studies across a range of NSW morphological settings are drawn together in Chapter 9 to test and improve the new CBL classification.

Ecological and management implications of the CBL dynamics are also explored in this discussion chapter.

4.4 References

Aiken, C.M., Moore, A.M. and Middleton, J.H. (2003) Non-normal perturbation growth in idealised island and headland wakes. Dynamics of Atmospheres and Oceans. 37, 171–195.

Church, J. A., H. J. Freeland and R. L. Smith (1986) Coastal-trapped waves on the east Australian continental shelf part I: propagation of modes. Journal of Physical Oceanography 16, 1929 - 1943.

Condie, S.A.,Mansbridge,J.V.,Cahill,M.L. (2011) Contrasting local retention and cross-shore transports of the East Australian Current and the Leeuwin Current and their relative influences on the life histories of small pelagic fishes. Deep-Sea Research II58(5), 606–615.

Cox, D.R., Lee, R.S., Howden, M.I. and Nalty, C.R. (1993) Sydney Deepwater Outfalls Environmental Monitoring Program Post-Commissioning Phase: Botany Bay Entrance Model Verification Experiment 11 January 1993, Australian Water and Coastal Studies Pty Ltd, Interim Report 93/01/02.

Csanady, G. (1972) The coastal boundary layer in Lake Ontario. Journal of Physical Oceanography. 2:41-53, 168-176.

Denniss, T. and Middleton, J.H. (1995) Effects of viscosity and bottom friction on recirculating flows. J. Geophys.Res. 99, 10183–10192.

Dyer, K. R. (1997) Estuaries, a physical introduction, 2nd ed. Wiley.

Fong, D. A. and Geyer, W. R., (2002). The alongshore transport of freshwater in a surface trapped river plume. Journal of Physical Oceanography, 32, 957-972.

Freeland, H. J., F. M. Boland, J. A. Church, A. J. Clarke, A. M. G. Forbes, A. Huyer, R. L. Smith, R. O. R. Y. Thompson and N. J. White (1986) The Australian Coastal Experiment: a search for coastal-trapped waves. Journal of Physical Oceanography 16, 1230 - 1249.

Garcia Berdeal, I., Hickey, B. M. and Kawase, M., (2002) Influence of wind stress and ambient flow on a high discharge river plume. Journal of Geophysical Research, 107, C9, p3130.

Griffin, D.A. and Middleton, J.H. (1991) Local and Remote wind forcing of New South Wales inner shelf currents and sea level. Journal of Geophysical Research, 21, 304-322.

Hill, K.L., Rintoul,S.R., Coleman,R., Ridgway,K.R. (2008) Wind forced low frequency variability of the East Australia Current. Geophysical Research Letters 35, L08602.

Holbrook N.J., Goodwin,I.D., McGregor,S., Molina,E., Power,S.B. (2011) ENSO to multi-decadal timescale changes in East Australian Current transports and Fort Denison sealevel: oceanic Rossby waves as the connecting mechanism. Deep-Sea Research II58(5), 547–558.

Huyer, A, Smith, R.L., Stabeno,P.J., Church, J.A. and White, N.J. (1988) Currents off South-eastern Australia: Results from the Australian Coastal Experiment, Aust.J.Mar.Freshwater Res., 39, 245-88.

Ingleton, T. and Large, D. (2002) Modelling Coastal Discharges: Scoping Study. NSW Environment Protection Authority Report. pp77.

Jirka G., R. Doneker and S. Hinton (1996) User's Manual for Cormix: A Mixing Zone Expert System for Pollutant Discharges into Surface Waters. U.S. EPA Office of Science and Technology, Washington, DC.

King, B. and E. Wolanski (1990). Coastal dynamics along a rugged coastline. Proceedings of the 5th Intemational Biennial Conference: Physics of estuaries and coastal seas. Gregynog, Wales.

Kingsford, M. J. 1995. Planktonic Processes. In, Coastal Marine Ecology of Temperate Australia. Ed AJ Underwood and MG Chapman. UNSW Press 1995.

Kourafalou, V. H., Oey, L.Y., Wang, J. D., and Lee, T. N., (1996) The fate of river discharge on the continental shelf. 1. Modelling the river plume and the inner shelf coastal current. Journal of Geophysical Research, 101,C2, pp3415-3434.

Lee, R.S., **Pritchard**, T.R., Ajani, P.A. and Black, K.P. (2007) The influence of the East Australian Current eddy field on phytoplankton dynamics in the coastal zone, Journal of Coastal Research, SI 50, 576-584.

Lee, R.S., Wallace, S.L., Holden, C. and Black, K.P. (2007) Scaling coastal upwelling features of the East Australian Current. Journal of Coastal Research, SI50.

Lee, R.S., **Pritchard**, T.R., Ajani, P.A. and Black, K.P. (2007) The influence of the East Australian Current eddy field on phytoplankton dynamics in the coastal zone, Journal of Coastal Research, SI 50, 576-584.

Lee, R. S. and **Pritchard**, T. R., (1999) Extreme Discharges into the Coastal Ocean: A Case Study of August 1998 Flooding on the Hawkesbury and Hunter Rivers. Pacific Coasts and Ports '99 Proceedings, Perth, W.A. 341-346. Institute of Engineers, Australia.

Lee, R. S. and **Pritchard, T. R.** (1996) "Dispersion of effluent from Sydney's new deepwater outfalls Part 1: ocean processes". In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), 430-438. American Geophysical Union, Washington.

Lefebvre, A., Ernstsen,V.B. & Winter,C. (2010) Influence of compound bedforms on hydraulic roughness in a tidal environment, Proceedings of the Fifteenth International Biennial Physics of Estuaries and Coastal Seas conference: Coastal and estuarine observations and modeling, 14–17 September 2010, Sri Lanka, http://www2.sese.uwa.edu.au/~pecs/index.html , 149-152.

Mata, M. M., Tomczak, M., Wijffels, S., Church, J. A., (2000) East Australian Current volume transports at 30°S: Estimates from the World Ocean Circulation Experiment hydrographic sections PR11/P6 and the PCM3 current meter array. J.Geophys. Res. 105, 28509–28526.

May, P.W. (1979) Analysis and interpretation of tidal currents in the coastal boundary layer. PhD thesis, MIT and Woods Hole Oceanographic Institute, May, 1979, 197p.

Nielsen, P & D J Hanslow (1991) Wave run-up distributions on natural beaches. J.Coastal Res, Vol 7, No 4, pp 1139-1152.

NSW (1990) NSW Coastline Management Manual, New South Wales Government, September 1990, ISBN 0730575063.

Oke, P.R. and Middleton, J.H. (2000) Topographically induced upwelling off Eastern Australia. Journal of Physical Oceanography 30, 512–531.

Oke, P.R. & Middleton, J.H (1999) Nutrient enrichment off Port Stephens: the Role of the East Australian Current. Continental Shelf Research.

Pritchard, T.R. (1997) Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, Vol 24, No.1. March/April 1997.

Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T.R. and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.

Pritchard, T.R, Lee,R.S., Ajani,P.A., Rendell.P.S., Black,K & Koop,K. (2003) Phytoptoplankton responses to nutrient sources in coastal waters off southeastern Australia. Aquatic Ecosystem Health and Management, 6(2): 105-117.

Pritchard, T. R., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Effect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.

Pritchard, T. R., Lee, R. S. and Davison, A. (1996) "Dispersion of effluent from Sydney's new deepwater outfalls Part 2: Observations of Plume Behaviour: Winter and Summer Examples" In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), pp. 430-438. American Geophysical Union, Washington.

Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N. (1997) Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

Ridgway, K.R., Coleman,R.C., Bailey,R.J., Sutton,P. (2008) Decadal variability of East Australian Current transport inferred from repeated high-density XBT transects, a CTD survey and satellite altimetry. Journal of Geophysical Research 113, C08039.doi:10.1029/2007JC004664.

Ridgway, K. R., and J. R. Dunn. (2003) Mesoscale structure of the mean East Australian Current System and its relationship with topography. Progress in Oceanography 56:189-222.

Ridgway, K.R. and Godfrey,J.S. (1997) Seasonal cycle of the East Australian Current. Journal of Geophysical Research102, pp22921–22936.

Roughan, M., Macdonald, H.S., Baird, M.E., Glasby, T.M. (2011) Modelling coastal connectivity in a Western Boundary Current: Seasonal and

inter-annual variability, Deep-Sea Research II, 58, 628–644.

Roughan, M. and Middleton, J.H. (2002) A comparison of observed upwelling mechanisms off the east coast of Australia. Cont.Shelf Res., pp2551-2572.

Roughan, M., Oke, P.R. and Middelton, J.H. (2003) A Modeling Study of the Climatological Current Field and the Trajectories of Upwelled Particles in the East Australian Current. Journal of Physical Oceanography, 33, 2551-2564.

Short, A. (1993) Beaches of the New South Wales Coast: a guide to their nature, characteristics, surf and safety. Australian Beach Safety and Management Program, ISBN 0646150553.

Stull, R. (1997) An Introduction to Boundary Layer Meteorology. Boston: Kluwer Academic Publishers. ISBN 9027727686.

Suthers, I.M., Everett,J.D., Roughan,M., Young, J.W., Oke, P.R., Condie,S.A., Hartog,J.R., Hobday, A.J., Thompson, P.A., Ridgway, K., Baird, M.E., Hassler, C.S., Brassington, G.B., Byrne, M., Holbrook, N.J. Malcolm, H.A. (2011) The strengthening East Australian Current, its eddies and biological effects — an introduction and overview. Deep-Sea Research II 58, 538–546.

Tate, P.M. and Middleton, J.H (2000) Unification Of Non-Dimensional Solutions To Asymptotic Equations For Plumes Of Different Shape, Boundary-Layer Meteorology, 94/2, 225-251.

Thorrold,S.R. and McKinnon,A.D. (1991) Biological significance of the coastal boundary layer off Townsville, North Queensland. Bureau of Rural Resources Proceedings, 15, pp 104-109.

Tomczak, M. (1988) Island wakes in deep and shallow water. J. Geophys. Res. 93 (12), 5153–5154.

von Kármán, Th (1930), "Mechanische Ähnlichkeit und Turbulenz", Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Fachgruppe 1 (Mathematik) 5: 58–76

Wolanski (2007). Estuarine Ecohydrology, 2007, Pages 17-39

Wolanski, E., (1988) Island wakes in shallow waters. J. Geophys. Res. 93 (12), 1335–1336.

Zaker, N. H., Imberger,J., Pattiaratchi,C. (2007) Dynamics of the Coastal Boundary Layer off Perth, Western Australia. Journal of Coastal Research: Vol. 23, No. 5, pp. 1112-1130.

5. SATELLITE REMOTE SENSING

5.1 Introduction

In this chapter remote sensing tools, especially satellite mounted ocean colour sensors, are reviewed to determine their usefulness for marine ecosystem assessments. The unsurpassed spatial coverage of satellite mounted sensors and high return frequencies offer vast potential for investigation of broad scale characteristics of marine waters. The increased spectral coverage of recent sensors presents new opportunities to link physico-chemical and biological processes. Integration of these inherently coupled physicochemical and biological components of the natural system promises to reveal greater scientific insights and deliver more pertinent information to environmental and natural resource managers.

The body of this chapter (Section 5.3) reviews published research and provides case studies of the application of mostly ocean colour and sea surface temperature data; it was peer reviewed prior to international publication as a book chapter by Taylor and Francis in 2005:

> **Pritchard, T.R.** and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.

5.2 Motivation and Relevance to Thesis Objectives

Relevant long term monitoring of NSW coastal waters, which extend out to 3 nautical miles offshore, is sparse (see chapters 2 and 3), comprising of near shore tide gauges (Manly Hydraulics Laboratory), a waverider buoy network (Manly Hydraulics Laboratory), an instrumented Ocean Reference Station off Sydney (Sydney Water Corporation), long term nutrient and temperature monitoring at two stations offshore from Port Hacking (CSIRO), bacterial water quality monitoring (DECC Beachwatch) and remote sensing.

This chapter focuses on available long term remote sensed data. It includes a general overview and review of ocean colour products and highlights those aspects relevant to the coastal boundary layer with examples from NSW coastal waters. Although remote sensed data offers the most comprehensive coverage of NSW coastal waters it has received comparatively little attention. The strengths and weaknesses of remote sensed data are reviewed in this chapter and areas for further research and development are highlighted especially in relation to the optically complex Type 2 waters of the coastal boundary layer.

The specific objective of this chapter is to:

- determine the utility of remotely sensed ocean colour and sea surface temperature (SST) data to characterise broad scale ecosystem and coastal boundary layer processes and to investigate applications to support coastal management

This is achieved by reference to previously published research and through case studies

The findings from this chapter provide the necessary limitations and caveats for the use of ocean colour data products and delivers specific examples that elucidate the characteristics and features of the NSW coastal boundary layer as developed in Chapter 4 and discussed in Chapter 9. In this way it also provides a context for case studies that follow in Chapter 6 and Chapter 8.

5.3 'Satellite Remote Sensing in Marine Ecosystem Assessments'

Citation: **Pritchard, T.R.** and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.

Introduction

Remote sensing technologies range from small scale high frequency devices such as towed video plankton recorders (Davies *et al*., 1992) to satellite mounted sensor arrays providing global estimates of primary production (Joint & Groom, 2000). This chapter describes a range of applications of satellite sensed data, especially ocean colour and sea surface temperature products, to illustrate how they can be used to develop an understanding of ecosystems and human impacts on them. Global, regional and local scale applications are summarised after which a more detailed case study is presented to illustrate how ocean colour technology can be employed to develop a predictive understanding of algal bloom development and associated issues in the coastal waters of New South Wales, Australia.

Satellite borne ocean colour products have improved in recent years and many are freely available, so with increased personal computer processing power, applications now fall within the reach of a vast number of potential users.

Background

The world's immense human population exerts profound stresses on aquatic ecosystems at all scales. Direct impacts occur through catchment run-off, discharge of wastes, atmospheric deposition of pollutants, over exploitation and habitat modification. Further, insidious impacts include the spread of introduced species and manifestations of global warming. Monitoring, predicting and managing changes within coastal ecosystems are clearly important: remote sensing technologies provide unsurpassed spatial coverage with ever increasing spatial, temporal and spectral resolutions to help address these issues.

Although this chapter deals with remote sensing and information technologies that are fast evolving, the type of information needed for assessment and management of aquatic ecosystems remains essentially the same.

History and Relevance of Ocean Colour

The colour of the ocean can indicate levels of phytoplankton activity. To the casual observer, the colour of seawater may vary from the dark green of eutrophic estuarine waters, to the deep blue of oligotrophic oceanic waters. Coastal water colourations, however, are often complex with various hues of grey, brown and yellow due to terrigenous influences such as estuarine plumes, anthropogenic discharges, re-suspended sediments, and the presence of dissolved organic substances.

Shipboard and aircraft studies first showed that radiance upwelling from the ocean in the visible region (400-700 nm) was related to the concentration of chlorophyll and other plant pigments.

Following this, the first satellite borne ocean-colour sensor – the Coastal Zone Colour Scanner (CZCS) – was launched in 1978 as a one year 'proof-of-concept' mission. Despite this, CZCS delivered ocean colour data for 8 years and led to the development of algorithms to estimate primary productivity in our surface oceans (e.g. Platt and Sathyendranath, 1988). Data from CZCS revolutionised the understanding of phytoplankton distributions and dynamics at a global scale and in many coastal systems (e.g. Shannon, 1985). Remote sensing provided a synoptic view of large zonal structures which had been overlooked in field studies and ignored in mathematical models because time and length scales were not easily detected by classical field investigations (Nihoul, 1984).

After a hiatus of nearly a decade, new ocean colour sensors were launched in the mid and late 1990s in response to the need to quantify the carbon cycle motivated by increasing concerns about climate change and an appreciation of interactions between climate effects and marine ecosystems.

Key Satellite Mounted Sensors

Present, future and past ocean colour scanners are summarised in Table 1 - information is updated by the International Ocean Colour Ocean Coordination Group at http://www.ioccg.org/sensors/500m.html.

Table 1: Satellite mounted ocean colour sensors

SENSOR	AGENCY	SATELLITE	LAUNCH DATE	SWATH (km)	RESOLUTION (m)	# OF BANDS	SPECTRAL RANGE (nm)
PRESENT:							
COCTS	CNSA (China)	HaiYang-1 (China)	15/05/02	1400	1100	10	402-12500
MERIS	ESA (Europe)	ENVISAT-1 (Europe)	01/03/02	1150	300/1200	15	412-1050
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	04/05/02	2330	1000	36	405-14385
MODIS-Terra	NASA (USA)	Terra (USA)	18/12/99	2330	1000	36	405-14385
OCI	NEC (Japan)	ROCSAT-1 (Taiwan)	27/01/99	690	825	6	433-12500
OCM	ISRO (India)	IRS-P4 (India)	26/05/99	1420	350	8	402-885
OSMI	KARI (Korea)	KOMPSAT (Korea)	20/12/99	800	850	6	400-900
SeaWiFS	NASA (USA)	OrbView-2 (USA)	01/08/97	2806	1100	8	402-885
FUTURE:							
S-GLI	NASDA (Japan)	GCOM (Japan)	2007	1600	750	11	412-865
VIIRS	NASA/IPO	NPP	2006	3000	370/740	22	402-11800
VIIRS	NASA/IPO	NPOESS	2009	3000	370/740	22	402-11800
OCM-II	ISRO (India)	IRS-P7 (India)	2005/06	--	--	--	--
KGOCI*	Korea	--	2008	3000	500	8	400 - 865
PAST:							
CMODIS	CNSA (China)	Shen Zhou-3 (China)	25/03/02 - 15/9/02	-	400	34	403-12500
CZCS	NASA (USA)	Nimbus-7 (USA)	24/10/78 - 22/06/86	1556	825	6	433-12500
CZI	CNSA (China)	HaiYang-1 (China)	15/05/02 - 1/12/03	500	250	4	420-890
GLI	NASDA (Japan)	ADEOS-II (Japan)	14/12/02 - 25/10/03	1600	250/1000	36	375-12500
MOS	DLR (Germany)	IRS P3 (India)	21/03/96 – early 04	200	500	18	408-1600

Source: International Ocean Colour Ocean Coordination Group at http://www.ioccg.org/sensors/500m.html.

* KGOCI will be in geostationary orbit. All others are in polar orbits with typical revisit times of 2-3 days.

The principal source of published ocean colour data presented or referred to in this chapter is the sea-viewing-wide field of view sensor (SeaWiFS). SeaWiFS was launched in 1997 as the operational successor to the CZCS and was one of the first of a new generation of ocean colour satellites (Hooker and McClain, 2000; Acker *et al*., 2002). Much of the processing, quality control and initial analysis of SeaWiFS data in this chapter was undertaken using SeaDAS software (freely available from http://seadas.gsfc.nasa.gov).

Analysis and interpretation of ocean colour data is often supported by data from the Advanced Very High Resolution Radiometers (AVHRR) aboard the US National Oceanographic and Atmospheric Administration (NOAA) series of satellites. AVHRR scanners deliver 4-5 channels (depending on model) including visible and sea surface temperature (SST) images at spatial resolutions comparable to most satellite borne ocean scanner data (Hastings and Emery, 1992). Successive satellites have resulted in a time series of AVHRR data back to 1986.

The launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) in December 1999 represented a further leap in ocean colour capability compared to SeaWiFS with more spectral bands, higher signal to noise ratio, more complex on-board calibration, and the capability of simultaneous observations of ocean colour and sea surface temperature (Joint and Groom, 2000). MODIS provides global coverage every 1-2 days. NASA provides free and open access to MODIS data, including access to merged data products (e.g. SeaWiFS/MODIS) – see http://modis.gsfc.nasa.gov/.

The MODIS sensors together with the European MEdium Resolution Imaging Spectrometer (MERIS) launched in March 2002 and the Chinese Moderate Resolution Imaging Spectroradiometer (CMODIS) launched in May 2002 provide increased coverage with correspondingly greater opportunities to capture short duration events.

Ocean Colour Products

Ocean colour sensors capture light scattered by the atmosphere and reflected from the sea surface as well as the light radiating from surface waters of the ocean. It is this 'water leaving radiance' which carries ecologically important signals. Ocean colour algorithms extract this signal and deliver various ocean colour products such as those listed in Table 2 (derived from Parslow *et al*. (2000)).

Table 2: Remote Sensed Products

Chlor	Chlorophyll fluorescence as a measure of phytoplankton biomass
ProductionW	Water column primary production using photosynthesis-irradiance relationships although suspended solids and dissolved organic matter in coastal waters may confound estimates of light attenuation which is required together with chlorophyll-a and surface irradiance, to calculate primary production.
Light	Light attenuation and water colour resulting from organic biomass (chlorophyll and other pigments), dissolved substances (yellow), and mineral particles
Pigment/type	Pigment composition and bloom type based on differences in absorption spectra (and perhaps back-scattering spectra) across algal classes
SS	Suspended sediments (particle back-scattering)
Yellow	Yellow substances – coloured dissolved organic matter
Dynamics	Physical dynamics using reflecting optical properties (ocean colour) of the upper layer which are considered better than infra red imagery.
Habitat	Bottom depth, benthic reflectance and habitat for optically shallow coastal waters (using hyperspectral sensor)
ProductionB	Benthic primary production may be derived from bottom light intensity (derived from surface irradiance and attenuation coefficients) and plant biomass distributions.

Note: Product identifiers relate to Table 3

Various texts describe the optical properties of ocean and coastal waters and provide the theoretical basis to extract signals of biological significance (e.g. Bukata *et al*., 1995; Kirk, 1994; Mobley, 1994).

Satellite mounted sensors have clear advantages over direct *in situ* observations but also suffer from some critical limitations mainly due to limited light penetration and 'noise' acquired as the signal passes through the water and atmosphere to the satellite.

Cloud cover fundamentally limits the areal extent of coverage although this can be minimised by extrapolation over time and space through modelling (Aiken *et al*., 1992) and, in some cases, by compositing successive images if features change slowly with respect to successive or complementary overpasses. Sun glint can also obscure the signal (Lockhart, 1994) although optimising the aspect of the sensor and careful analysis (e.g. appropriate stray light thresholds) can reduce this.

Another fundamental limitation is limited light penetration through water which restricts vertical coverage. Ocean colour sensors receive radiance from the 'optical depth' (depth of light penetration) which is related to the visible depth and ranges from >20m in oligotrophic tropical oceans to 5-10m in typical mesotrophic conditions and as little as 1-2m in high concentration phytoplankton blooms or sediment laden waters (Aiken *et al*., 1992). This can be a critical limitation for sub-surface chlorophyll maxima.

Other confounding factors relate to the effects of the water and atmosphere through which the signal passes. Algorithms must account for the bulk optical properties of the upper water column in order to extract relevant ocean colour products (Bukata *et al*., 1995) and optical effects due to gases and aerosols in the atmosphere must be addressed (Joint and Groom, 2000).

The development of inverse modelling techniques for the interpretation of ocean colour measurements is an ongoing process. Ground truth data are required to better quantify confidence limits for ocean colour products, especially for coastal applications including benthic mapping.

Recognition of these limitations of satellite borne ocean colour data and the need for integrated assessments has led to emphatic recommendations for remote sensing to complement rather than entirely replace *in situ* observations (e.g. IOCCG, 2000).

Chlorophyll and Primary Productivity

Ocean colour sensors were primarily developed for their potential to monitor chlorophyll and primary production. In general, chlorophyll-a can be measured more accurately *in situ* than from space (Engelsen *et al*., 2002) but remotely mounted sensors provide synoptic coverage over un-paralleled spatial scales and at frequencies unobtainable by any other sampling procedure.

Chlorophyll pigments are among the principal ocean colourants, but estimates of chlorophyll concentrations from satellite data are subject to the non-uniform distribution of chlorophyll concentration with depth. Furthermore, the non-linear relationship between photosynthetic primary production and photosynthetically available radiance can confound estimations of primary productivity.

Despite these problems, good estimates of open ocean primary production can be obtained and it is possible to estimate phytoplankton primary production for coastal waters by using algorithms which take local water characteristics into account (e.g. Bukata *et al*., 1995). Standard algorithms for estimating water column primary production are based on photosynthesis-irradiance relationships which rely on remote sensed chlorophyll-a, light attenuation and estimated surface irradiance. These estimates of primary production are extremely sensitive to light attenuation by substances other than phytoplankton (Platt *et al*., 1988) which can be problematic in coastal waters where high levels of suspended sediments and dissolved organic matter may be present. Furthermore, remotely sensed surface chlorophyll concentrations must be extrapolated to vertical chlorophyll profiles in order to estimate primary production. Historical *in situ* data, or supplementary sea surface temperature data, or physical modelling of mixed layer depths are usually used to extrapolate to chlorophyll profiles (Parslow *et al*., 2000).

Optically Complex Coastal Waters (Case 2 Waters)

Initial applications of ocean colour data focused on open ocean systems (Case 1 Waters) but with improved sensors, interest has focused on applications in coastal waters which are optically more complex (Case 2 Waters).

Unfortunately, the degree of optical complexity of a natural water body is, in general, directly related to its proximity to land masses (Bukata *et al*., 1995). In particular, coastal waters contain a variety of absorbing and scattering centres due to distributions of dissolved organic matter, suspended matter and air bubbles. Algorithms continue to be developed to improve both atmospheric corrections and chlorophyll-a estimates for Case 2 Waters. For instance, early atmospheric correction algorithms for open ocean (Case 1) waters assumed zero water leaving radiance from red or near infra-red wavelengths; these wavebands were used together with a prescribed aerosol reflectance spectrum to extrapolate and remove aerosols effects. However, the assumption of negligible near infra-red water leaving radiance breaks down for Case 2 waters. Additional wave bands and new algorithms have overcome some of these added complexities (e.g. Ruddick *et al*., 2000) but further scope remains for improvements.

The International Ocean Colour Coordination Group (IOCCG) reviewed algorithm development for Case 2 waters (IOCCG, 2000). The limited number of wavebands on CZCS did not allow the development of elaborate multi-waveband algorithms required for optically complex coastal waters. Significant advances have been made with the advent of the latest generation of satellite mounted ocean colour sensors and associated algorithm development. However, quantitative remote sensing of Case 2 waters will remain challenging because it is fundamentally a multivariable, non-linear problem. Accuracy of remotely sensed products will improve as the inherent optical properties of coastal waters are better understood. The development of inverse modelling techniques for coastal regions requires precise multispectral radiances, with contemporary optical and concentration measurements of the water constituents (Doerffer *et al*., 1999). IOCCG (2000) identified a general trend in Case 2 algorithm approaches towards model based techniques based on the first principles of ocean optics rather than on purely empirical approaches. Regional algorithms, optimised for local conditions, were found to perform well compared to global algorithms. Considerable scope exists for integration of regional or special case algorithms within an overarching branching algorithm.

IOCCG have emphasised a need for further work to ensure that error information is routinely available to avoid inappropriate application of remotely sensed data. The accuracy and precision of remote sensed products varies over conditions and concentrations due to the non-linearity of the system and the extreme ranges in the concentrations of individual components that contribute to ocean colour. Error estimates can be obtained from sensitivity analysis (models) and comparisons with *in situ* data recognising that there may be a mismatch in temporal and spatial scales of *in situ* data.

Environmental Issues and Applications

Satellite ocean colour imagery can provide cause and effect indicators at appropriate time and space scales for assessment and management of coastal systems (Parslow *et al.*, 2000). Satellite mounted ocean colour sensors provide complete global coverage, unencumbered by political and military sensitivities which can limit other observing systems, such as aerial photography. Potential and actual applications of ocean colour products have been categorised by issue or sector - see Table 3. The focus in this chapter will be on the top five issues in Table 3 because relevant ocean colour products are well established and freely available (e.g. MODIS and research applications using SeaWiFS). Published applications of data from more recent satellite scanners such as COCTS, MERIS and MODIS-aqua are less numerous than those from SeaWiFS, although recognised applications are equally varied (Doerffer *et al.*, 1999).

Table 3: Environmental and management issues served by remote sensed products*

Issues	Key Products**
global change and regional biogeochemical cycles The fundamental dynamics of coastal ecosystems and their role in the global carbon cycle will continue to change due to the cumulative effects of: climate induced changes to sea level, upper ocean temperatures and storm activity/erosion; coastal habitat change; fresh water impoundments; nutrient loading to coastal waters from catchments, sewage and atmospheric sources; and, over fishing. Changes need to be monitored, understood and where possible managed.	*Chlor* *ProductionW* *Dynamics*
eutrophication Excessive nutrient loadings from catchment and point sources can increase algal biomass and change species composition often favouring nuisance algae.	*Chlor*
harmful algal blooms Evidence suggests worldwide increase in incidence of harmful algal blooms over the last few decades (Anderson, 1995) possibly due to anthropogenic nutrient loadings, changed flushing regimes and introduced exotic species which can threaten wild and cultivated fisheries and tourism.	*Chlor* *Pigment/type*
impacts of catchment activities on estuarine and coastal waters Agriculture, forestry, mining, dams, irrigation schemes and urban/industrial development can change patterns of freshwater, sediment and nutrient and pollutant delivery and thus impact on coastal waters.	*Light* *Chlor* *SS*
wild fisheries Effective management of fisheries requires an ecosystem approach which in turn requires development of understanding and tools relating to many of the above.	*Light* *Chlor* *Pigment/type* *Dynamics*
aquaculture The rapidly growing aquaculture industry needs appropriate siting and monitoring of environmental impacts of, and on, the industry: *Macroalgae culture* depends on water quality including light attenuation *Shellfish culture* depends on phytoplankton biomass and composition (including harmful algae), and particle bound contaminants *Crustacean/fish ponds* are typically highly eutrophic so interactions with adjacent waters can be problematic *Fish cage culture* represents a large source of recycled nutrients but requires high water quality and is vulnerable to harmful algal blooms and anoxic sediments and bottom waters.	*Light* *Chlor* *Pigment/type* *Habitat* *ProductionW* *ProductionB* *SS* *Dynamics*
maritime operations Navigation, shipping, diving and hazard detection	*Light* *Habitat* *Dynamics*
impacts of coastal development on coastal habitats and changes in flushing rates Urban/tourist development, port/harbour development, dredging	*Light* *Habitat* *SS*

and outfalls can disturb or remove critical habitats, remobilise sediments and pollutants and change circulation patterns	
conservation Effective conservation requires an understanding of the spatial and temporal patterns of environmental forcing and the dynamical response of the marine ecosystem.	*all*
tourism Healthy coastal environments are critical in attracting visitors especially in high conservation areas which in turn can be threatened by tourist development.	*Light* *Chlor* *SS*
integrated coastal zone management Issues and uses of remote sensed data (above) interact strongly through coastal ecosystems. Core and derived remote sensed products contribute to assessments and a predictive understanding that will facilitate integrated management.	*all*

* based on Parslow *et al*. (2000)
** Key Products relate to Table 2.

Benthic habitat mapping requires spatial and spectral resolutions typically restricted to commercial airborne scanners and experimental satellite mounted hyperspectral scanners which are beyond the scope of this chapter. Green *et al*. (2000) provide general practical guidance on reliability, accuracy and cost of a wide range of remote sensing products, including habitat mapping with a focus on tropical coastal management.

The examples that follow serve to illustrate the spectrum of existing and potential applications of remote sensed ocean colour data. These applications are considered here: at the global scale (hundreds to thousands of kilometres) where emphasis has been on climate change and biogeochemical cycles; at the scale of regional seas (many tens to hundreds of kilometres) where mesoscale systems and processes have been investigated; and, within the coastal zone (scales of several to many tens of kilometres) where the effects of human activity on ecosystem health are often most apparent.

Global scale phenomena - biogeochemical cycles, climate change and El Niño Southern Oscillation

Early CZCS data revealed significant differences between northern and southern hemispheres: in the northern regions spring blooms dominated distributions of chlorophyll concentration whereas, in the southern ocean, currents and prevailing winds were the dominant factors explaining chlorophyll concentrations (Harris *et al*., 1993). A comprehensive re-analysis of CZCS data with improved algorithms incorporating *in situ* data now permits quantitative analysis of trends in global ocean chlorophyll spanning two decades (Gregg *et al*., 2002). CZCS (1979-1986) data have been reprocessed for comparison with SeaWiFS data (September 1997 – present) processed using the same algorithms (Antoine *et al.*, 2003; data available at http://www.rsmas.miami.edu/groups/rrsl/lpcm-seawifs-CZCS).

The oceans contain approximately 85% of the carbon circulating in the earth's biosphere and provide the main long term control of atmospheric CO_2 and the strength of the natural 'greenhouse effect' (Aiken *et al*., 2000). Remotely sensed ocean colour has been used with models and other data to estimate carbon 'removal' through the fixation of dissolved carbon by phytoplankton and its subsequent burial in sediment or export to deep ocean waters. Such research has suggested that the global ocean is a major sink for fossil and biogenic carbon released to the atmosphere by human activities (Parslow *et al*., 2000) while coastal areas appear to act globally as a net source because rivers inject massive quantities of land derived carbon (Smith and Hollibaugh, 1993). However, there is significant variability between various coastal zones (Smith and Hollibaugh, 1993) and through time (Kempe, 1995).

Ocean colour was used to assess sequestration of carbon to depth following the first *in situ* iron fertilisation experiment in the region of intermediate and deep water formation in the Southern Ocean (Boyd and Law, 2001). Iron limitation of phytoplankton growth was confirmed during summer but SeaWiFs imagery together with modelling suggested no significant downward particulate export of the accumulated phytoplankton. Boyd and Law speculated that mass algal sedimentation may have been prevented by horizontal dispersion of high chlorophyll-a waters to adjacent waters.

SeaWiFS has provided routine global chlorophyll observations since 1997 capturing the response of ocean phytoplankton to major El Niño and La Niña events as well as observing interannual variability unrelated to these phenomena.

SeaWiFS data, such as those presented in Figure 1, revealed seasonal chlorophyll distributions across the surface waters of the world's ocean as described by Gregg (2002). High latitudes regions experience a very wide seasonal range of chlorophyll, with a prominent and large local spring/summer bloom and a large die-off in local winter. Mid latitude regions exhibited much smaller seasonal differences, with local winter maxima. Chlorophyll patterns around India are associated with the northwest monsoon in December and the larger southwest monsoon in July (Gregg, 2002). Elevated chlorophyll levels in the equatorial Atlantic correspond to maximum upwelling (Monger *et al.*, 1997) while high levels during winter (e.g. December 1997) are associated with maximum discharge from the Congo River (Gregg, 2002).

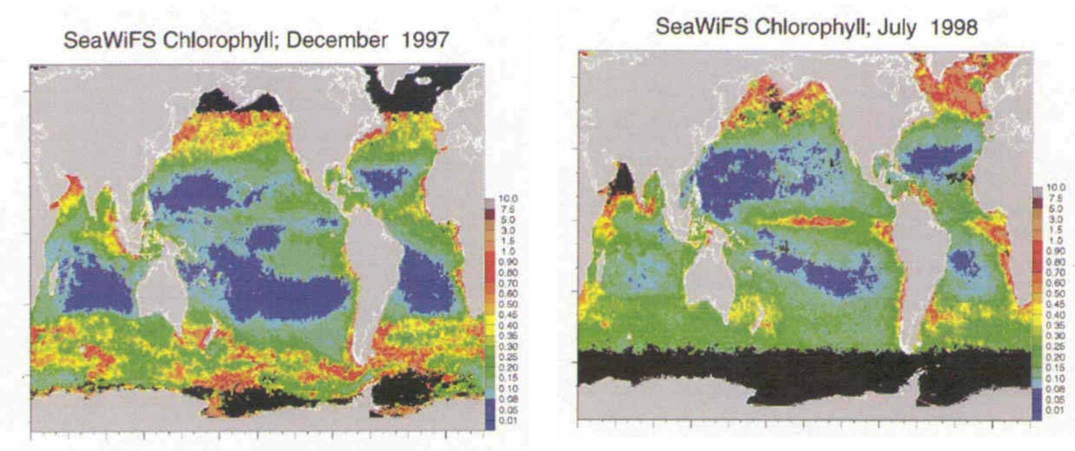


Figure 1: Monthly mean SeaWiFS chlorophyll for December 1997 and July 1998. These observations span a major transition from El Niño to La Niña. Areas of the Arabian Sea failed SeaWiFS criteria due to aerosol effects in December 1997. (modified from Gregg, 2002).

A major El Niño was underway in September 1997 when SeaWiFS was launched and continued until May 1998 when it was succeeded by a La Niña episode in the tropical Pacific. El Niño suppressed upwelling in equatorial Pacific resulting in a band of low chlorophyll just above the equator corresponding to the equatorial counter current (Figure 1). During the El Niño, abnormally high wind stresses in the eastern tropical Indian Ocean produced anomalous upwelling which resulted in high chlorophyll levels during December 1997. Re-establishment and intensification of upwelling conditions occurred in the equatorial Pacific when La Niña conditions developed.

A bloom developed rapidly during mid-1998 with a wave pattern centred on the equator culminating in the highest surface chlorophyll concentrations ever observed in the central equatorial Pacific, i.e. >1 mg m^{-3} (McClain *et al*., 2002). The magnitude and persistence of this bloom is self evident in the time sequence of estimated primary production shown in Figure 2. These data pose as yet unanswered questions about the mechanism that caused the bloom and how it was maintained for so long. In this region, iron is assumed to be the primary limiting nutrient (e.g. Coale *et al*., 1996) although wind data appear to discount Ekman upwelling as a source of iron and atmospheric iron supply remains equivocal (McClain *et al*., 2002). The persistence of the bloom and the apparent absence of a sustained source of iron suggest efficient retention within the surface layer and ineffective sedimentation over a few weeks or even months.

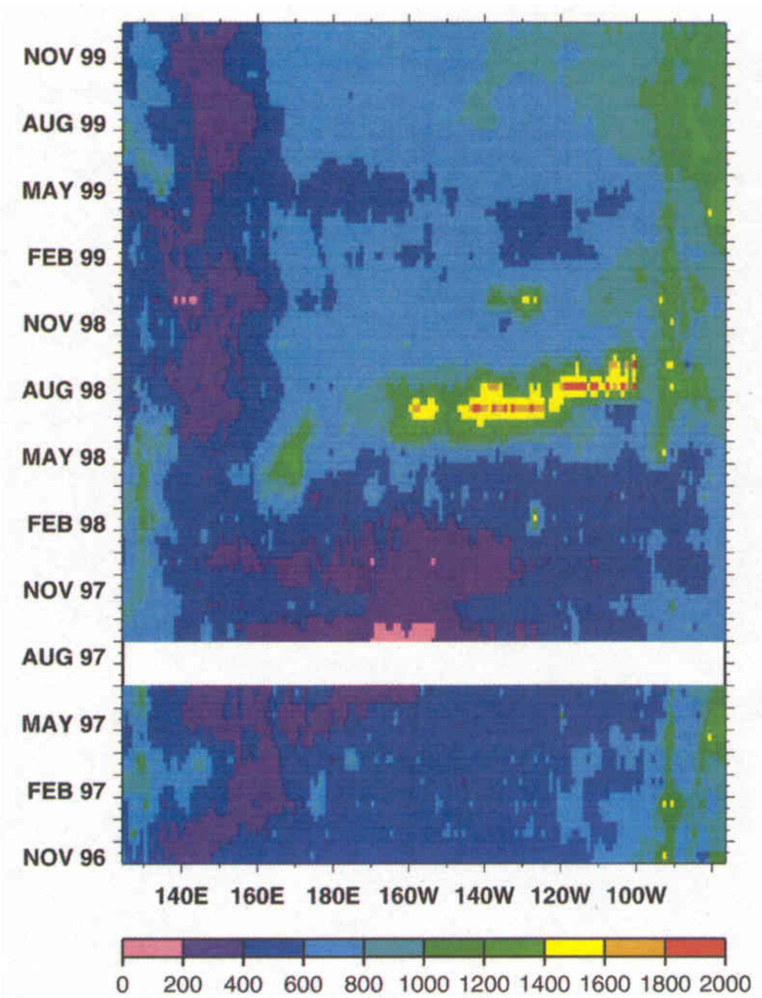


Figure 2: Longitude-time plot of primary production (mg C m^{-2} day^{-1}) based on OCTS and SeaWiFS monthly mean chlorophyll from McClain et al. (2002).

Recent research has focused on numerical modelling to investigate causal mechanisms and interrelationships of the variability observed in the ocean colour data. For example, Gregg (2002) tracked the SeaWiFS record with a coupled physical/biogeochemical/radiative model of the global oceans. Simulations suggested different phytoplankton responses of the Pacific and Indian ocean basins to El Niño: diatoms were predominant in the tropical Pacific during the La Niña, but other groups were predominant during El Niño – however, the opposite condition occurred in the tropical Indian Ocean.

Other studies have established linkages to meteorological forcing. Follows and Dutkiewicz (2002) used SeaWiFS data to identify meteorological modulation of the spring bloom in the North Atlantic and to examine the implications of decadal changes on biological productivity with a simplified model; Yakov et al. (2001) related seasonal phytoplankton cycles to meteorological factors influencing water stratification of the water column.

SeaWiFS data have also been used to develop and verify ocean general circulation models (OCMCs) which are critical in global warming assessments. For example, global monthly mean fields of the attenuation of photosynthetic radiation derived from SeaWiFS data have been used to investigate the importance of subsurface heating on surface mixed layer properties in OGCMs resulting in a marked increase in the sea surface temperature (SST) predictive skill of the OGCM at low latitudes (Rochford *et al*., 2002).

SeaWiFS data have also been used together with UV irradiance at the ocean surface (remotely sensed via the Total Ozone Mapping Spectrophotometer) to investigate the potential ecological effects of ozone depletion via a model of seawater optical properties in the UV spectral region (Vasilkov *et al*., 2001).

These studies are examples from a much larger body of work that has employed remote sensed ocean colour data to better understand global scale impacts resulting from human activities.

Regional seas – mesoscale processes and biological variability

Ocean colour data have been crucial in relating mesoscale processes to continental shelf ecology through studies of frontal features (Armstrong, 1994), eddies (Bardey *et al*., 1999), upwelling zones (Sathyendranath *et al*, 1991; Barlow *et al*. 2001), island wakes (Blain *et al*., 2001; Caldeira *et al*., 2002), current patterns (Lee *et al*., 2001), water mass distributions (Van Der Piepen *et al*., 1999; Karabashev *et al*., 2002 ; Gomes *et al*., 2000), and various water quality parameters.

Research has increasingly focused on integration of various remote sensed and *in situ* data. For example, McClain *et al*. (2002) analysed chlorophyll concentrations derived from SeaWiFS together with winds (in part from the satellite mounted scatterometer SeaWinds), sea surface temperature distributions (from AVHRR) and bathymetry data to investigate upwelling phenomena off the west coast of Central America. This region was known for strong upwelling and jets driven by winds that blow from the Atlantic through three narrow mountain passes (McCreary *et al*., 1989). Synoptic coverage of recent remote sensed data allowed elucidation of interactions between coastal upwelling jets and mesoscale eddies (McClain *et al*., 2002). Figure 3 shows monthly average data for March 1999 when all three upwelling regions were active. High chlorophyll levels (>1 mg m^{-3}) extended many hundreds of kilometers offshore from the three mountain passes and were associated with strong offshore wind stress and cool surface waters (1-3ºC contrast) consistent with jet-driven upwelling. Large mesoscale eddies were spawned by these wind driven offshore jets (McClain *et al*.,2002).

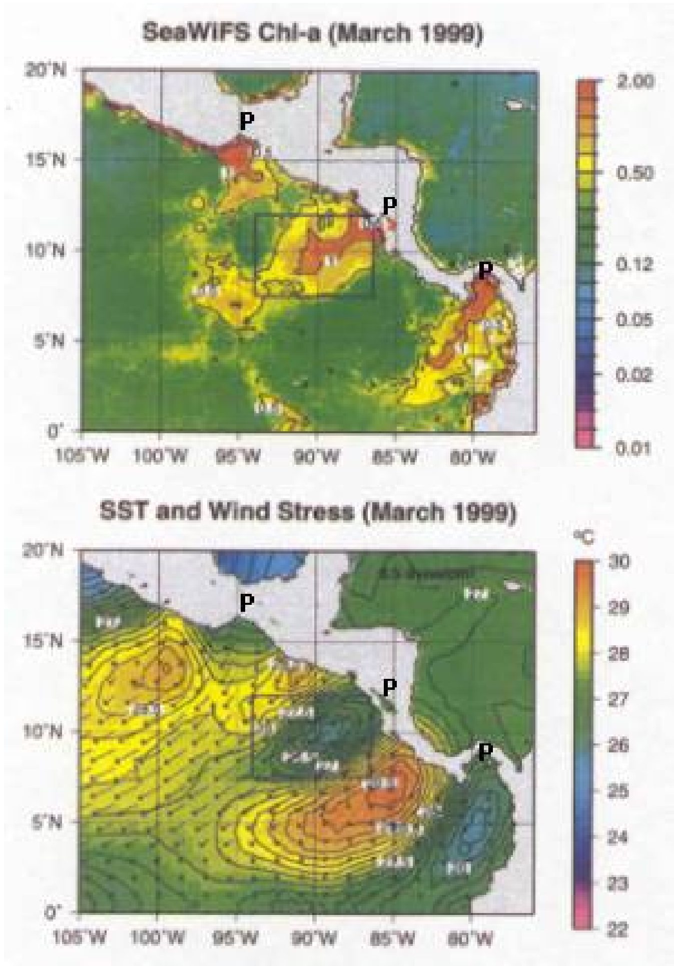


Figure 3: Monthly mean SeaWiFS chlorophyll-a (mg m^{-3}) and monthly mean sea surface temperature and wind stress vectors for March 1999. 'P' indicates location of mountain pass - modified from McClain et al. (2002).

A similar multi-faceted study used a range of simultaneous remote sensed data to investigate interactions between flow fields and topography/bathymetry around Madeira Island in the Northeast Atlantic (Caldeira, *et al*., 2002). AVHRR, CZCS and SeaWiFS data revealed: wind spiral vortices (Von Karman Vortex Street) in the lee of Madeira Island which served to expose the sea surface layer to intense solar radiation compared to cloud covered waters surrounding it; a warm water wake possibly associated with this solar heating (Figure 4); geostrophically balanced lee eddies spinning off both flanks of the island including cold core eddies associated with high productivity; localised upwelling and high productivity associated with an underwater ridge; and, evidence of the presence of a subtropical front at Madeira's latitude which may influence dispersion.

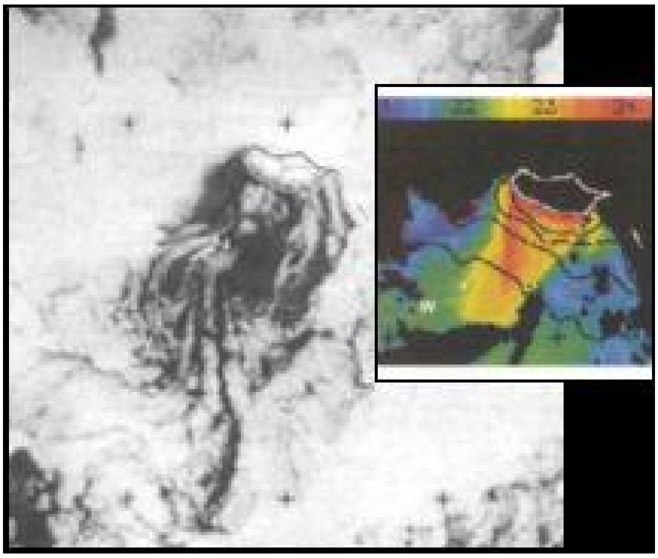


Figure 4: AVHRR image showing island mass effects causing interrupted cloud cover and spiral vortices in the lee of Madeira Island, North East Atlantic (19/8/94). An AVHRR sea surface temperature image illustrates typical warm water island wake off Madeira Island (28/7/96) when the wind was north northeast. Modified from Caldeira et al. (2002).

Semovski *et al*. (1999) used CZCS chlorophyll estimates together with AVHRR sea surface temperature data, AVHRR channel 1 data as a turbidity indicator, *in situ* data and modelling to describe the three dimensional ecosystem structure of mesoscale features in Baltic coastal waters.

A number of studies have used remote sensed ocean colour to monitor population dynamics of organisms dependent on phytoplankton. For example, early CZCS studies by Shannon (1985) related ocean colour to phytoplankton and pelagic fish distributions. Jaquet *et al*. (1996) showed that the distribution of sperm whales was strongly correlated with ocean colour (chlorophyll) and identified the time (and space) lag between peak chlorophyll concentration and peak sperm whale density with the coefficient of correlation increasing with increasing spatial scales. Polovina *et al*. (2000) identified an association between loggerhead turtles and frontal zones through analysis of remote sensed sea surface temperature, chlorophyll and geostrophic currents; this conclusion was offered to explain high incidental catches of loggerhead turtles when long line fishing coincided with frontal zones off Hawaii.

Understanding seasonally high primary productivity can be of great importance in some regions. For example, spring blooms in the Barents Sea provide a strong pulse of energy through the ice-associated and pelagic marine food webs which directly influences the abundance of upper trophic levels including large marine mammal and sea bird populations (Engelsen *et al*., 2002). Empirical formulae developed by Engelsen *et al*. (2002) provided estimates of integrated water column phytoplankton biomass using SeaWiFS data which held provided that light was the limiting factor.

Together these studies show that a great deal of mesoscale variability can only be observed using satellite remote sensing.

Coastal zones - human activity and ecosystem health

The feasibility of using remote sensing techniques for monitoring water quality in inland and coastal waters was initially limited by their complex optical properties (e.g. Kondratyev *et al*., 1998), but advances in sensors and algorithms deliver a means to discriminate the three main components that account for the optical complexity of Case 2 waters: phytoplankton, suspended sediments and dissolved organic matter. These same components may be used for assessing WATER QUALITY, ALGAL BLOOMS and FISHERIES in the coastal zone.

WATER QUALITY

Ocean colour (SeaWiFS data) supported by *in situ* observations has been used to investigate outpourings from rivers and coastal catchments. For instance: Mertes and Warrick (2001) found that disproportionately large plumes with high concentrations of suspended solids emanated from small coastal Californian catchments compared to large rivers; Siddorn *et al*. (2001) found an inverse relationship between salinity and yellow substances that could be used to determine the distribution of the Zambezi River plume; Del Castillo (2001) mapped the intrusion of the Mississippi River plume in the West Florida Shelf; and Andrefouet *et al*. (2002) found that river plumes off Honduras may extend to offshore coral reefs, indicating connectivity of these reefs with the mainland.

Turbid plumes originating from five coastal catchments in south east Australia after a high rainfall event are shown in Figure 5 (from Lee and Pritchard, 1999). *In situ* observations during this event confirmed low ocean chlorophyll levels

(<1μg/L) thus verifying that the plume images were due to terrigenous matter: the ocean colour scale corresponded to log ranges in measured total suspended sediments. A similar logarithmic relationship was found for the Gironde turbid plume in the Bay of Biscay (Froidefond *et al*., 2002). Spatial analyses were used in the Australian example to estimate the areal extent of the flood plumes as tabulated in Figure 5. The Hunter plume carried an estimated sediment load ~7000 tonnes based on remotely sensed areal extent and direct observations along offshore transects which indicated a plume layer thickness of ~1m out to 10 km from the entrance. Significant fallout and dispersion was inferred from the difference between the load carried within the plume and the discharge load estimated at the river mouth.

Woodruff *et al*. (1999) suggested that photosynthetically available radiation (PAR) attenuation may be estimated from long term AVHRR satellite data sets as a measure of turbidity: they developed a robust relationship between reflectance observed by AVHRR and light attenuation in Pamlico Sound estuary in North Carolina, USA although consistent relationships between reflectance and suspended sediment concentrations were elusive due to changing sediment characteristics.

Most studies focus on biological responses (of phytoplankton) to water quality but Budd *et al*. (2001) focused on water quality responses to biological activity (filter feeding). AVHRR reflectance imagery indicated distinct and persistent increases in water clarity after zebra mussels (*Dreissena polymorpha*) were discovered in 1991 in Saginaw Bay, Lake Huron, USA.

Few if any investigations of sewage plumes were found in the international scientific literature because, for satellite mounted ocean sensors, spatial scales are typically too coarse to resolve sewage plumes. However, untreated sewage discharged from Iraq via a man-made river was implicated as the source of pollution and algal blooms evident in SeaWiFS imagery off the shores of Kuwait in the Persian Gulf (Antonenko *et al*., 2001).

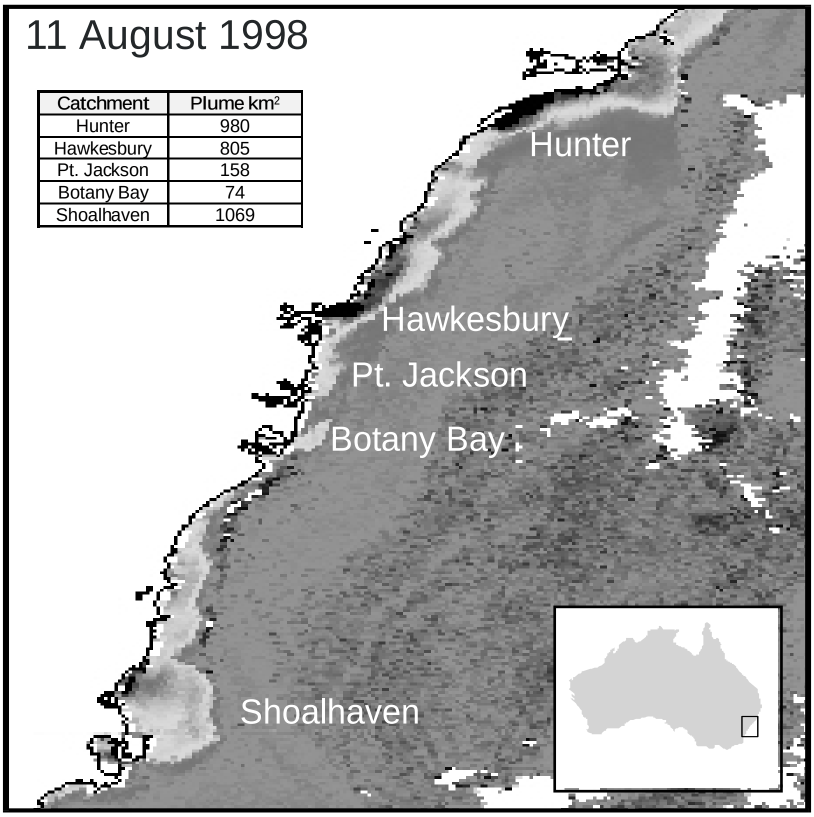


Figure 5: SeaWiFs image for 11 August 1998 indicated plumes emanating from the Hunter, Hawkesbury, Pt. Jackson, Botany Bay and Shoalhaven catchments in New South Wales, Australia (modified from Lee and **Pritchard**, 1999).

ALGAL BLOOMS

The ability to track harmful algal blooms from space can provide coastal communities and seafood harvesting industries with warnings of approaching blooms (Antonenko *et al*., 2001).

Algorithms are currently unavailable to distinguish between most types of phytoplankton blooms although SeaWiFS data have been used together with field data to monitor and predict specific harmful algal blooms (e.g. *Karenia brevis* blooms in the Gulf of Mexico – Stumpf, R.P., 2001).

Some bloom types have distinctive ocean colour signatures which allow them to be recognised from SeaWiFS data. Examples are the highly reflective coccolithophores which can have a profound effect on the ecosystem mainly due to extreme reductions in water clarity (Vance *et al*., 1998) – see Figure 6 - and, *Trichodesmium erythraeum* due to its distinctive spectral response (Subramaniam *et al*., 2002). Indeed SeaWiFS-derived *Trichodesmium* chlorophyll concentration has been used for remote estimation of nitrogen fixation by *Trichodesmium* (Hood *et al*., 2002).

Opportunities exist to use multiple sensors to monitor algal blooms: Lin *et al.* (1999) attempted to assess the relative performance of nine different types of satellite mounted ocean colour and high resolution visible sensors to monitor algal blooms while Rud and Gade (2000) have explored the benefits of using multi-sensor data (AVHRR, SeaWiFS, Landsat Thematic Mapper and ERS Synthetic Aperture Radar) for algal bloom monitoring.

Figure 6: Coccolithophore bloom off Cornwall, United Kingdom, on 18 May, 1998. True colour (Modular Optoelectric Scanner - MOS) from Deutsches Zentrum für Luft- und Raumfahrt, DLR (German Aerospace Centre).

The utility of remote sensed data for diagnostic and prognostic assessment of algal blooms is demonstrated in the Case Study later in this chapter.

FISHERIES

SeaWiFS data were used to demonstrate the relatively clear, pigment poor, surface waters of the Mediterranean with a generally increasing oligotrophy eastwards. Turley *et al*. (2000) suggested that the combination of low primary production and bacterial dominance of secondary production in the east could account for the low fisheries production, the low vertical flux of material and low biomass of benthic organisms in this region.

At a finer scale of resolution, Agostini and Bakun (2002) used mean seasonal satellite-sensed ocean colour, wind data and bathymetry to identify potentially favourable fish reproductive habitats in the Mediterranean based on nutrient enrichment, larval food distributions and local retention of eggs and larvae.

Platt *et al.* (2003) used ocean colour data from the periods 1979-81 (CZCS), 1997 (POLDER) and 1998-2001 (SeaWiFS) to demonstrate that the survival of larval fish (haddock - *Melanogrammus aeglefinus*) off the eastern continental shelf of Nova Scotia, Canada, depends on the timing of the local spring bloom of phytoplankton. They compared an index of survival (the year-class size at age 1 year divided by the spawning stock biomass) with anomalies in the timing of spring blooms (the difference in bloom timing from the mean timing for the series). 89% of the variance in larval survival could be accounted for by variation in the timing of the spring bloom. Early spring blooms favoured high survival rates, possibly due to greater overlap of spawning and bloom periods. Direct evidence for a putative trophic link such as this is an important factor in analysis of dwindling fish stocks.

Routine synergistic analysis of satellite borne ocean colour and sea surface temperature data sets is currently possible (eg. Solanki *et al*., 2001) for targeting fishing efforts and monitoring algal bloom development. In the future more frequent coincidence of data from existing and future sensors will deliver synergy between a greater range of remote sensed data including synthetic aperture radar data and data from thermal and optical satellite sensors as demonstrated by Ufermann *et al*. (2001).

Parslow *et al.* (2000) suggest that ocean colour data could best contribute to integrated coastal management via diagnostic and prognostic models that also assimilate *in situ* observations and supplementary remote sensed data (e.g. sea surface temperature via AVHRR, sea surface height via TOPEX/POSON, and winds via GEOSAT). At present, integration of ocean colour data for the coastal zone with corresponding physical/biogeochemical/radiative models remains a challenge due to the optical complexity of Case 2 waters and the requirement for higher spatial resolution compared to open ocean approaches.

Case study: marine algal blooms in coastal waters off southeast Australia

Management Issues

Eutrophication has been recognised as a serious threat to the health of coastal ecosystems both globally (e.g. Pelley, 1998) and within Australia (e.g. Zann, 1995). Phytoplankton represent the floating pastures of the ocean so changes in phytoplankton type and abundance due to eutrophication may profoundly affect the food web. Furthermore, some evidence exists for a worldwide increase in the occurrence of harmful algal blooms (Anderson, 1995; Paerl, 1997). Some biotoxins selectively kill fish by inhibiting their respiration while others affect humans generally via seafood.

Visible and/or harmful algal blooms have the potential to affect tourism in New South Wales (NSW), Australia, which is focused on coastal regions and is worth more than $A6 billion p.a. In NSW coastal waters, the magnitude and frequency of ‘red tides’ of the non-toxic dinoflagellate *Noctiluca scintillans* appear to have increased during the last two decades (Ajani *et al*., 2001a).

Prior to the 1990's, *N. scintillans* appeared as a relatively minor component of the phytoplankton community in NSW coastal waters (Dakin and Colifax, 1933), blooming infrequently (Hallegraeff, 1995; Ajani *et al*., 2001b). Since 1990, most 'red tides' in NSW have been due to *Noctiluca scintillans* (Figure 7) and in weekly sampling at Port Hacking off Sydney Ajani *et al.* (2001a) found *N. scintillans* in most samples. Major visible blooms of *Noctiluca scintillans* have aroused community and media concern in recent years such as that during January 1998 (see below).

Figure 7: Spectacular *Noctiluca scintillans* bloom off the popular tourist beach at Manly near Sydney, New South Wales, Australia during 1997. Frontal processes (local convergence) accumulated *Noctiluca* which was then fragmented by the wind into bright red streaks directed shoreward (windrows). Photo courtesy of Beachwatch, NSW EPA.

The NSW aquaculture industry, currently worth $A 42-45 million pa, is projected to increase to $A 250 million pa by 2010. Phytoplankton have been implicated in seafood contamination and fish kills at different times elsewhere in NSW coastal waters (Ajani *et al*., 2001b). For example, *Dinophysis acuminata*, a producer of diarrhetic shellfish poisoning (DSP), was implicated in the contamination of pipis (edible surf clam, *Donax sp*) at Ballina ~700km north of Sydney (December 1997) and Newcastle just south of Port Stephens (February 1998) with a total of 82 cases of gastroenteritis in consumers.

Regional Algal Coordination Committees have been established by the state government to manage responses to reports of algal blooms while seafood (biotoxin) issues are addressed through a *Pipi Biotoxin Management Plan* and a *SafeFood Marine Algal Biotoxin Contingency/Management Plan*. The *Pipi Biotoxin Management Plan* requires focused routine monitoring of phytoplankton in water samples while other plans are responsive to alerts (e.g. visible algal blooms). Prognostic and diagnostic tools would assist risk management of algal blooms relating to both recreational and seafood issues.

Developing a predictive understanding using remote sensed data

Natural upwelling/uplifting have been identified as the principal driver of marine (offshore) algal blooms in NSW coastal waters despite significant sewage inputs near major urban centres (Hallegraeff and Reid, 1986; Ajani *et al*., 2001a; Pritchard *et al*., 2003). This finding together with an understanding of upwelling/uplifting processes provides an opportunity to use remote sensed products together with meteorological data to predict periods of increased risk of marine algal blooms.

The combination of EAC activity on the shelf break (enhancing stratification and bottom stress) and upwelling favourable winds promotes upwelling (Tranter *et al*., 1986; Oke and Middelton, 1999, 2000; Pritchard *et al*., 2003). The thermal signatures of the East Australian Current and associated eddies are readily identifiable from remotely sensed sea surface temperature (via NOAA/AVHRR).

Most slope water intrusions that precede phytoplankton blooms on the NSW continental shelf do not outpour at the surface although in many instances surface water temperatures are depressed and can be identified on AVHRR images (Cresswell, 1994; Pritchard *et al*., 1999). Phytoplankton responses were found to lag several days behind intrusions of nutrient rich slope water so AVHRR images can provide early indications of risk of algal blooms.

Companion synoptic ocean colour can indicate oligotrophic EAC waters and monitor phytoplankton responses through time due to nutrient enrichment and cycling, and through space due to advection.

The vast majority of 'red tide' (visible) blooms in NSW marine waters have been due to either *Noctiluca scintillans* or *Trichodesmium erythraeum*. Remote sensed data provide a predictive and diagnostic capability as illustrated by the events described below.

Noctiluca Bloom – January 1998

AVHRR SST (Figure 8) and SeaWiFS ocean colour (Figure 9) for 11-12/1/98 identify the warm oligotrophic East Australian Current waters diverging from the coast off Port Stephens with cool water and high phytoplankton activity on the inside edge of this southward EAC flow. Meteorological observations indicated upwelling favourable winds during early and mid January 1998 (Lee *et al*., 2001). Investigative modelling has shown a tendency for intrusions of cool nutrient rich slope water onto the shelf associated with the changing shelf configuration to the north of Port Stephens (Oke and Middelton, 2000). More localised phytoplankton activity near Jervis Bay (12/1/98) is associated with a bathymetric protrusion which has also been shown to favour upwelling (Gibbs *et al*., 1997). A similar scenario appears to be in operation off Eden on the NSW south coast where a mesoscale anticyclonic eddy has intensified the divergent flow from the coast.

Regional southward flows on the shelf are indicated by wake effects in the lee of most major changes in the orientation of the coastline (SeaWiFS 12/1/98). Time series of ocean colour imagery provided greater resolution of flow features than AVHRR SST imagery although ocean colour cannot be regarded as a conservative tracer.

SeaWiFS imagery for 20/1/98 indicates the formation of a cyclonic (clockwise) back eddy inshore of the EAC front in the lee of a major change in shelf orientation near Port Stephens. Baroclinic instabilities, such as this eddy also favour upwelling and tend to be associated with along-shelf topographic variability such as that seen near Port Stephens (and Jervis Bay). Cyclonic eddies promote localised upwelling ('Ekman Pumping') because bottom stress associated with the clockwise rotation promotes convergence of bottom waters (towards the centre of the eddy) and, consequent upward transport together with divergence at the surface. Intense phytoplankton activity in this re-circulation cell, evident in Figure 9 (20/1/98), is consistent with further localised upwelling. The cell also tends to isolate nutrient rich waters, incubating phytoplankton which leaks southward with the regional flow on the shelf.

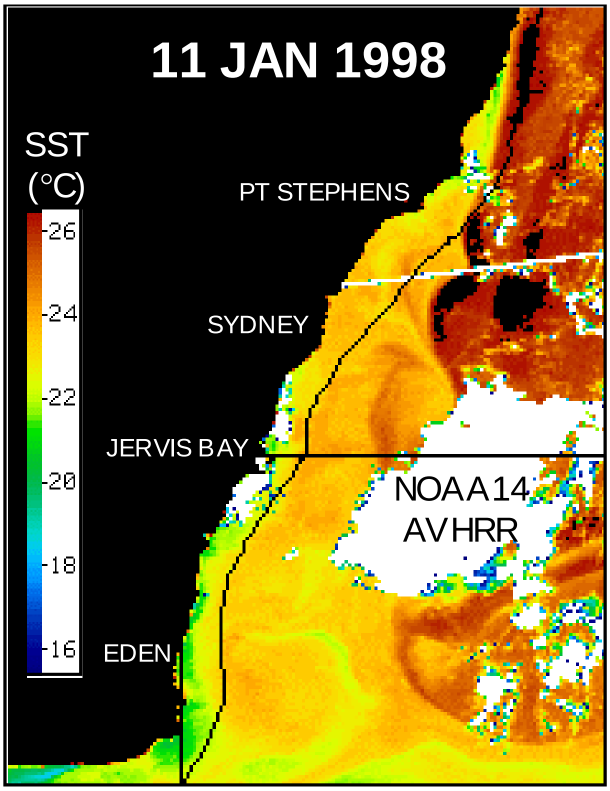


Figure 8: Sea surface temperature (SST) image showing separation of the East Australian Current from the shelf off Port Stephens (200m isobath shelf break indicated). Image courtesy of CSIRO Marine Laboratory.

In situ observations of temperature and chlorophyll-a throughout the water column off Sydney (Figure 10) support the notion of a remote source – that is, near simultaneous arrival of both slope water (nutrients to the euphotic zone) and phytoplankton with no evidence of a lag corresponding to expected phytoplankton response times. The notion of a remote source is consistent with indications of a maturing *Noctiluca* population with increasing southerly extent (Murray and

Suthers, 1999); modelling suggesting propensity for uplifting of slope water north of Port Stephens and subsequent southward transit (Oke and Middleton, 2000); and previous observations of EAC induced upwellings being advected southward as a plume by ambient flows (Cresswell, 1994).

In situ observations (Figure 10) were important in verifying SeaWiFS chlorophyll-a distributions with respect to the vertical position of chlorophyll-a maxima. CTD data (not shown) along the transect between PH50 and PH100 on 15/1/98 indicated prominent shoreward tilting of isotherms, consistent with the vertical distribution of chlorophyll-a at PH100 due to the upwelling forcing. Figure 10 shows phytoplankton blooms were clearly within the upper mixed layer and thus amenable to mapping by satellite borne ocean colour scanners. *In situ* data complements remote sensed data by highlighting the role of thermal structure in controlling the vertical distributions of phytoplankton and raising questions about the relative importance of temperature, nutrient and light limitation and the effects of density stratification.

Widespread visible blooms ("red tides") of the heterotrophic dinoflagellate *Noctiluca scintillans* were recorded from 22 January, consistent with the end stages of the bloom when senescent cells become buoyant and accumulate along surface zones of convergence (Ajani *et al*, 2000b).

Clearly, remote sensed ocean colour together with SST supported by some *in situ* observations provide the means to forecast algal bloom risk and diagnose initiation sites, which in this case were distant from major anthropogenic nutrient discharges off Sydney. Indeed during the summer of 1998 all major visible blooms reported in the NSW marine waters were preceded by predictions of high algal bloom risk based mainly on remote sensed data.

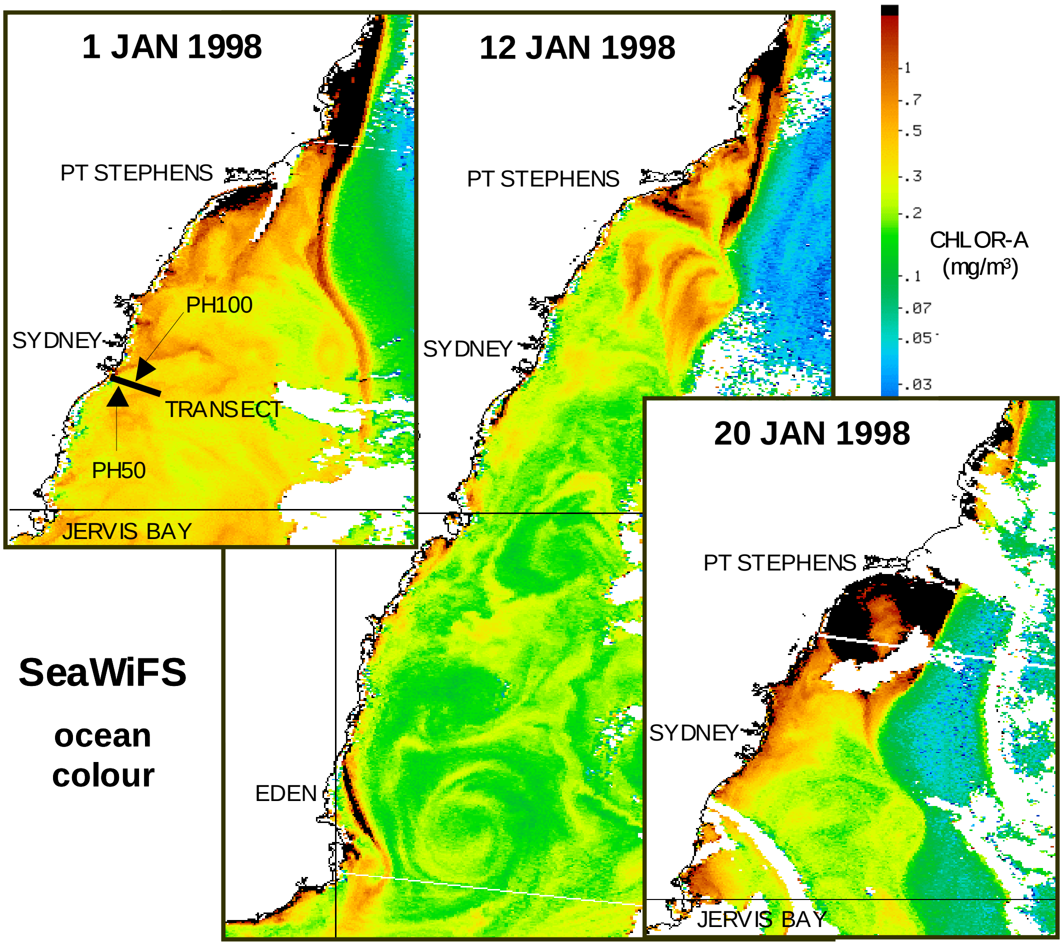


Figure 9: SeaWifS chlorophyll-a estimates during January 1998 indicate phytoplankton accumulations along fronts in the lee of major changes in the orientation of the coastline especially along the inner edge of the East Australian Current south of Port Stephens which ultimately formed a plankton-rich cyclonic eddy on 20/1/98. Images courtesy of CSIRO Marine Laboratory.

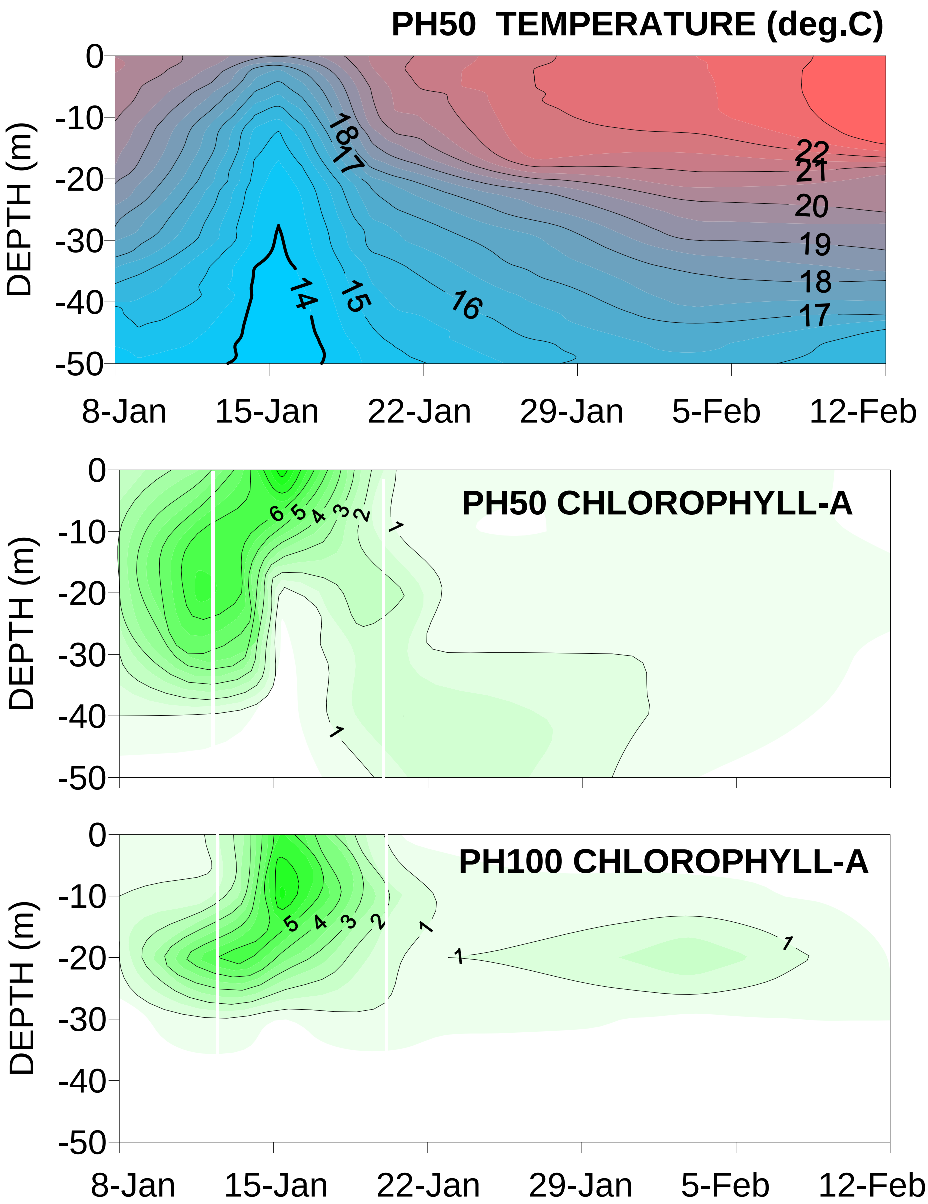


Figure 10: Contoured time series CTD temperature data (ºC) and in situ chlorophyll-a data (µg/L) off southern Sydney at PH50 (2km offshore in 55m of water) and chlorophyll-a at PH100 (5km offshore in 105m of water) - based on sampling at 10m depth intervals on 8,13,15 & 20 January and 3 & 12 March 1998. SeaWiFS images were obtained for dates indicated by white stripes.

Trichodesmium Bloom – March/April 1998

A large *Trichodesmium erythraeum* bloom developed at Batemans Bay on the south coast of NSW in early April 1998. The cyanobacterium *T. erythraeum* is a common 'red tide' organism in NSW coastal waters transported there from northern tropical waters by the East Australian Current. The annual distribution of this species monitored off Port Hacking shows peak concentrations in the coastal waters off Sydney in mid-April when surface waters were >~22^{o}C (Ajani *et al.,* 2001a).

One week before the bloom was reported, AVHHR imagery for 28th March 1998 showed unusually warm water throughout the NSW south coast area associated with a strong manifestation of the EAC (Figure 11). Corresponding SeaWiFS data showed low levels of chlorophyll-a within the EAC filament but high levels of productivity accumulated and entrained along the inner edge of EAC water. The zone of high productivity moved southward to Batemans Bay (5 April 1998) where the resulting *Trichodesmium erythraeum* bloom caused oysters from the estuary to be withdrawn from markets over Easter. Toxicity testing using a mouse bioassay technique revealed a present, but unknown, toxin. Previous reports (Hahn and Capra, 1992; Endean *et al*. 1993) also suggest that *T. erythraeum* can produce compounds with mouse intraperitoneal potency but this requires further investigation. No human health impacts were reported.

This case study provides a powerful example of the ability of remote sensed synoptic data to diagnose the origins and suggest the likely prevalence of algal blooms.

Conclusions

The purpose of this chapter was to demonstrate the utility of remote sensed ocean colour data in order to expose opportunities for future marine ecosystem assessments.

Remotely sensed data have been critical in developing mechanistic connections between meteorological/climate change, biological productivity, carbon sequestration and thus oceanic ecosystem health. Satellite mounted ocean colour sensors deliver a range of products including chlorophyll estimates that provide a synoptic (and global) view of phytoplankton distributions in near real time. A myriad of applications to coastal ecosystems have been spawned by the current generation of ocean colour sensors. Together these studies show that a great deal of mesoscale variability can only be observed using satellite remote sensing.

The main limitations in the use of ocean colour are cloud cover, confounding optical effects and limited penetration in cases where maximum phytoplankton biomass occurs at depth. Algorithms for open ocean (Case 1) waters are reasonably robust while algorithms for coastal (Case 2) waters are less reliable. Precise multispectral radiances, with contemporary optical and concentration measurements of the water constituents are required to further develop and validate these algorithms.

There is a concerted effort to correlate the data collected by different scanners to realise the combined coverage offered by various ocean colour sensors currently in orbit. Furthermore, new algorithms have been developed to provide greater consistency between new and archived ocean colour data in order to investigate trends in global ocean chlorophyll since the 1980's.

Most current research using ocean colour data includes synergistic analysis of a range of remote sensed and *in situ* data often through modelling approaches. Ocean colour data are increasingly applied for initialisation, assimilation, calibration and verification of physical/biogeochemical models.

Further developments are expected for monitoring marine primary production (and its role in sequestering atmospheric carbon), algal blooms, impacts of human activities on coastal waters, and to support wild and aquaculture fisheries. Opportunities exist and will continue to emerge for synergistic analysis of multiple synoptic data sensed from space.

Free and open access of ocean colour data such as that from NASA's MODIS sensors and access to merged data products promises to launch a new era of accelerated ocean colour research with broad applications in ecosystem assessments.

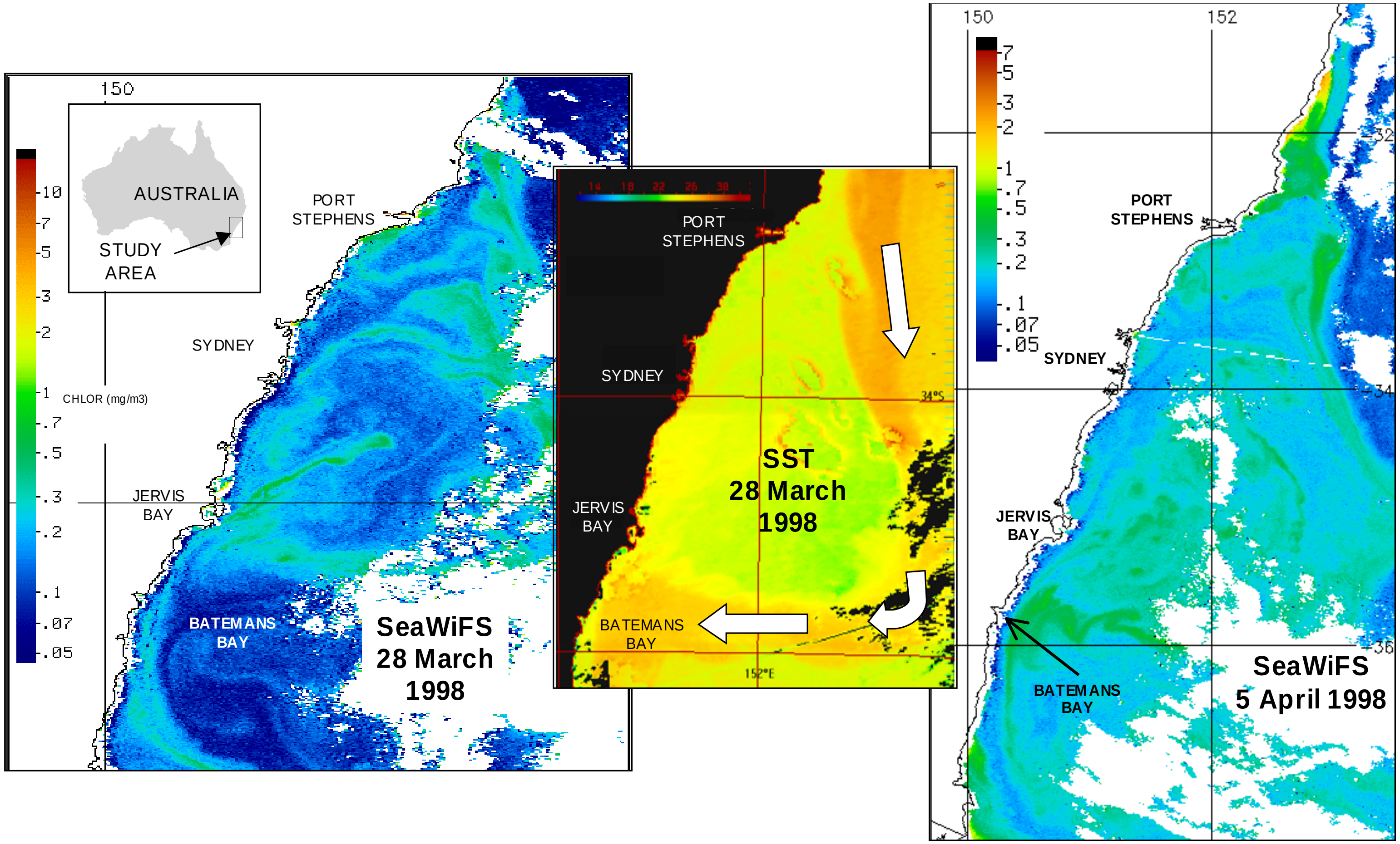


Figure 11: East Australian Current waters depicted by warm sea surface temperature (SST in °C) carried *Trichodesmium erythraeum* with high chlorophyll waters on the EAC front to Batemans Bay (depicted by SeaWiFS chlorophyll-a in mg/m^3) where oyster fisheries were disrupted during Easter 1998. Images courtesy of CSIRO Marine Laboratory.

Acknowledgements

Jocelyn Dela Cruz assisted with an extensive literature search and suggested approaches to support the literature review. NSW Department of Environment and Conservation (formerly Environment Protection Authority) funded much of the research that led to the case studies and Commonwealth Scientific and Industrial Research Organisation Marine Research provided many of the remote sensed images

References

Acker, J.C., Shen, S., Leptoukh, G., Serafino, G. Feldman, G, and McClain, C. 2002. SeaWiFS ocean colour data archive and distribution system: Assessment of system performance. IEEE Tranactions on Geoscience and Remote Sensing, 40 (1), 90-103.

Agostini, V.N. and Bakun, A., 2002. 'Ocean triads' in the Mediterranean Sea: physical mechanisms potentially structuring reproductive habitat suitability (with example application to European anchovy, *Engraulis encrasicolus*). Fish.Oceanogr. 11:3, 129-142.

Aiken, J., Moore, G.F. and Holligan, P.M., 1992. Remote sensing of oceanic biology in relation to global climate change. J.Phycol., 28, 579-590.

Aiken, J., Rees, N., Hooker, S., Holligan, P., Bale, A., Robins, D., Moore, G., Harris, R. and Pilgrim, D., 2000. The Atlantic Meridinal Transect: overview and synthesis of data. Progress in Oceanography, 45, 257-312.

Ajani, P.A., Lee, R.S., Pritchard, T.R., and Krogh, M., 2001a. Phytoplankton patterns at CSIRO's long-term coastal station off Sydney, Journal Coastal Res., 34, 60-73.

Ajani, P.A., Hallegreaff, G.M., Pritchard, T.R., 2001b. Historic overview of Algal blooms in marine and estuarine waters of New South Wales, Australia, Proc. Linn. Soc. NSW, 123, 1-22.

Anderson, D. M., 1995. Toxic red tides and harmful algal blooms: a practical challenge in coastal oceanography. Rev. Geophysics, Suppl. U. S. National Report to the Int. Union of Geodesy and Geophysics. 1991-1994. pp. 1189-1200.

Andrefouet, S., Mumby, P.J., McField, M., Hu, C. and Muller, F.E., 2002. Revisiting coral reef connectivity. Coral Reefs, 21, 43-48.

Antoine, D., Morel, A., Gentili, B., Gordon, H.R., Branzon, V.F., Evans, R.H., Brown, J.W., Walsh, S., Baringer, W. and Li, A. 2003. In search of long-term trends in ocean colour. EOS, 84 (32), 301-309.

Antonenko, I., McClain, C. and Feldman, G., 2001. Coastal applications of SeaWiFS data. Proceedings of the 2nd Biennial Coastal Geotools Conference, Charlestown, SC, January 8-11, 2001.

Armstrong, R.A., 1994. Oceanic fronts in the northeastern Caribbean revealed by satellite ocean colour imaging. Int.J.Remote Sens., 15 (6), 1169-1994.

Bardey, P., Garnesson, P., Moussu, G. and Wald, L., 1999. Joint analysis of temperature and ocean colour satellite images for mesoscale activities in the Gulf of Biscay. Int.J.Remote Sensing, 20 (7), 1329-1341.

Barlow, R.G., Aiken, J., Sessions, H.E., Lavender, S. and Mantel, J., 2001. Phytoplankton pigment, absorption and ocean colour characterization in the southern Benguela ecosystem. South African Journal of Sciences, 97, 230-238.

Blain, S., Treguer, P., Belviso, S., Bucciarelli, E., Denis, M., Desabre, S., Fiala, M., Jezequel, V.M., Le Fevre, J., Mayzaud, P., Marty, J.C. and Razoul, S., 2001. A biogeochemical study of the island mass effect in the context of the iron hypothesis: Kerguelen Islands, Southern Ocean. Deep-Sea Research I, 48, 163-187.

Boyd, P.W. and Law, C.S., 2001. The Southern Ocean Iron Release Experiment (SOIREE) – introduction and summary. Deep-Sea Research II, 48, 2425-2438.

Budd, J.W., Drummer, T.D., Nalepa, T.F. and Fahnenstiel, G.L., 2001. Remote sensing of biotic effects: Zebra mussels (*Dreissena polymorpha*) influence on water clarity in Saginaw Bay, Lake Huron. Limnol. Oceanogr., 46 (2), 213-223.

Bukata, R.P., Jerome, J.H., Kondratyev, K.Y. and Pozdnyakov, D.V., 1995. Optical Properties and Remote Sensing of Inland and Coastal Waters. CRC Press, ISBN 0-8493-4754-8.

Caldeira, R.M.A., Groom, S., Miller, P., Pilgrim, D. and Nezlin, N.P., 2002. Sea-surface signatures of the mass effect phenomena around Madeira Island, Northeast Atlantic. Remote Sensing of Environment, 80, 336-360.

Coale, K.H. *et al*., 1996. A massive phytoplankton bloom induced by an ecosystem scale iron fertilisation experiment in the equatorial Pacific Ocean. Nature, 383, 495-501.

Cresswell, G., 1994. Nutrient enrichment of the Sydney continental shelf. Aust. J. Mar. Freshwater Res. 45, 677-691.

Dakin, W. J. and Colifax, A. 1933. The marine plankton of the coastal waters of New South Wales. 1. The chief planktonic forms and their seasonal distribution. Proceedings Linnean Society N.S.W 58: 186-222.

Davis, C. S., S. M. Gallager, and A. R. Solow. 1992. Microaggregations of oceanic plankton observed by towed video microscopy. Science 257: 230-232.

Del Castillo, C.E., 2001. Multispectral *in situ* measurements of organic matter and chlorophyll fluorescence in seawater: Documenting the intrusion of the Mississippi River plume in the West Florida Shelf. Limnol.Oceanogr., 46 (7), 1836-1843.

Doerffer, R., Sorensen, K. and Aiken, J., 1999. MERIS potential for coastal zone applications. Intl. J. Remote Sens., 20(9): 1809-1818.

Endean, R., Monks, S. A., Griffith, J. K. and Llewellyn, L. E., 1993. Apparent relationships between toxins elaborated by the cyanobacterium *Trichodesmium erythraeum* and those present in the flesh of the narrowbarred Spanish mackerel *Scomberomorus commersoni*. Toxicology. 31(9):1155-1165.

Engelsen, O., Hegset, E.N., Hop, H., Hansen, E. and Falk-Petersen, S., 2002. Spatial variability of chlorophyll-a in the Marginal Ice Zone of the Barents Sea, with relations to sea ice and oceanographic conditions. Journal of Marine Systems, 35, 79-97.

Follows, M. and Dutkiewicz, S., 2002. Meteorological modulation of the North Atlantic spring bloom. Deep-Sea Research II, 49, 321-344.

Froidefond, J.M., Lavender, S. Laborde, P., Herbland, P. and Lafon, V. 2002. SeaWiFS data interpretation in a coastal area in the Bay of Biscay. International Journal of Remote Sensing, 23 (5), 881-904.

Gibbs,M.T., Marchesiello, P. and Middleton, J.H., 1997. Nutrient enrichment of Jervis Bay during the massive 1992 coccolithophorid bloom. Mar.Freshwater Res, 48, 473-8

Gomes, H.R., Goes, J.I. and Saino, T., 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. Continental Shelf Research, 20, 313-330.

Green, E.P., Mumby, P.J., Edwards, A.J., Clarke, C.D. (Ed. A.J.Edwards), 2000. Remote Sensing Handbook for Tropical Coastal Management. Coastal Management Sourcebooks 3, UNESCO, Paris.x +316pp.

Gregg, W.W., 2002. Tracking the SeaWiFS record with a coupled physical/biogeochemical/radiative model of the global oceans. Deep-Sea Research II, 49, 81-105.

Gregg, W.W., Conkright, M.E., O'Reilly, J.E, Patt, F.S. Wang, M.H.H, Yoder, J.A. and Casey, N.W. 2002. NOAA-NASA coastal zone colour scanner reanalysis effort. Applied Optics, 41 (9), 1615-1628.

Hahn, S. T. and Capra, M. F., 1992. The cyanobacterium Oscillatoria erythraea- a potential source of toxin in the ciguatera food-chain. Food Additives and Contaminants. 9: 351-355.

Hastings, D.A. and Emery, W.J. 1992. The Advanced Very High Resolution Radiometer (AVHRR): A Brief Reference Guide. Photogrammetric Engineering and Remote Sensing, 58 (8), 1183-1188.

Hallegraeff, G. M., 1995. Algal blooms in Australian waters. Water, July/August, 19-23.

Hallegraeff, G. M. and Reid, D.D., 1986. Phytoplankton species successions and their hydrological environment at a coastal station off Sydney. Aust .J. Mar. Freshwater. Res. 37, 361-377.

Harris, G.P., Feldman, G.C. and Griffiths, F.B. In Barale, V. and Schlittenhardt, P.M. (Eds), 1993. Ocean Colour: Theory and Applications in a Decade of CZCS Experience. Kulwer Academic Publishers, 237-270.

Hood, R.H., Subramaniam, A., May, L.R., Carpenter, E.J. and Capone, D.G., 2002. Remote estimation of nitrogen fixation by *Trichodesmium*, Deep-Sea Research II, 49, 123-147.

Hooker, S.B. and McClain, C.R., 2000. The calibration and validation of SeaWiFS data. Progress in Oceanography, 45, 427-465.

IOCCG, 2000. Remote Sensing Ocean Colour in Coastal, and Other Optically-Complex, Waters. Sathyendranath, S. (ed.), Reports of the International Ocean-Colour Coordinating Group, No.3, IOCCG, Dartmouth, Canada.

Jaquet, N., Whitehead, H. and Lewis, M., 1996. Cogerenece between 19th cebtury sperm whale distributions and satellite-derived pigments in the tropical Pacific. Mar.Ecol.Prog.Ser., 145, 1-10.

Joint, I. and Groom, S.B., 2000. Estimation of phytoplankton production from space: current status and future potential of satellite remote sensing. Journal of Experimental Marine Biology and Ecology, 250, 233-255.

Karabashev, G., Evdoshenko, M. and Sheberstove, S. 2002. Penetration of coastal waters into the Eastern Mediterranean using SeaWiFS data. Oceanologica Acta, 25 (1), 31-38.

Kempe, S., 1995. Coastal Seas: a net source or sink of atmospheric carbon dioxide? Land-Ocean Interactions in the Coastal Zone (LOICZ) Reports and Studies, Number 1, p.27.

Kirk, J.T.O., 1994. Light and Photosynthesis in Aquatic Ecosystems, 2nd ed., Cambridge University Press.

Kondratyev, K.Y., Pozdnyakov, D.V. and Pettersson, L.H., 1998. Water quality remote sensing in the visible spectrum. Int.J.Remote Sensing, 129:5, 957-979.

Lee, R. S. and Pritchard, T. R., 1999. Extreme Discharges into the Coastal Ocean: A Case Study of August 1998 Flooding on the Hawkesbury and Hunter Rivers. Pacific Coasts and Ports '99 Proceedings, Perth, W.A.

Lee, R. S. and Pritchard, T. R., Ajani, P., Wallace, S., Pritchard, T. and Black, K. 2001. Anomalous Upwelling along Australia's East Coast. Journal Coastal Res., 34, 96-109.

Lin, I-I, Khoo, V., Holmes, M., Teo, S., Koh, S.T. and Gin, K., 1999. Tropical Algal Bloom Monitoring by Sea Truth, Spectral and Simulated Satellite Data. IEEE, 931-933.

Lockhart, R., 1994. Remote Sensing of Ocean Bio-mass Productivity. Curtain University of Technology, Dept Applied Physics, Rep No. UG249/1994.

McClain, C.R., Christian, J.R., Signorini, S.R., Lewis, M.R., Asanuma, I., Turk, D., Dupouy-Douchement, C.D., 2002. Satellite ocean colour observations of the tropical Pacific Ocean. Deep-Sea Research II, 49, 2533-2560.

McCreary, Jr.,J.P., Lee, H.S., Enfield, D.B., 1989. The response of the coastal ocean to strong offshore winds; with application to circulations in the Gulfs of Tehuantepec and Papagayo. Journal of Marine Research, 47. 81-109.

Mertes, L.A.K. and Warrick, J.A., 2001. Measuring flood output from 110 coastal watersheds in California with field measurements and SeaWiFS. Geology, 29:7, 659-662.

Mobley, C.D., 1994. Light and Water, Radiative Transfer in Natural Waters. Academic Press.

Monger, B., McClain, C., Murtugudde, R, 1997. Seasonal phytoplankton dynamics in the eastern tropical Atlantic. Journal of Geophysical Research, 102, 12389-12411.

Murray, S., and Suthers, I.M., 1999. Population ecology of Noctiluca scintillans Macartney, a red-tide-forming dinoflagellate, Mar. Freshwater Res., 50, 243-252.

Nihoul, J.C.L. (Ed.) 1984. Remote Sensing of shelf sea hydrodynamics. Elsevier Oceanographic Series, 38.

Oke, P.R. and Middleton, J.H., 1999. Nutrient enrichment off Port Stephens: the Role of the East Australian Current. Continental Shelf Research.

Oke, P.R. and Middleton, J.H., 2000. Topographically Induced Upwelling off Eastern Australia. Journal of Physical Oceanography, 30, 3, pp.512-531.

Parslow, J.S., Hoepffner, N., Doerffer, R., Campbell, J.W., Schlittenhardt, P., Sathyendranath, S., 2000. Case 2 Ocean Colour Applications. In: IOCCG (2000). Remote Sensing Ocean Colour in Coastal, and Other Optically-Complex, Waters. Sathyendranath, S. (ed.), Reports of the International Ocean-Colour Coordinating Group, No.3, IOCCG, Dartmouth, Canada.

Paerl, H., 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnology and Oceanography, 42(5), 1154-1165.

Pelley, J., 1998. ‘Is Coastal Eutrophication Out of Control?’ Environmental Science and Technology, October 1998, 462-466.

Platt, T., Fuentes-Yako, C. and Frank, K.T., 2003. Spring algal bloom and larval fish survival. Nature, 423, 398-399.

Platt, T. and Sathyendranath, S., 1988. Oceanic primary production: estimation by remote sensing at local and regional scales. Science, 241, No.4873, 1613-1620.

Platt, T., Sathyendranath, S.,Caverhill, C.M. and Lewis, M.R., 1988. Ocean primary production and available light: Further algorithms for remote sensing. Deep-Sea Res. 135: 855-897.

Polovina, J.J., Kobayashi, D.R., Parker, D.M., Seki, M.P. and Balazs, G.H., 2000. Turtles on the edge: movement of loggerhead turtles (Caretta caretta) along oceanic fronts, spanning longline fishing grounds in the cetral North Pacific, 1997-1998. Fisheries Oceanography, 9, 71-82.

Pritchard, T., Lee, R. and Ajani, P., 1999. Anthropogenic and oceanic nutrients in NSW’s dynamic coastal waters and their effect on phytoplankton populations. 14th Australian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference – Coasts and Ports 1999

Pritchard, T.R, Lee,R.S., Ajani,P.A., Rendell.P.S., Black,K. and Koop,K, (2003) Phytoptoplankton responses to nutrient sources in coastal waters off southeastern Australia. Aquatic Ecosystem Health and Management. 6 (2), 105-117

Rochford, P.A., Kara, A.B., Wallcraft, A.J. and Arnone, R.A. 2002. Importance of solar subsurface heating in ocean general circulation models. J.Geophys.Res- Oceans, 106 (C12), 30923-30938.

Rud, O. and Gade, M., 2000. Using Multi-Sensor Data for Algal Bloom Monitoring. IEEE, 1714-1716.

Ruddick, K.G., Ovidio, F. and Rijkeboer, M., 2000. Atmospheric correction of SeaWiFS imagery for turbit coastal and inland waters. Applied Optics, 39 (6), 897-912.

Sathyendranath, S., Platt, T., Home, E.P.W., Harrison, W.G., Ulloa, O., Outerbridge, R. and Hoepffner, N., 1991. Estimation of new production in the ocean by compound remote sensing. Nature, 353, 129-133.

Semovski, S.V., Dowell, M.D., Hapter, R., Szczucka, J., Beszcynska-Moller, A. and Darecki, M., 1999. The integration of remotely sensed, seatruth and modelling data in the investigation of mesoscale features in the Baltic coastal phytoplankton field. Int.J.Remote Sensing, 20 (7), 1265-1287.

Shannon, L.V. (Ed.), 1985. South African Ocean Colour and Upwelling Experiment. Sea Fisheries Research Institute, Cape Town [ISBN 0 621 07386 5].

Siddorn, J.R., Bowers, D.G. and Hoguane, A.M., 2001. Detecting the Zambezi River Plume using Observed Optical Properties. Marine Pollution Bulletin, 42:10, 942-950.

Smith, S.V. and Hollibaugh, J.T., 1993. Coastal metabolism and the oceanic carbon balance. Rev.Geophys. 31: 75-89.

Solanki, H.U., Dwivedi, R.M. and Nayak, S.R. 2001. Synergistic analysis of SeaWiFS chlorophyll concentration and NOAA-AVHRR SST features for exploring marine living resources. International Journal of Remote Sensing, 22 (18), 377-3882.

Stumpf, R.P. 2001. Applications of satellite ocean colour sensors for monitoring and predicting harmful algal blooms. Human Health and Ecological Risk Assessment, 7 (5), 1363-U15.

Subramaniam, A., Brown, C.W., Hood, R.R., Carpenter, E.J. and Capone, D.G., 2002. Detecting Trichodesmium blooms in SeaWiFS imagery. Deep-Sea Research II, 49, 107-121.

Tranter, D. J., Carpenter, D. J. and Leech, G. S. 1986 The coastal enrichment effect of the East Australian Current eddy field. Deep-sea Res. 33, 1705-1728.

Turley, C.M., Bianchi, M., Christaki, U., Conan, P., Harris, J.R.W., Psarra, S., Ruddy, G., Stutt, E.D., Tselepides, A. and Van Wambeke, F., 2000. Relationship between primary producers and bacteria in an oligotrophic sea – the Mediterranean and biogeochemical implications. Mar.Ecol.Prog.Ser, 193,, 11-18.

Ufermann, S., Robinson, I.S. and Da Silva, J.C.B 2001. Synergy between synthetic aperture radar and other sensors for the sensing of the ocean. Annals of Telecommunications, 56 (11-12), 672-681.

Vance, T.C., Schumacher, J.D. and Stabeno, P.J., 1998. Aquamarine waters recorded for first time in eastern Bering Sea. EOS Trans.Am.Geohphys.Union, 79 (10), 121.

Van Der Piepen, H., Amman, V. and Barrot, K.W., 1999. Distinction of different water masses by means of remote sensing data collection during the Alboran Sea Experiment. Int.J.Remote Sens., 20 (7), 1319-1327.

Vasilkov, A., Krotov, N., Herman, J., McClain, C., Arrigo, K. and Robinson, W.T. 2001. Global mapping of underwater UV irradiances and DNA-weighted exposure using total ozone mapping spectrophotometer and sea-viewing wide field-of-view sensor data products. Journal of Geophysical Research-Oceans, 106 (C11), 27205-27219.

Woodruff, D.L., Stumpf, R.P., Scope, J.A. and Paerl, H.W., 1999. Remote Estimation of Water Clarity in Optically Complex Estuarine Waters. Remote Sens.Environ. 68:41-52.

Yakov, D.A., Nikolay, P.N. and Kostianoy, A.G., 2001. Patterns of seasonal dynamics of remotely sensed chlorophyll and physical environment in the Newfoundland region. Remote Sensing og Environment, 76, 268-282.

Zann, L., 1995. Our Sea, Our future. Major findings of the state of the Marine Environment report for Australia, Great Barrier Reef Marine Park Authority (Australia) for Ocean Rescue 2000.

5.4 Summary and Outcomes

This chapter has shown that while AVHRR SST observations are well established, there is promising scope for significant improvement in remotely sensed ocean colour products in the optically complex wasters of the coastal boundary layer.

- A great deal of mesoscale variability can only be observed using satellite remote sensing of ocean color especially when combined with AVHRR SST and other observations.
- Satellite ocean color imagery can provide cause-and-effect indicators at appropriate time and space scales for assessment and management of coastal systems.
- NSW coastal boundary layer features and processes have been elucidated by satellite remote sensed observations (in case studies).
- Continuous SeaWiFS ocean colour time series data have been available since August 1997 although SeaWiFS has exceeded its mission life; MODIS (Aqua and Terra) ocean colour time series data are freely available since late 1999 (Dec 1999 for MODIS Terra; May 2002 for MODIS Aqua); and, various other satellite ocean colour data are available with various degrees of accessibility/cost.
- Key limitations include cloud cover, confounding optical effects, especially for the optically complex coastal boundary layer, and limited penetration in cases where maximum phytoplankton biomass occurs at depth.
- In NSW optical depths may vary from 1-2m in extremely sediment ladened stormwater plumes to >20m in oligotrophic EAC waters.
- Quantitative remote sensing of Case 2 waters, such as the NSW coastal boundary layer, remains challenging.
- The accuracy and precision of remote sensed products varies over conditions and concentrations due to the non-linearity of the system and the extreme ranges in the concentrations of individual components that contribute to ocean colour.
- Regional algorithms, optimised for local conditions, perform well compared to global algorithms but no NSW regional algorithms are

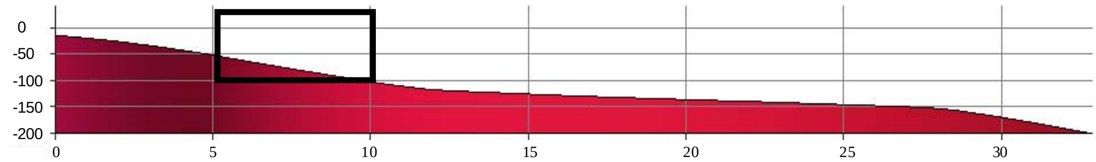
- The development of more sophisticated inverse modelling techniques for NSW coastal waters (& other coastal regions) requires precise multispectral radiances, with contemporary optical and concentration measurements of the water constituents.
- Remote sensed observations complement (not replace) *in situ* observations.
- Satellite remote sensing is a key tool to understanding the broad spatial extent (> 1km resolution) and temporal variance (~1day resolution) of coastal boundary layer features.
- Remote sensed ocean colour together with SST supported by some *in situ* observations provide the means to forecast algal bloom risk and diagnose initiation sites.

6 SYDNEY: A CASE STUDY OF OUTER CBL DISPERSION

6.1 Introduction

The continental shelf off Sydney section is similar in width (~30km) to that off Coffs Harbour (Figure 6.1) although it slopes more steeply to a depth of over 100m less than 10km from the coast. Furthermore, Sydney lies south of the EAC separation point, in the EAC eddy field.

Sydney (Port Hacking) continental shelf profile



Coffs Harbour (Boambee Beach) continental shelf profile

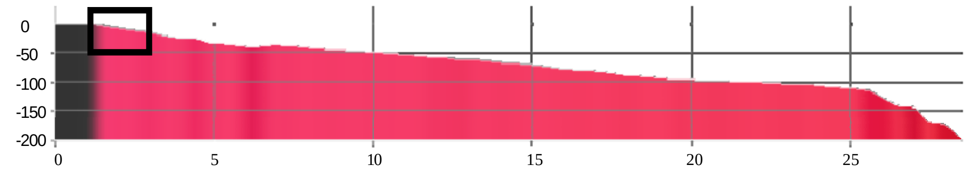


Figure 6.1 Cross shelf profiles off Sydney and Coffs Harbour (WNW-ESE). Boxes depict the principal focus of each case study presented in this thesis. Depths in metres and distances in kilometres.

Unlike Coffs Harbour, most of Sydney's sewage effluent is discharged beyond the direct influence of coastal bays and headlands of the *Inner CBL*. Nevertheless the dynamic physical processes that dominate these waters are heavily influenced by interactions with the continental shelf, through bottom stress, and the physical constraint imposed by the coastline. As such coastal boundary layer effects in the mid shelf region off Sydney are less variable over smaller spatial scales and more readily investigated by exploring temporal patterns of variability associated with larger scale processes.

This Chapter focuses mostly on the potential impacts of the single largest pollutant discharge to Sydney's coastal waters; that is, the ~1000 ML/day of nutrient rich sewage effluent that is discharged to coastal waters via Sydney's three deepwater outfalls. Sydney's sewage effluent management strategy is based on the premise that the current levels of environmental impact are acceptably low. Huge investment decisions would be required to increase levels of treatment (from less than primary to secondary or tertiary) or to develop alternatives to ocean discharge. Clearly there were management as well as scientific imperatives for the research reported in this chapter.

As outlined in Chapter 2, a five year multi-disciplinary Environmental Monitoring Program (EMP) in the 1990's measured the environmental performance of Sydney's deepwater outfalls against a wide range of criteria related to impacts on marine ecosystems and on human utilisation of marine resources (Philip and **Pritchard**, 1996; **Pritchard** et al., 1996; and, **Pritchard**, 1997 in Appendix 3 of this thesis). Residual concerns at the conclusion of this major study included possible nutrient enrichment of coastal waters and its effect on phytoplankton growth (algal blooms). This concern was heightened by a dramatic increase in the number of visible blooms of the heterotrophic dinoflagellate *Noctiluca scintillans* beginning at about the time that Sydney's deepwater outfalls were commissioned (Ajani, Hallegraeff and **Pritchard**, 2001; Ajani, Ingleton, **Pritchard** and Armand, 2011). *Noctiluca scintillans* also began to be found at dramatically higher frequencies in the water column in the absence of conspicuous blooms compared to previous studies (Ajani Lee, **Pritchard** and Krogh, 2001).

'Natural' nutrient enrichment resulting from slope water intrusions ('upwellings') is an inherently physical process constrained and affected by shelf bathymetry. Roughan and Middleton (2002) identified four physical nutrient enrichment mechanisms and demonstrated that both the strength of the current and its proximity to the coast determine the nature of the upwelling response.

Physical processes also control the fate of anthropogenic nutrients, from sewage treatment plants and from diffuse sources in coastal catchments via estuaries although direct interactions with the seafloor are unlikely because of the buoyant nature of these 'freshwater' discharges. The behaviour of effluent discharged from Sydney's deepwater ocean outfalls has been investigated, especially initial mixing processes (**Pritchard** et al., 1993, 1996, and **Pritchard**,1997). The dispersion (and biochemical) processes that operate over times scales necessary for algal bloom responses (~several days) are not well understood and have not been quantified for specific outfalls in Australia or overseas.

Sydney is fortunate to have significant long-term time series data for winds, waves, currents and temperature through the water column off Ben Buckler Head, Bondi (~15 years of near continuous ORS data) and for nutrients and temperatures through the water column off Port Hacking (several decades of mostly monthly CSIRO data), as described in Chapter 3.

This Chapter interrogates these and other data sets to describe scales of variability, relates them to dominant physical processes and demonstrates how this variability can affect anthropogenic disturbances, impacts and biotic distributions. Specific attention is then given to the effects of sewage nutrients by determining ambient (non outfall) nutrient distributions and patterns and quantifying nutrient enrichment patterns due to major outfall sources in relation to phytoplankton activity.

The body of this chapter (Section 6.3 and 6.4) has been published as international peer reviewed papers:

> **Pritchard, T.R**., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

> **Pritchard, T. R**., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Affect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.

The first paper (**Pritchard** et al., 2005) analyses long term time series data (winds, currents, temperature) and explores various scales of variability (frequency bands within the power spectra) ranging from high frequency internal waves to inter annual variability associated with teleconnections such as the El

Niño Southern Oscillation. These key dynamic processes are described in relation to their effects on the dispersion and fate of anthropogenic pollutants

The second paper (**Pritchard** et al., 2001) quantifies patterns of nutrient enrichment due to ocean outfalls using a 6 year record of hourly effluent plume modelling, effluent quality data and long term records (~25yrs) of ambient nutrient concentrations. This was used to assess the potential for enhanced or anomalous algal growth.

Further background information on the study region is provided in Chapter 2 while sampling methodologies, data validation and quality assurance procedures are described in detail in Chapter 3.

6.2 Motivation and Relevance to Thesis Objectives

The purpose of this chapter is to investigate and characterise the local expression of regional phenomena on the inner and mid shelfs in areas removed from the direct effects of coastal irregularities like headlands and bays. This is a transition zone where coastal boundary layer effects are dominated by the effects of cross shelf shoaling, bottom stresses and the land boundary rather than local bathymetric irregularities.

The research presented here investigates the principal forcing mechanisms that drive flows and density structures within inner and mid shelf waters off Sydney and relates this to nutrient enrichment and the potential for environmental impacts. As such this chapter relates directly to the following thesis objectives:

⇨ investigate CBL processes, their relationship to coastal morphology, and their role in controlling the dispersion, fate and potential impacts of pollutants discharged to the New South Wales coastal waters

⇨ investigate physical processes and dispersion characteristics for specific pollutant discharges to New South Wales coastal waters through case studies off <u>Sydney</u> (outer coastal boundary layer) and Coffs Harbour (inner coastal boundary layer)

To understand the local expression of regional forcing in inner shelf waters off Sydney it was necessary to quantify:

- power spectra to define: semi-diurnal tides; diurnal energy peaks representing sea/land breeze effects, transient weather systems and inertial motions; synoptic weather band energy driven by local and distant weather systems (including coastal trapped wave trains); EAC effects which can span weeks; and, seasonal peaks due to latitudinal shifts in atmospheric pressure systems and seasonal EAC effects.
- inter annual variability and low frequency signals that may be related to teleconnections.

To understand potential nutrient enrichment due to sewage effluent discharges from Sydney's deepwater outfalls it was necessary to quantify:

- long term distributions of near-field effluent plume behaviour (initial dilution, plume thickness and position in the water column).
- concentrations of target pollutants in effluent (total and dissolved fractions of nitrogen and phosphorus).
- distributions of ambient nutrient concentrations throughout water column and through seasonal cycles prior to the commissioning of Sydney's deepwater outfalls.
- possible bias due interpolation and extrapolation of limited data throughout the water column (discrete current meter observations) and due to various source data spanning different periods (effects of teleconnections such as the El Niño Southern Oscillation).

To assess the potential for pollutant impacts in Sydney coastal waters it was necessary to estimate:

- relative contributions from other nutrient sources (slope water, coastal catchments, atmospheric).
- downstream spatial extent of effluent plumes.
- possible indirect effects such as entrainment and uplift of ambient waters in buoyant plumes.
- nutrient enrichment factors, nutrient speciation, nutrient ratios (w.r.t. natural stoichiometric ratios) and observed phytoplankton patterns.

- periods of the year and depth intervals in the water column at most risk of nutrient impacts.

6.3 'Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts'

Citation: **Pritchard, T.R**., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Abstract

A near-continuous 13-year time series of current, wind and temperature data, from the Sydney Ocean Reference Station (ORS) was evaluated and analysed to determine scales of variability in the dominant near-shore dynamics. Deficiencies due to the current ORS configuration are quantified, highlighting non-linear shear within the water column, which may have significant implications for near field modelling. Key dynamic processes are described in relation to their effects on the dispersion and fate of anthropogenic pollutants and on distributions of planktonic biota, including: sub inertial internal wave energy; weatherband phenomena such as coastal trapped waves, local wind induced de-stratification and slope water intrusions; and, seasonal and inter-annual variability. Evidence of significant inter-annual variability in flow patterns was observed at the ORS. Long term data sets such as the ORS, together with satellite oceanography and numerical models provide a process based understanding that can improve impact assessments and the management of natural resources in NSW coastal waters.

Keywords: *Tasman Sea, coastal processes, ocean reference station, pollutant dispersion, anthropogenic impacts*

.

1 Introduction

The dispersion and fate of pollutants discharged to coastal waters and the distributions of planktonic and pelagic biota that they may affect are critically dependent on velocity fields and density structures of ambient waters. Unfortunately direct long-term marine observations of velocity fields and density structures are scarce in New South Wales (NSW) coastal waters. Here we explore flow, temperature and wind data from a moored instrumented buoy, the Sydney Ocean Reference Station.

This paper evaluates and analyses these time series data to describe scales of variability and demonstrates how this variability affects anthropogenic disturbances, impacts and biotic distributions.

1.1 Regional Setting

The NSW continental shelf is narrow, varying in width from about 20 km to 50 km with overlying waters exhibiting complex current structure often dominated by the East Australian Current (EAC) as indicated in Figure 1. The physico-chemical setting of Sydney has been summarised by Rendell and Pritchard (1996).

2 Methods

2.1 Sydney Ocean Reference Station (ORS)

The Sydney Ocean Reference Station (ORS) is located in 65 m of water, ~3km due east of Ben Buckler Head, Bondi at 33° 53.685’ S, 151° 18.972’ E. It has captured wind, wave, current and temperature data (5-minute block averages) for the thirteen year period from November 1990 to November 2003 (Figure 2). The ORS is operated by Sydney Water Corporation.

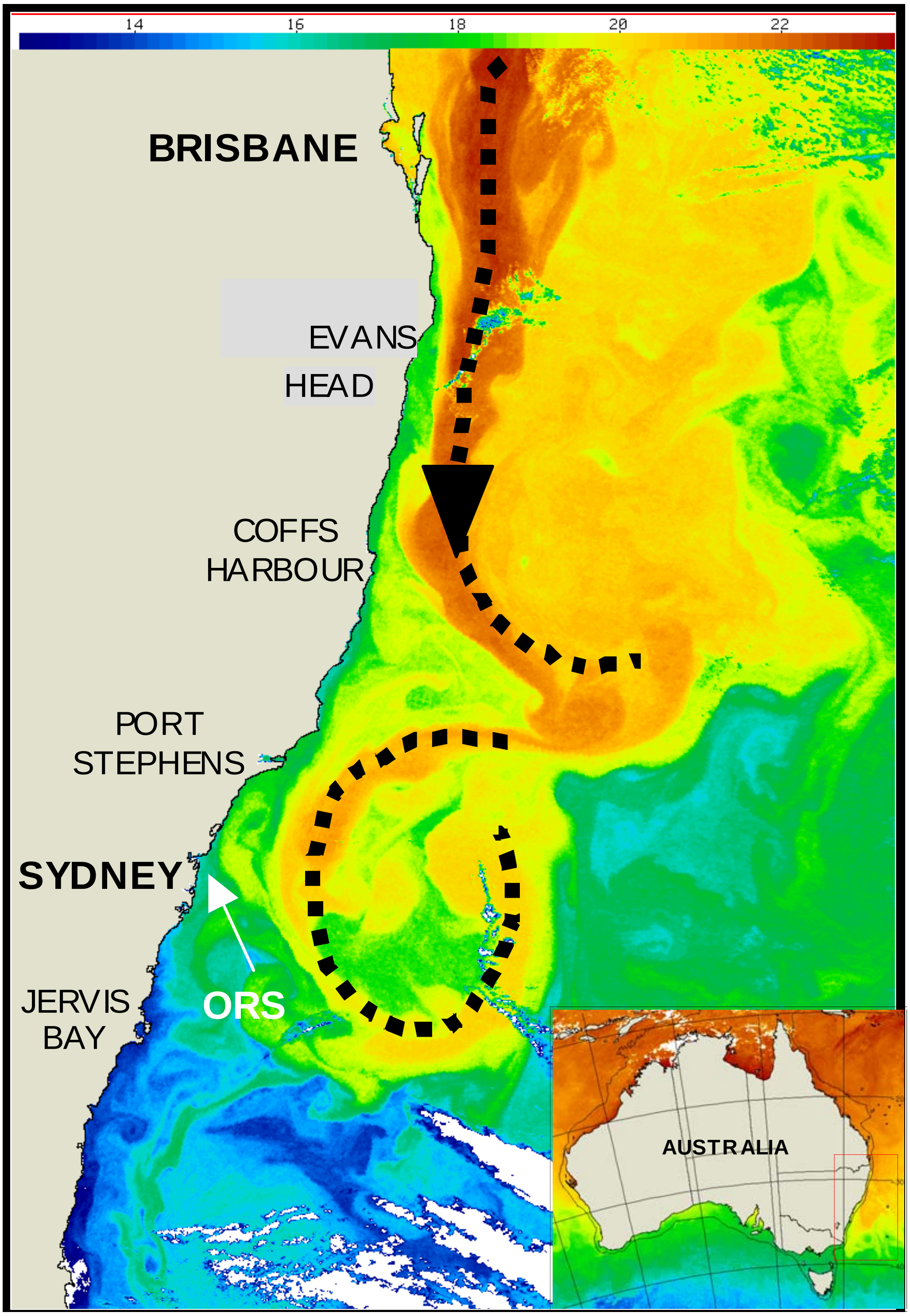


Figure 1 Remotely sensed sea surface temperatures (NOAA AVHRR) showing dynamic EAC features.

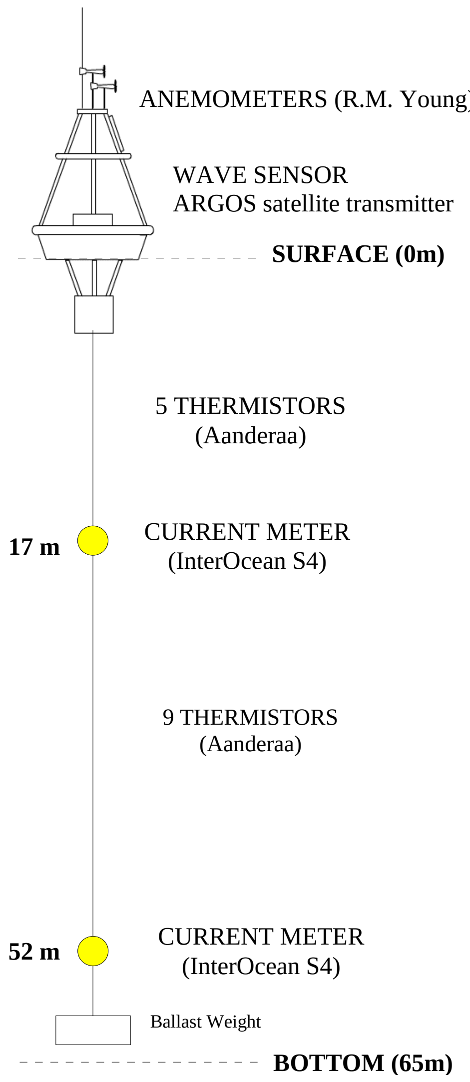


Figure 2 Ocean Reference Station configuration

Summary plots, displacement plots and times series analyses were used to characterise and interrogate the vast ORS data set. Figures 8, 9 and 10 show water temperatures observed at depths of 0.6, 6.5, 10.5, 14.5, 17, 22.7, 26.1, 29.5, 32.9, 36.3, 39.7, 43.1, 46.5, 49.9, 52 (metres from the surface warmest at the surface and no inversions).

Variance-preserving spectra of the ORS wind and current meter data were estimated, using the method of Emery and Thomson (2001), to quantify the dominant periodic events that affect the Sydney coastal region.

Contour plots of weekly average displacements were produced to depict low frequency (long term) characteristics of surface current velocities (see Figure 12). For each week, the frequency and average current speed were calculated for each 10 ° (directional) bin in the range between 0° and 360°. The relative weekly average displacement was calculated as the frequency multiplied by the average velocity (m/s) within each 10° bin. Absolute weekly average displacement (m/week) can be obtained by multiplying relative displacement by 300 (seconds corresponding to each 5 minute data interval). For example, the peak displacement per 10° bin in Figure 12 is about 6 km/week.

ORS and effluent flow data were used to estimate initial effluent dilution, plume thickness, and plume centre line depth using the near-field model JETLAG (Lee and Cheung, 1990). Dilution generally increases with ambient current strength and decreases with density stratification (buoyant rise).

It must be noted that data observed at the ORS cannot be extrapolated to shallow water coastal environments where local wind effects are likely to dominate resulting in less density stratification and diminished EAC effects.

2.2 ADCP Observations

A 300KHz Acoustic Doppler Current Profiler (ADCP) was deployed approximately 500m south of the ORS at 33° 53.958’ S, 151° 18.934’ E in 64m of water for the period from 30/12/03 to 28/01/05 to determine the degree to which ORS current meters characterised vertical flow structures throughout the water column.

ADCP observations in 1 m bins spanned from 3m above the sea floor to up to 60m above the sea floor although sea conditions occasionally limited quality in the upper 10m. In order to visualise comparative times series, a Chebyshev type 1 low-pass filter was used to suppress periods shorter than 24 hours and the record was sub-sampled to 3 hour intervals.

3. Results

3.1 Comparison of ORS and ADCP data

It was prudent to investigate the degree to which the two ORS S4 current meters can be used to estimate (interpolate) the current structure within the water column. Linear interpolation between average north-south speeds at depths corresponding to ORS S4 current meters delivers mid point errors of ~1cm/s (w.r.t. ADCP observations) as shown in Figure 3.

Time series anomalies between actual (ADCP) and interpolated currents have also been evaluated because near field effluent plume models for Sydney's deepwater outfalls use hourly means. Figure 4 shows significant time series anomalies which may be problematic for the purpose of near field modelling.

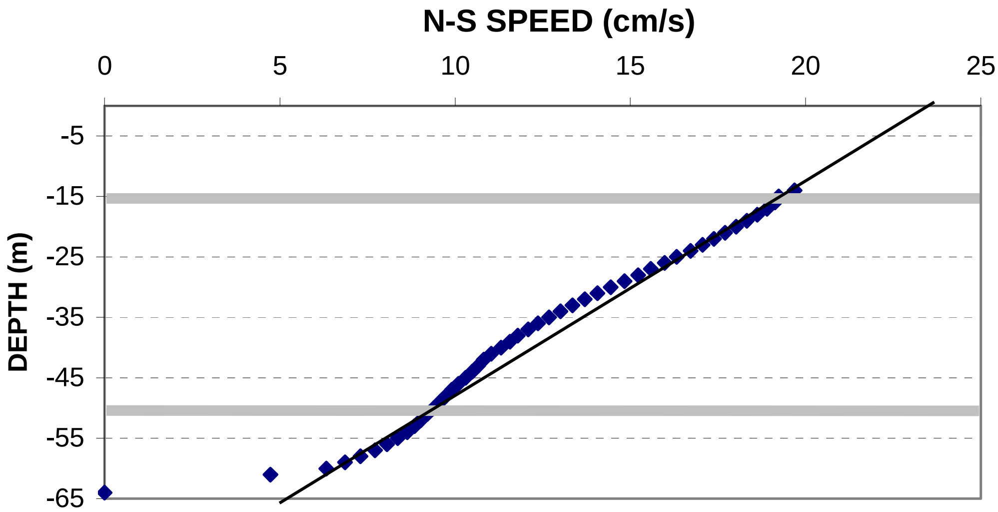


Figure 3 Mean N-S speed profile - ADCP average N-S speeds for 30/12/03 to 28/01/05 (diamonds for each 1m depth bin); S4 depths (grey line 1-2m thick); and, linear interpolation/extrapolation of mean speeds at S4 depths (thin black line).

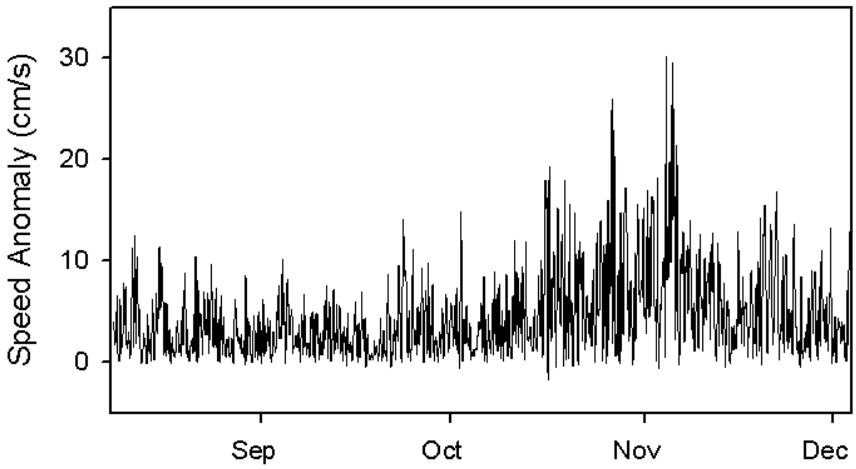


Figure 4: Time series anomalies for mid point interpolation of N-S current velocity between S4 depths during August to December 2004.

Special consideration must be given to observations of current (and temperature) stratification below the bottom ORS current meter because investigations of plume behaviour (Pritchard *et al*., 2001) suggest that most initial mixing can occur within the bottom 10-15 m of the water column. Figure 3 demonstrates that ADCP data are vastly superior to extrapolation below the bottom ORS current meter.

3.2 Progressive Vector Displacements

Progressive vector displacements (Figure 5) allow visualisation of ADCP data sets and suggest bounds on advection of conservative pollutants and plankton. Flows observed near the ORS may not be representative of flows at distant locations so progressive vector plots must not be confused with actual flow paths. Figure 5 indicates prevailing southward transport punctuated by a number of ‘events’ when rapid accelerations and/or flow reversal interrupted the southward trajectory. However, these events were rarely significant in terms of overall displacement trajectories. The similarity of total displacements at 5m, 10 & 20m above sea floor indicates remarkable overall consistency in the lower water column in contrast to the pronounced increase in displacements towards the surface. When viewed from above, vectors exhibit clockwise rotation downward through the water column which is consistent with surface wind stress and bottom stress: that is, southwards flows, tend to drive the bottom boundary layer towards the coast in much the same way as wind stress drives surface waters to the left of wind direction.

Curvature of vector trajectories in the upper water column suggest possible seasonal effects which are not evident lower in the water column.

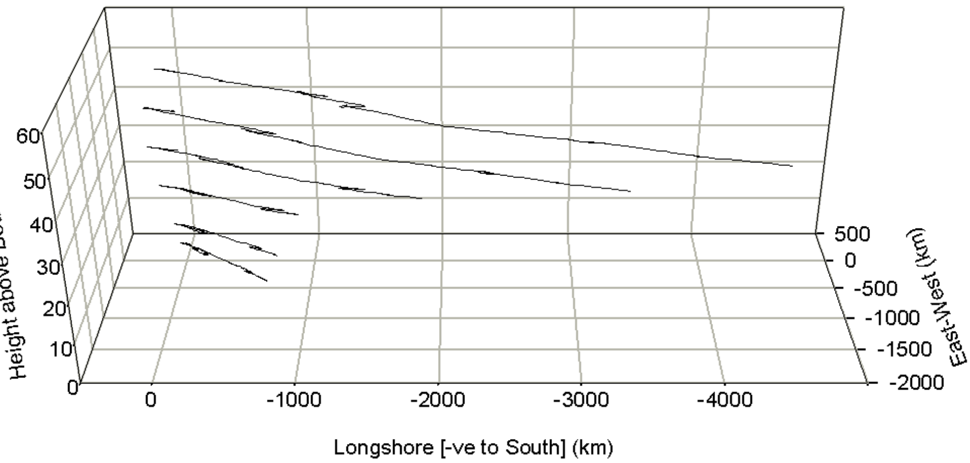


Figure 5. Current progressive vectors at 5m, 10m, 20m, 30m, 40m, and 50m above the bottom. Record spans 30 December 2003 to 28 January 2005.

Lower water displacements derived from ADCP observations (Figure 5) correspond to a velocities of ~0.03m/s or ~2.4km/day while upper equivalent velocities reach 0.14 m/s or 12.0km/day.

3.3 Scales of Variability

3.3.1 Power spectra

Variability about mean conditions affects distributions of pollutant concentrations and patterns of biotic exposure. This variability (extreme deviations from mean conditions) can also affect the inherent vulnerability of natural systems. Variance preserving power spectra (Figure 6) illustrate variability by partitioning energy according to scales of temporal variability (frequency) - equal areas under the curve represent equal energies.

Semi-diurnal tides are prominent but relatively low energy. The lack of significant phase difference along the coast generally results in weak tidal currents. Strong, coincident (wind and current), *diurnal* energy peaks represent sea/land breeze effects, transient weather systems and inertial motions (inertial period 23.6hrs at ORS). *Synoptic weather band* energy dominates the signal driven by local weather systems (several days as shown in the wind spectra), distant weather systems (e.g. coastal trapped waves) and EAC effects which can span weeks. Both winds and currents show prominent *seasonal* peaks due to latitudinal shifts in atmospheric pressure systems and seasonal differences in EAC effects. The *annual* cycle is subtle in the current meter record and virtually absent in the wind record.

The physical expression of these scales of variability is illustrated and explored in relation to anthropogenic impacts and planktonic distributions below.

3.3.2 Examples of high frequency and diurnal variability

High frequency internal waves are evident in the ORS record (Figures 6 and 7). These may be baroclinic response to tidal forces at the shelf break, changes in atmospheric pressure, lateral movement of oceanic fronts, shear instabilities and bathymetric features.

Although there is no net movement associated with the passage of internal waves (unless breaking occurs due to shoaling near the coast), they can operate at time frames relevant to initial mixing processes for primary treated effluent (total ~1000ML/day) discharged at depths of 60-80m from Sydney’s deepwater outfalls.

Figure 7 shows high frequency internal waves observed at the ORS: period ~30 minutes and amplitude ~10 m compared to the buoyant rise of effluent plume from Sydney’s deepwater outfalls which operates over periods of about 5-10 minutes. Modelling by Tate & Middleton (submitted) showed that buoyant plumes rising through internal wave fields may differ in height of rise and dilution by a factor of two or more compared to plume behaviour under mean stratification.

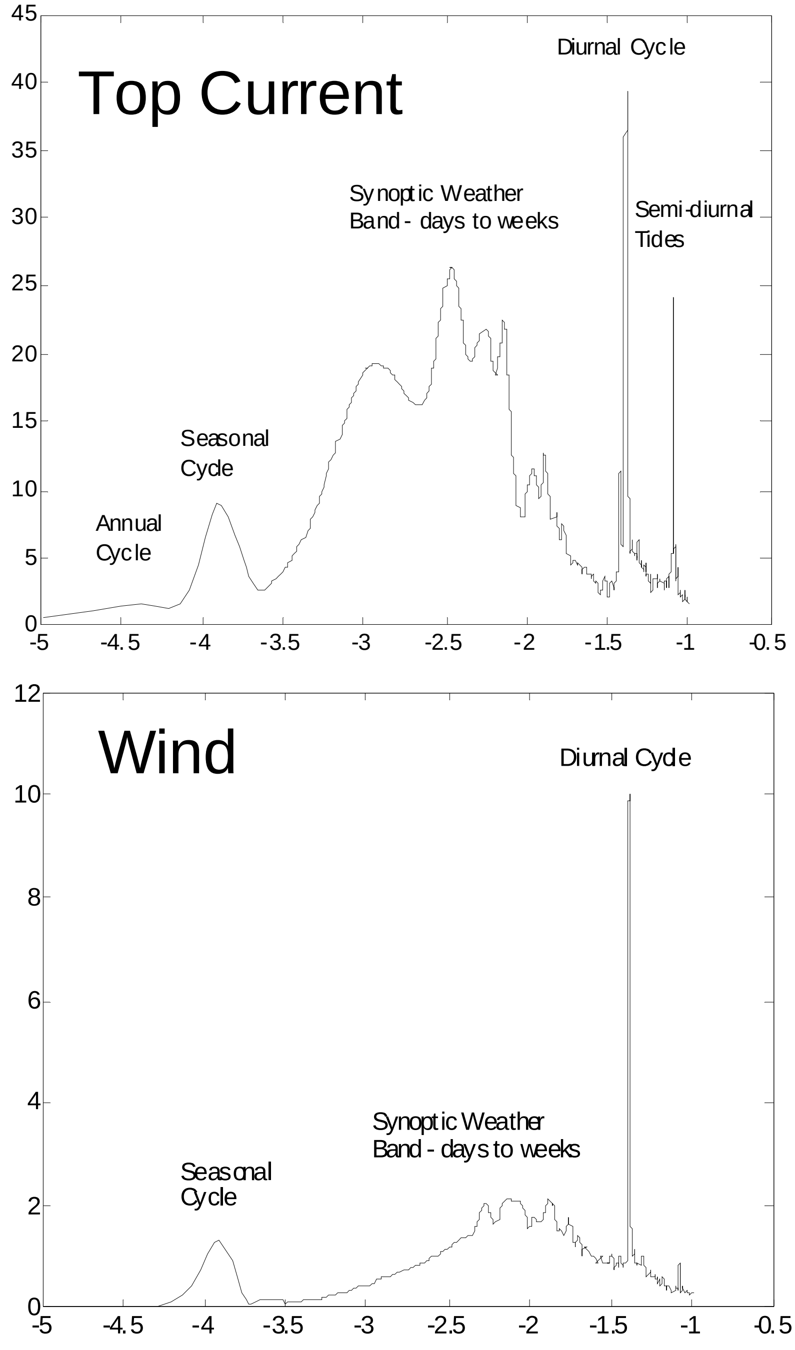


Figure 6. ORS variance preserving power spectrum for upper ORS currents and ORS winds (1990-2003)
[$(cm/s)^2$ for current and $(m/s)^2$ for wind vs $\log_{10}$ cycles per hour]

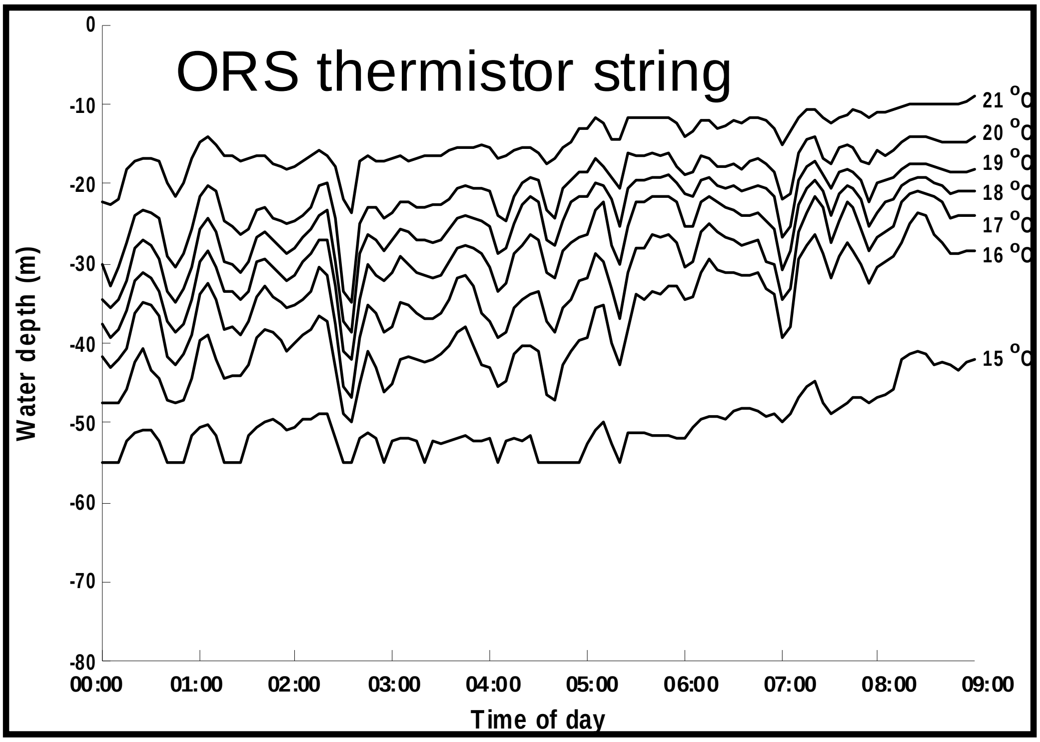


Figure 7 High frequency internal waves observed in ORS isotherms (modified with permission from Tate & Middleton, submitted).

The passage of internal waves is also expressed as rotational shear in the water column as illustrated by the ORS current and temperature record in Figure 8: semi-diurnal oscillations dominate the temperature record close to the bottom, whereas a diurnal signal is clearly visible in near surface isotherms.

Cross-shelf flows such as those quantified by the ORS (Figure 8) can result in large variances in the distributions of ichthyoplankton concentrations within similar water masses off Sydney (Dempster *et al.*, 1997). These flows must, therefore, be considered when selecting reference sites for impact assessment studies such as those associated with ocean outfalls.

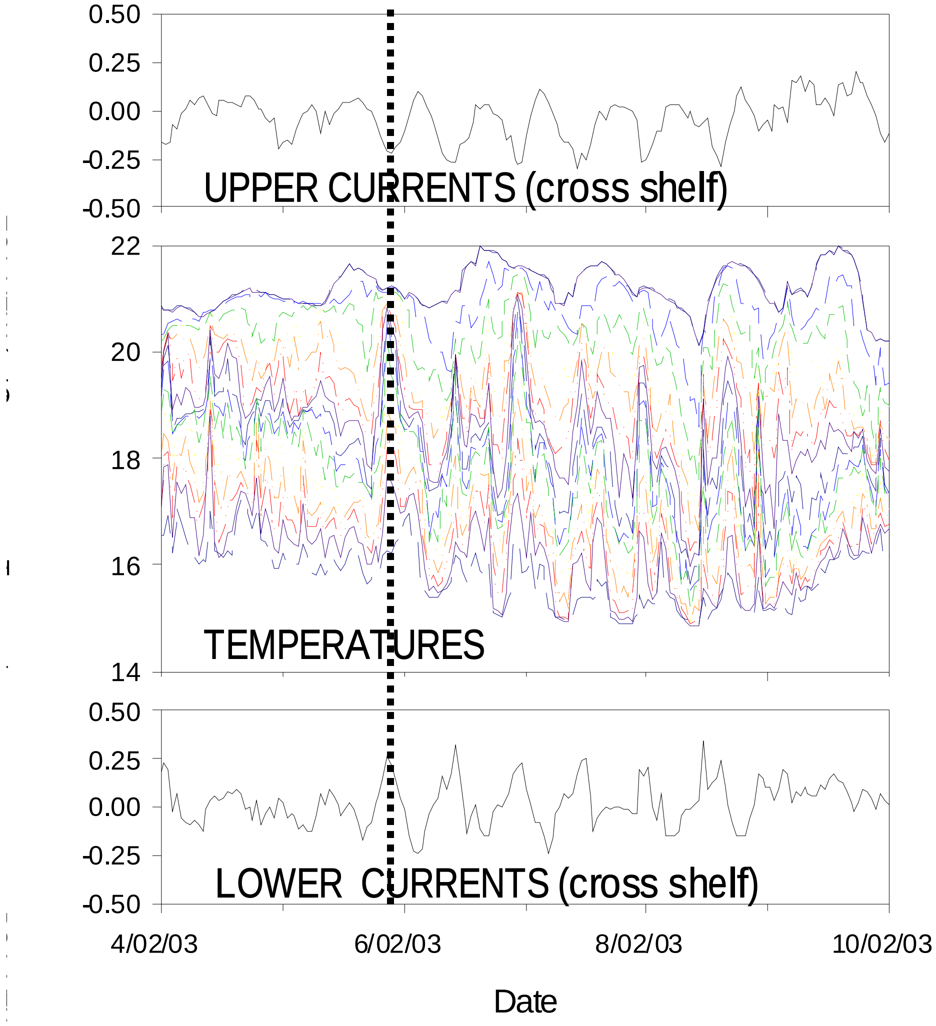


Figure 8 Semi-diurnal waves evident in both upper and lower current meter records which are 180 degrees out of phase.

3.3.3 Examples of synoptic weather band variability

Weather band variability dominates the power spectrum (Figure 6). Griffin and Middleton (1991) showed that approximately 60% to 70% of the 'weather band' (40 hour to 20 day period) current variance is wind driven, with the major contributors being the southern New South Wales and Bass Strait winds, both lagged by intervals corresponding to the propagation speed of the first Coastal Trapped Wave (CTW) mode. Coastal trapped waves can be expressed by 7-20 day current reversals which affect the fate of both biota and pollutants and increase the potential for re-entrainment of effluent discharged from Sydney's deepwater outfalls.

Local winds can prompt a more rapid response with faster de-stratification of the water column as illustrated by the top down mixing associated with a strong south-easterly (20 knots) wind during early January 1995 (Figure 9). A second event during late January 1995 illustrated combined effects of a southerly wind and cool slope water intrusion dynamics (indicated by water ~14°C). In this case vertical mixing reduced surface water temperatures. A diurnal signal is also apparent in the wind and sea surface temperature.

Reduced stratification allows buoyant effluent released near sea floor to penetrate higher within the water column (see Figure 11). Furthermore, vertical mixing associated with these events brings naturally nutrient rich bottom waters up into the euphotic zone to stimulate higher levels of primary production.

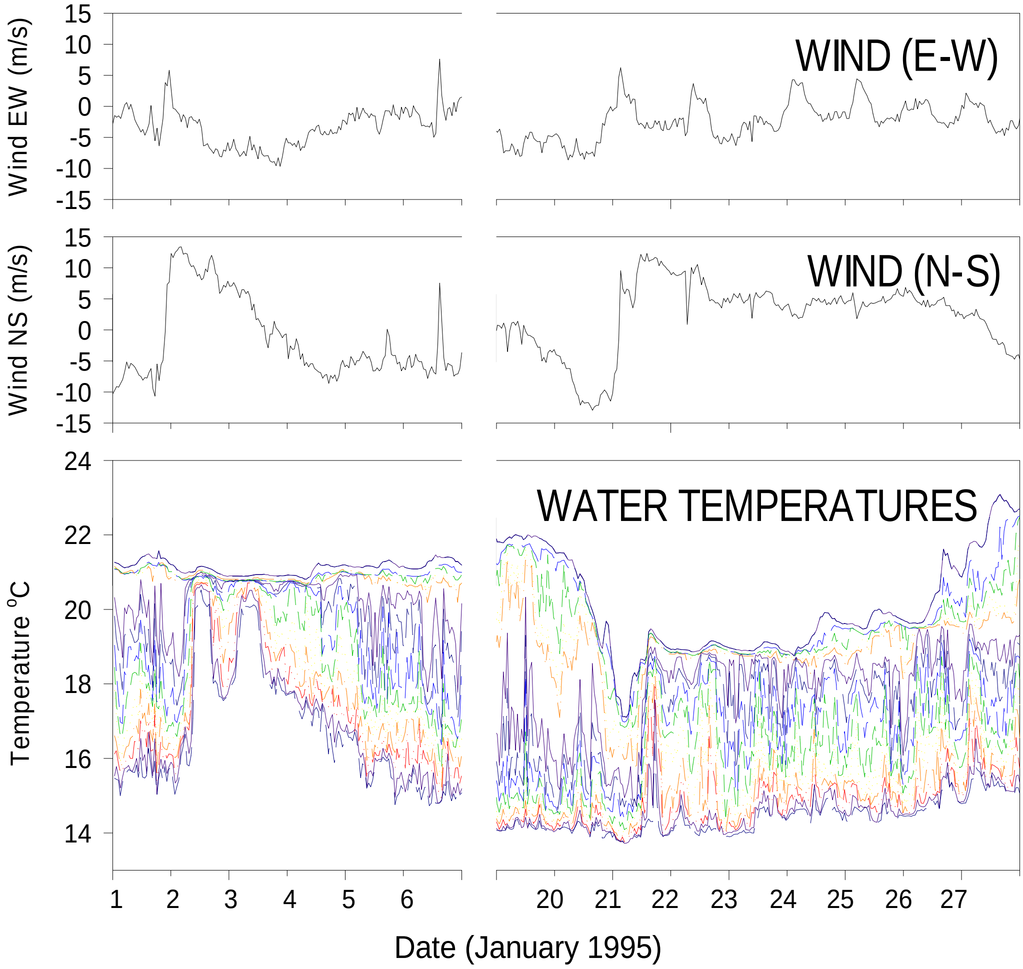


Figure 9. De-stratification: ORS wind and temperature

The generally oligotrophic coastal waters of NSW experience nutrient enrichment due to slope water intrusions driven by upwelling favourable winds (persistent northeastly winds) and interactions between regional flows (EAC & eddies) and continental shelf bathymetry (Pritchard *et al*., 1999; Roughan & Middleton, 2002). Both winds and upwelling favourable dynamics are monitored by ORS (and satellite oceanography) thus providing a diagnostic and predictive tool. Figure 10 illustrates slope water dynamics sensed at the ORS with offshore transport of surface waters during the second week of January 1998 together with progressive cooling of bottom waters. Observations at CSIRO Port Hacking monitoring station (from Lee *et al*., 2001) indicate phytoplankton bloom responses to this event.

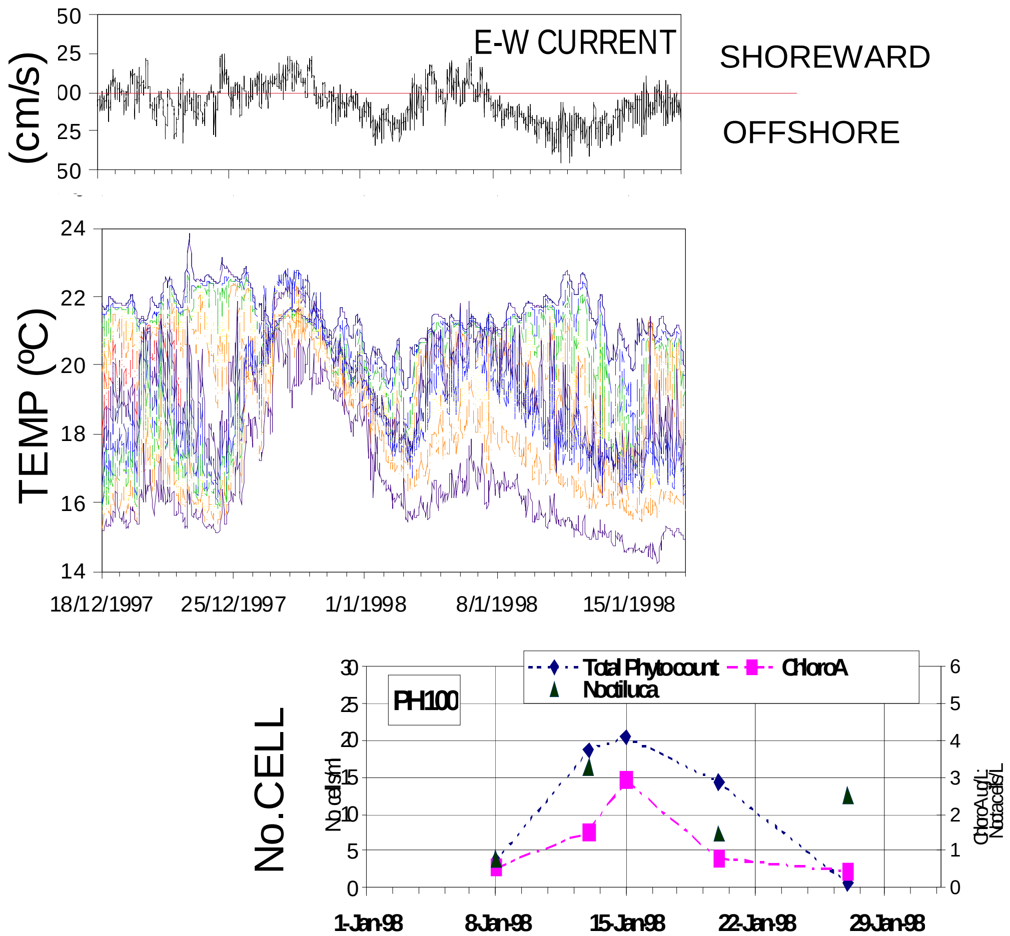


Figure 10. Upper ORS E-W currents (top), temperature profile (middle) and plankton counts (bottom) for January 1998.

3.3.4 Examples of seasonal & inter annual variability

Figure 11 shows seasonal temperature stratification with significant inter annual variability: peak stratification ranges from ~7°C in summer 1993 to ~4°C in summer 1994. Near field model time series in Figure 11 reflect similar seasonal and interannual variability although current speed and effluent flow also effect dilution and height of rise. Plumes generally surface (and achieve high effluent dilutions) when stratification is less that 1°C as exemplified by winter 1993. Stratification minima and associated high plume surfacing frequencies are confined to the El Niño episodes which dominated the period in Figure 11 (grey bar).

Interannual variability associated with teleconnections such as the El Niño Southern Oscillation (ENSO) affects the physico-chemical environment and phytoplankton populations. For example, empirical orthogonal function analysis of long term data collected off Port Hacking, Sydney (at CSIRO PH50) suggested that ENSO was responsible for 1/3 to 1/8 of mean seasonal range of temperature, salinity, nitrate, phosphate and oxygen (Hsieh and Hamon, 1991).

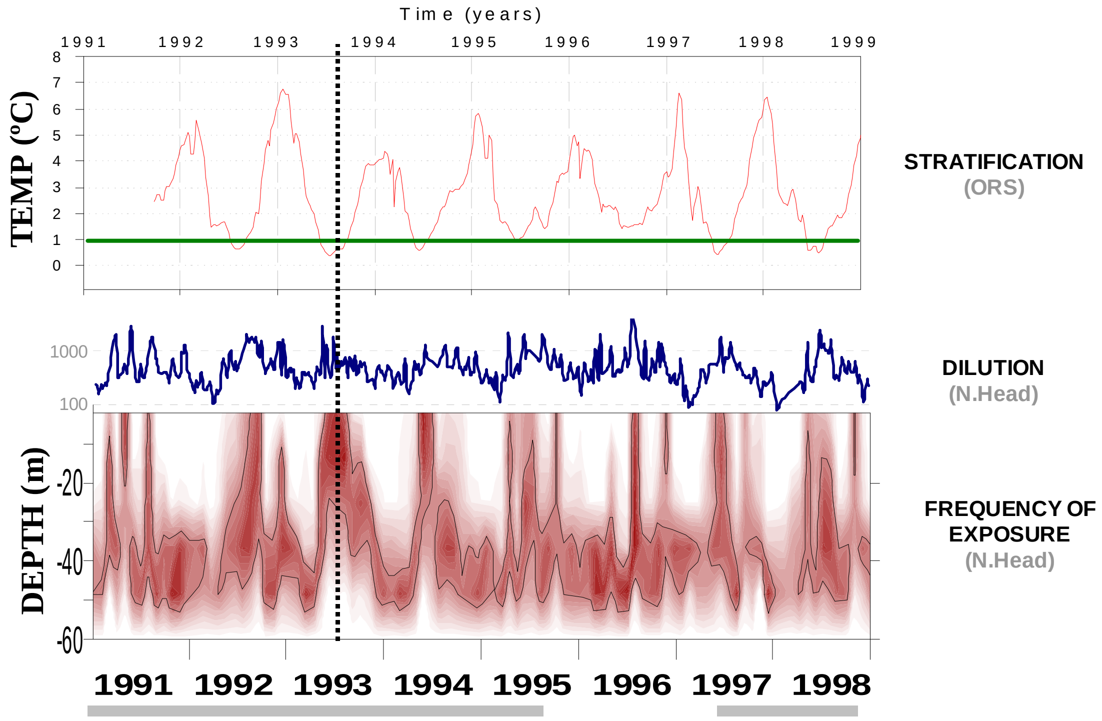


Figure 11. Stratification ($[T_{0m} - T_{52m}]$ °C) and near field model results (initial dilution & median exposure) for North Head ocean outfall.

A low frequency signal is apparent when the directional current displacements for the entire ORS time series are plotted in Figure 12. Here a spline has been fitted to peak values of current displacement and shaded bars at top indicate warm El Niño episodes. Eastward deviations are apparent for events centred on 1996 and 2001 prompting validation and investigation.

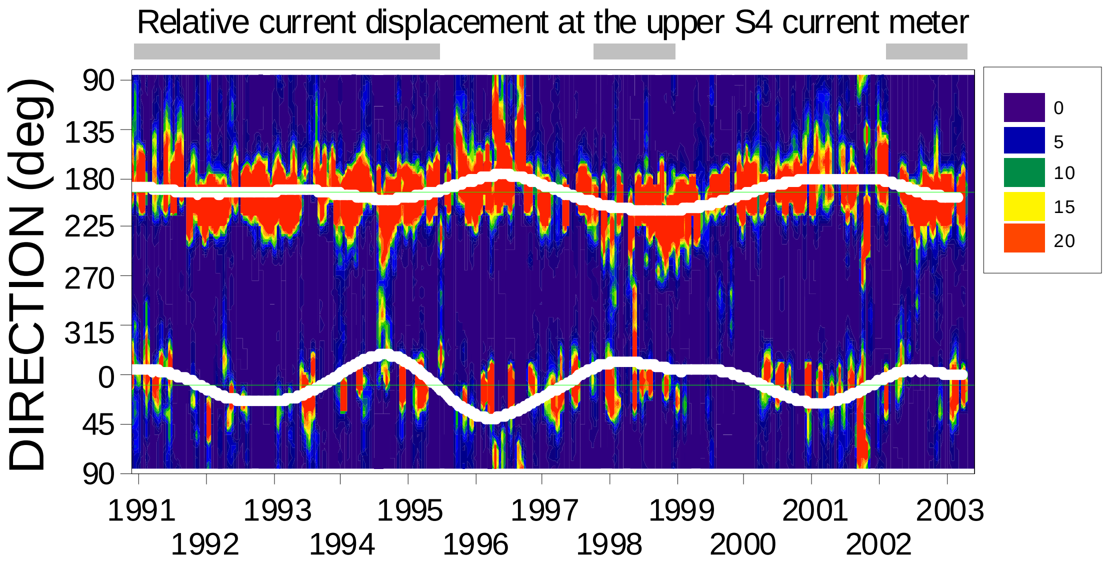


Figure 12. Relative average weekly displacements for upper ORS currents calculated as the frequency multiplied by the average velocity (m/s) within each 10° bin. Multiply by data interval (300 s) to obtain absolute weekly displacements (m/week).

Investigations of responses to climate variability such as ENSO may provide insights and sensitivity analysis relevant to (as yet poorly defined) climate change scenarios for NSW coastal marine environments.

4 Discussion

The relevance of simple but extensive physico-chemical data sets to impact assessments and biotic distributions is explored in this discussion.

4.1 Impact Assessments

The original purpose of the Ocean Reference Station was to drive hydrodynamic and effluent dispersion models to investigate the dilution and fate of treated effluent from Sydney's deepwater ocean outfalls. Ongoing near field modelling utilises ORS data to report on outfall performance and thus provides the basis (initial dilution) to assess the environmental significance of results from ongoing whole effluent toxicity testing.

However, time series observations of dynamic coastal waters also deliver an understanding of physical processes, which is necessary for effective design, and interpretation (including extrapolation) of impact assessments.

Experimental approaches derived from laboratory methodologies such as Before and After Control Impact (BACI) assessments (Green 1979, Underwood, 1992) have been embraced to detect anthropogenic impacts. These studies involve data collection before and after an intervention or putative impact at replicated "control" and "impact" locations. In this way BACI designs take into account variability at both control and impacted sites.

However, in many cases impact assessments are unable to satisfy the full requirements and assumptions of rigorous BACI (and 'Beyond BACI') designs. Often 'before' data are limited, 'control' sites may be compromised (respond in a fundamentally different way to each other and to the putative impact site/s) and statistical assumptions may be challenged (e.g. homogeneity of variances). In these circumstances, an understanding of the relative importance of various drivers of temporal and spatial variability can assist in the interpretation of impact assessments especially when ambient conditions are dissimilar before and after the disturbance/impact.

Even when BACI investigations are appropriately designed variability in ambient conditions must be considered in order to extrapolate (generalise) outcomes to other times because hydrodynamic factors can change the nature of the impact by affecting: fates of pollutants; distributions of potentially impacted organisms; and, the environmental sensitivity to pollutants or disturbance impacts.

Long term data sets such as those from the ORS (and satellite oceanography) provide the opportunity to place time limited impact assessments within a broader range of possible ambient conditions.

4.2 Hydrodynamic controls on biotic distributions

Hydrodynamic processes profoundly affect primary productivity (e.g. Pritchard *et al*., 1999) as well as higher trophic levels such as zooplankton (e.g. Tranter *et al.*, 1983), crustaceans and fish (e.g. Griffiths & Wadley, 1986) and marine birds (e.g. Mickelson *et al*., 1992).

Instrumented platforms such as the ORS have broad application as they provide the basis for the hydrodynamic understanding necessary to understand/predict and investigate biotic distributions. For example, physical phenomena such as island and headland wakes, re-circulation and turbulence, frontal features, windrows, and wave driven currents result in zones of convergence and accumulation for biota as well as pollutants.

Regional flows observed at the ORS and inferred from satellite oceanography affect both dispersion (Lee & Pritchard, 1996) and biological connectivity (e.g. Murray-Jones & Ayre, 1997).

Although Eulerian observations from moored instrumented buoys cannot be extrapolated to distant locations, data can be used to develop testable connectivity hypotheses especially when used in conjunction with satellite oceanography and hydrodynamic models.

Likewise, temporal patterns of phytoplankton biomass due to slope water intrusions can be predicted from simple physico-chemical observations especially when combined with satellite oceanography.

5 Conclusions

Moored instrumented buoys such as the ORS deliver fundamental information necessary to determine pollutant dispersion and reveal key driving mechanisms leading to a predictive understanding of dynamic coastal waters. Such information is necessary to develop testable biophysical hypotheses, to focus monitoring and evaluation programs and to interpret the results from impact assessments.

Significant opportunities exist to improve the ORS configuration, especially by focusing on more complete coverage of the water column using contemporary technology.

Quality assured, long-term time series data, when used in conjunction with remote sensed data and numerical models, becomes a pre-requisite for the effective management of our natural marine resources in a time of rapid change.

6 Acknowledgements

The NSW Department of Environment and Conservation supported this study. The authors grateful acknowledge the provision of Ocean Reference Station data from Sydney Water Corporation. Near field modelling was undertaken by the Water Research Laboratory and authors are grateful to Paul Rendell for his constructive review of this paper.

7 References

Dempster, T., Gibbs, M.T., Rissik, D. & Suthers, I.M. 1997. Beyond hydrography: Daily ichthyoplankton variability and short term oceanographic events on the Sydney continental shelf. *Cont. Shelf Res*., 17, 12, pp 1461-1418.

Emery, W. J. & Thomson, R. E., 2001. *Data Analysis Methods in Physical Oceanography*. Second Ed. Elsevier. ISBN 0-444-50756-6.

Green R. H. 1979: *Sampling Design and Statistical Methods for Environmental Biologists.* Wiley & Sons. New York.

Griffin, D.A. and Middleton, J.H. (1991) Local and Remote wind forcing of New South Wales inner shelf currents and sea level. *Journal of Geophysical Research*, 21, 304-322.

Griffiths, F.B. & Wadley, V.A. 1986: A synoptic comparison on the fishes and crustaceans from a warm core eddy, the East Australian Current, the Coral Sea and the Tasman Sea. *Deep-sea Res*., 33, 11a-12a, pp.1907-1922.

Hsieh, W.W., and Hamon, B.V., 1991: The El Niño Southern Oscillation in South-eastern Australian waters. *Aust. J. Mar. Freshw. Res*., 42, pp. 263-275.

Lee, L. H. W. & Cheung, Y. K., 1990. Generalised Lagrangian model for buoyant jets in a current. Proc. ASCE, *J. Env.Engineering*, 116(6), 1085-1106.

Lee, R.S., Ajani, P.A., Wallace,S., **Pritchard, T.R.** and Black, K.P., 2001: Anomalous Upwelling along Australia's East Coast. *J. Coastal Res*., 34, 87-95.

Lee, R. S. and **Pritchard, T. R**. 1996: Dispersion of effluent from Sydney's new deepwater outfalls Part 1: ocean processes. In *Mixing Processes in Estuaries and Coastal Seas* (C. Pattiaratchi, ed), 430-438. American Geophysical Union, Washington.

Mickelson, M.J., Dann,P., & Cullen, J.M. 1992:Sea temperature in Bass Strait and breeding success of Little Penguin Eudyptula minor at Phillip Island, south-eastern Australia. *Emu*, 91, 5, pp 355-368.

Murray-Jones, S.E. & Ayre, D.J. 1997: High levels of gene flow in the surf bivalve Donax deltoides on the east coast of Australia. *Mar.Biol*., 128, 1, pp 83-89.

Pritchard, T. R., Lee, R. S., Rendell, P., Ajani, P. and Black, K. 2001. How do Ocean Outfalls Effect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? *J.Coastal Res*., 34, 96-109.

Pritchard, T., Lee, R. and Ajani, P., 1999. Anthropogenic and oceanic nutrients in NSW's dynamic coastal waters and their effect on phytoplankton populations. *14th Australian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference – Coasts and Ports* 1999, 537-543.

Rendell, P.S. and **Pritchard, T. R**. "Physicochemical Conditions in Coastal Waters off Sydney, Central NSW, Australia" (1996) *Mar. Pollut. Bull*. 33, 132-139.

Roughan, M. and Middleton, J.H. 2002: A comparison of observed upwelling mechanisms off the east coast of Australia. *Cont.Shelf Res*., pp2551-2572.

Tate, P.M. Middleton, J.H. (submitted): The effect of internal waves on the rising and dilution of buoyant jets. *Journal of Hydraulic Engineering*.

Tranter, D.J., Tafe, D.J. & Sandland, R.L.1983: Some zooplankton characteristics of warm core eddies shed by the East Australian Current, with particular reference to copepods. *Aust.J.Mar.Freshwat.Res*., 34, 4, pp 587-607.

Underwood, A. J. 1992: Beyond BACI: The Detection of Environmental Impacts on Populations in the Real, but Variable, World. *Journal of Experimental Marine Biology and Ecology*, 161, pp. 145-178.

6.4 'How do ocean outfalls affect nutrient patterns in coastal waters of New South Wales, Australia?'

Citation: **Pritchard, T. R**., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Affect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.

ABSTRACT

We investigated the effects of major sewage and estuarine discharges on nutrient distributions in the central New South Wales (NSW) coastal waters. The hinterland of the study region includes the sewerage and rainwater catchments of major population centres of Newcastle, Sydney and Wollongong. New South Wales discharges the majority of its treated sewage to the ocean, with about 80% from just three deepwater outfalls off Sydney. These discharges were found to be the principal, continuous, anthropogenic source of nutrients to NSW coastal waters. The deepwater outfalls delivered most of their nitrogen as ammonia and were responsible for nutrient (NH_4-N and PO_4-P) enrichment within usually submerged effluent plumes. Direct observations and modelling indicate that after initial dilution, effluent plumes typically occupy ~30m of the water column (60-80m). Rapid initial dilution was observed with subsequent gradual far field dispersion typically broadening the effluent field to1-2 kilometres by about 10 kilometres downstream. Flows generally follow isobaths, predominantly to the south. Vertical and seasonal distributions of sewage derived nutrients, were estimated from a 6 year record of initial dilution modelling and effluent data. Comparisons were made with ambient nutrient distributions derived from long term monitoring prior to the commissioning of the outfalls (1990), at the CSIRO Port Hacking Station (5 to 10 kilometres south of the deepwater outfalls). The pycnocline seasonally limited the vertical extent of sewage plumes emitted from the deepwater outfalls. Upwelling/uplifting processes were associated with stratified conditions during spring and summer. Therefore, density stratification was a critical factor in determining the vertical movement of oceanic and sewage derived nutrients into the euphotic zone. Despite clear nutrient enrichment due to sewage discharges, no new evidence has been presented to contradict previous findings that algal blooms are principally driven by oceanic nutrient enrichment. However, by considering simulations of near field effluent plume behaviour in relation to long term ambient nutrient patterns we have identified specific periods of the year and depth intervals with maximum risk of outfall impacts, such as the upper half of the water column during late summer.

ADDITIONAL INDEX WORDS: *New South Wales, sewage outfalls, nutrients, algal blooms.*

INTRODUCTION

New South Wales's (NSW) population is concentrated along the coast and in particular in Sydney, Newcastle, Wollongong and adjacent areas. Most of the sewage generated in the coastal zone of NSW is discharged to the ocean after being treated to varying degrees. High levels of nutrients are found in sewage effluent.

In NSW coastal waters, there have been concerns that the periodic occurrence of marine algal blooms, particularly 'red tides' of the dinoflagellate *Noctiluca scintillans* (HALLEGRAEFF, 1993, AJANI et al., 2001), may be related to major anthropogenic nutrient loadings such as those from sewage treatment plants.

Eutrophication has been recognised as a serious threat to the health of coastal ecosystems both in Australia (e.g. ZANN, 1995) and globally (e.g. PELLEY, 1998). Furthermore, some evidence exists for a worldwide increase in the occurrence of harmful blooms (ANDERSON, 1985; PAERL,H., 1997). Anthropogenic discharges such as from sewage treatment plants have been identified as a possible factor in the increased eutrophication of some coastal waters (SMAYDA 1990, 1997). And, some laboratory studies have shown that sewage effluent enrichment (dilution range 1:200 to 1:5) can increase the populations of 'nuisance' and potentially harmful phytoplankton at the expense of naturally occurring benign diatoms as well as increasing overall phytoplankton production (PAN and RAO, 1997).

The purpose of this paper was to investigate the contributions to coastal waters of nutrients from major sewage ocean outfalls. In order to achieve this we attempted to determine ambient (non outfall) nutrient distributions and patterns, quantify nutrient enrichment patterns due to major outfall sources and, discuss the importance of outfall nutrients in relation to phytoplankton activity.

Study Region

Our study focused on the waters of the continental shelf between Port Stephens and Jervis Bay (Figure 1). In this region the continental shelf (to 200m isobath) is relatively narrow, ranging from about 45 kilometres in the north to about 20 kilometres off Jervis Bay in the south. The hinterland of this region includes the sewerage and rainwater catchments of the major population centres of Newcastle, Sydney and Wollongong. At least twenty outfalls discharge sewage effluent directly to the ocean in this region.

Particular emphasis was given to the Sydney coastal waters which receive the vast majority of sewage effluent mainly via three deepwater ocean outfalls off North Head, Bondi and Malabar. These outfalls were commissioned between September 1990 and August 1991 to replace cliff face outfalls.

The study region lies in a transitional zone. From the north the warm, oligotrophic waters of the East Australian Current (EAC) carry plankton of tropical origin. The main EAC flow typically separates from the NSW coast and flows eastward just north of the study region. Instability along the front between the warm EAC water and the colder Tasman Sea water often leads to the formation of both large (~150km) warm core anticyclonic eddies and smaller (20-50km) cold core cyclonic eddies which may persist for days to many weeks (CRESSWELL and LEGECKIS, 1986). Ekman pumping can lead to the uplifting of nutrient rich bottom waters shoreward across the shelf when southward EAC flows impinge on the shelf and can also lead to more localised uplifting/upwelling at the centre of cold core eddies (OKE and MIDDLETON, 1999). Local changes in coastal bathymetry/orientation appear to pre-dispose certain locations, such as areas Port Stephens to Newcastle, Port Hacking to Wollongong and Jervis Bay, to EAC induced nutrient rich slope water intrusions (LEE et al., 2001).

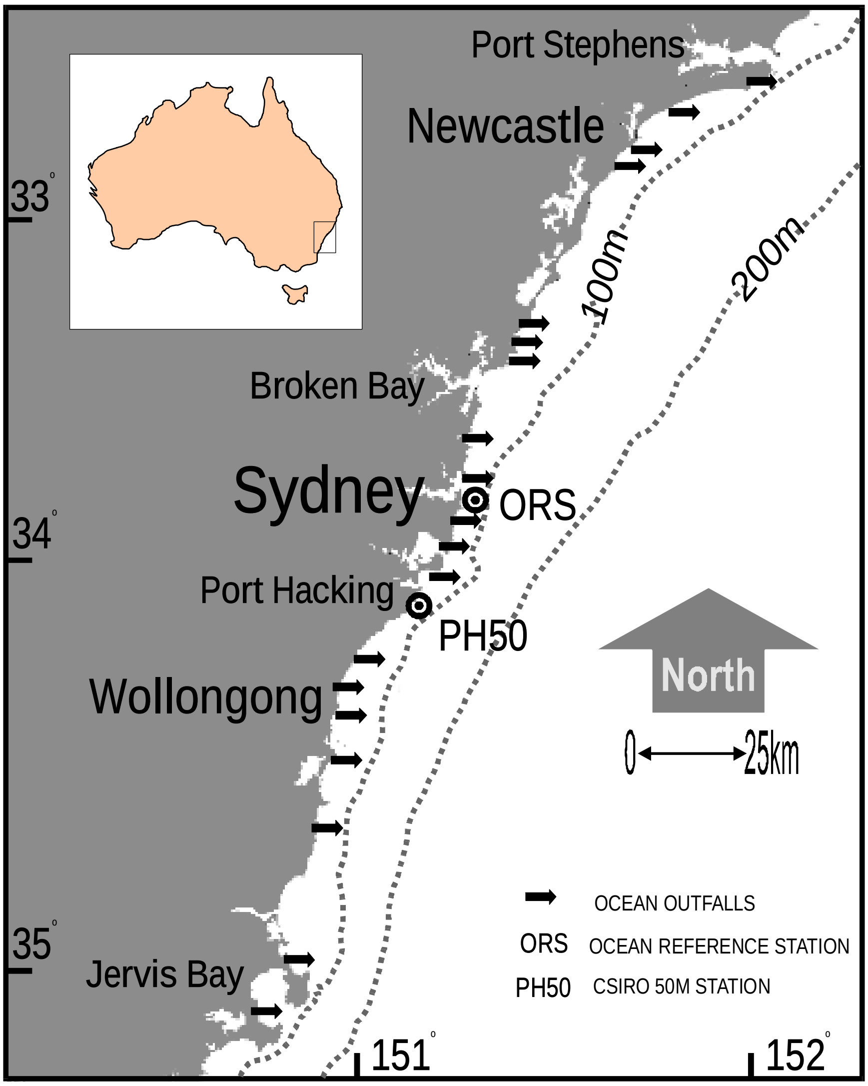


Figure 1. Study location showing ocean outfalls and locations of principal data sources.

Other dynamic processes controlling the introduction and dispersion of oceanic and anthropogenic nutrients in the study region include local winds (GRIFFIN and MIDDLETON, 1991), northward propagating coastal trapped waves (CHURCH et al., 1986; GRIFFIN and MIDDLETON, 1991), relatively high frequency internal waves and tides (GRIFFIN and MIDDLETON, 1992) and swell waves. Local winds operate over distances of 10 to 100 km and periods of hours to a few days: south-easterly winds favour downwelling while upwelling favourable north-easterly winds have been shown to be critical in pre-conditioning for upwelling (GIBBS et al., 1998).

Vertical mixing of nutrients is critical to light limited phytoplankton populations. Offshore waters remain stratified for most of the time with temperature stratification of up to nearly 10°C reported by WILSON et al. (1995). Some vertical mixing may occur across the thermocline due to current shear but significant stratification generally persists unless either an oceanic water mass moves in to swamp shelfwaters or a vigorous mixing process erodes the thermocline. De-stratification of the entire water column has been observed over periods of less than 24 hrs under the influence of strong winds and waves (LEE and PRITCHARD, 1996). Internal waves may also contribute to vertical mixing if they shoal and break on the inner shelf.

METHODS AND DATA ASSESSMENT

In addressing our objectives we analysed data and information from a range of sources.

Various catchment and effluent monitoring data were accessed to indicate the relative importance of various non-oceanic nutrient loadings to coastal waters although sparse or inappropriate data coverage limited the extent to which load data could be analysed. Nutrient exports from coastal catchments were based on various observed and modelled estimates for 11 major catchments from the Hunter (Newcastle) in the north to Jervis Bay in the south as described by SKM (1997). Flow data were generally well represented but temporal and spatial coverages of nutrient concentration data were variable (especially for smaller catchments) limiting some quantitative assessments.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has collected mainly physico-chemical data offshore from Port Hacking (PH) since the 1940’s (HUMPHREY, 1963). Ambient nutrient concentrations were obtained for the surface and at 10 m depth intervals to 50 m at CSIRO PH50 (34° 05’S, 151°13'E.) in water depths of 50-60 m. Data were limited to those from periods of more consistent chemical analyses prior to the commissioning of Sydney's first deepwater outfalls: nitrate (NO_3-N) from 1965 to September 1990 and phosphate (PO_4-P) from 1957 to September 1990. Prior to 1990, similar quantities of effluent were discharged via shoreline outfalls resulting in surface plumes but extensive monitoring prior to the commissioning of deepwater outfalls suggested little or no impact at PH50 (Pritchard et al., 1996). Analytical methods have been described elsewhere by LEE et al. (2001), MAJOR et al (1972), AIREY and SANDERS (1987). Sampling frequencies varied from approximately weekly (~47 $year^{-1}$) before 1985 to about monthly (~10 $year^{-1}$) after 1985. The change in sampling frequency was not expected to bias nutrient distributions with respect to variability associated with El Niño Southern Oscillation (see LEE et al., 2001 – this volume) because the period of reduced sampling included similar periods of cold (La Nina) and warm (El Niño). For the purpose of contouring, CSIRO PH50 data were grouped by month of the year and depth before percentiles were calculated (as in Figure 4).

Sydney Water's Ocean Reference Station (ORS) located 3 to 4 kilometres off Bondi in 64m of water, provided near continuous current measurements at 17 m and 52 m depths (Interocean S4 current meter accuracy 0.01 m/s) and temperatures throughout the upper 52 m of the water column. Sydney Water continuously monitors Sewage Treatment Plant (STP) flows while Sydney Water effluent nutrient concentrations were obtained from focused sampling during 1993/94 and 1996/97 (SYDNEY WATER, 1997; MHL, 1997). Organic nitrogen was calculated as the difference between total Kjeldahl nitrogen (TKN), and ammonia-N (plus nitrate). Its splitting into dissolved and particulate organic nitrogen was done on the basis of unpublished concentration data collected by Sydney water in 1993/94.

For Sydney's deepwater outfalls, the near-field model JETLAG (LEE and CHEUNG, 1990) was used, together with ORS and STP data to estimate initial effluent dilution, plume thickness, and plume centre line depth. The formulation of JETLAG tracks the evolution of the average properties of plume elements at various time steps by conservation of horizontal and vertical momentum, conservation of mass accounting for entrainment, and conservation of tracer mass.

Sensitivity testing and comparisons with data obtained from plume tracing experiments conducted off Malabar indicated that JETLAG provided a good representation of plume behaviour (CATHERS and PEIRSON, 1991). JETLAG was therefore selected to simulate a time series of the average effluent dilutions and the vertical positions of the plume after initial mixing; that is, after the plume had reached its level of neutral buoyancy or the surface.

Hourly average JETLAG model results were obtained for periods when both STP and ORS data were available during the period from January 1991 to December 1998 (54856 records or 78% coverage). When compared to cold and warm episodes, modelled coverage was equivalent to a ~17% bias to El Niño conditions. That is, when a simple scoring system was employed, the modelled period included an excess of El Niño conditions equivalent of nearly 400 (of 2290) days of moderate El Niño conditions.

The water column was divided into 2m depth bins in order to represent the effluent contribution to the water column after initial dilution. For each model run, the average initial dilution was assigned to those depth bins spanned by the vertical extent of the plume and a null result was assigned to bins which fell outside the plume. Depth bins were then grouped by month of the year and 10m depth intervals in order to estimate frequency of occurrence of effluent (percent effluent present – as in Figure 6) and percentile effluent concentrations (1/dilution) over a 12 months x 5 depths grid. Nutrient contributions were then calculated for each grid element based on fixed average nutrient concentrations observed in primary treated effluent, modelled (percentile) effluent plume dilutions and ambient (percentile) nutrient concentrations observed during long term monitoring at PH50 (as in Figures 7 and 8).

In addition, all near-field model results for each outfall were allocated to 2m depth bins irrespective of month of the year and results were grouped by 10m depth intervals. Percentile effluent dilutions were then estimated for each 10m depth interval (i.e. 5 x 2m bins) by including only results for when effluent was present. In this way, it was possible to estimate initial effluent dilutions with respect to plume depth (as in Figure 6).

Effluent plume behaviour was illuminated using data drawn from various near-field model verification experiments conducted using a SEABIRD SBE25 Sealogger CTD (temperature accuracy 0.004ºC and conductivity 0.0003 S/m) and radioisotope tracer (introduced Tritium, Gold-198 and Technetium-99m isotopes) techniques similar to those described by PRITCHARD et al. (1993). Radioisotope studies were conducted in collaboration with Australian Nuclear Science and Technology Organisation.

NUTRIENT SOURCES

In nutrient limited systems, algal responses are driven by the concentration of nutrients in the water column while the overall algal biomass (extent and longevity of blooms) is also a function of the nutrient load entering the system. Therefore, both concentrations and loads of nutrients are important when considering nutrient sources.

Nutrients enter the study region from discrete point sources such as ocean outfalls and estuaries (coastal catchments), from diffuse atmospheric and sediment sources at the upper and lower boundaries of the system and from oceanic sources such as the cross shelf nutrient fluxes associated with slope water intrusions. Various bio/geo-chemical processes act to exchange and transform these nutrients within the system.

Nutrient concentration data (Table 1) for ambient ocean waters and key sources of nutrients to coastal waters indicate the potential for enrichment of surface waters due to estuarine discharges (especially nitrate and ammonia) and outfalls (especially ammonia) on those occasions when sewage effluent plumes surface. Bottom waters may be enriched by slope water intrusions (especially nitrate and phosphate) and by outfalls (especially ammonia). There is also a potential for vertical transport (upwelling or mixing) to dramatically enrich surface waters.

Table 1 Indicative Nutrient Concentrations

	Nitrate NO_3-N (µg/L)	Ammonia NH_4-N (µg/L)	Phosphate PO_4-P (µg/L)
Reference [1]	10-60	<5	1-10[I]
Primary Effluent [2]	30	23,000 – 28,000	3,200 – 6,400
Run-off [3]	110 – 450 [NOx]	50 - 360	40 - 90
Ambient shelf Upper waters [4]	10	8*	7
Ambient shelf Lower waters [4]	70	8*	15
Slope Waters [5]	> ~ 140	~ 6-8[#]	22

Sources: 1 ANZECC (1992); 2 Range of geometric means for Sydney Water's Sewage Treatment Plants at North Head, Bondi and Malabar 1994-95 (no dilution); 3 Range of 90 percentile values across a variety of catchment types based on 1993 & 1994 data from the Sydney Water Corporation's Stormwater Monitoring Program (from SKM, 1997). Values relate to stormwater entering the estuarine system which may or may not be representative of estuarine discharges to the ocean; 4 Median concentrations observed at CSIRO Port Hacking Station (PH50) in surface (0m) and bottom (50m) waters for periods 1965-95 (NO_3-N) and 1957-95 (PO_4-P); 5 TRANTER et al. (1986) and CRESSWELL (1994).
* median concentrations based on NSW EPA data collected along transects across the shelf at Pt Stephens, Pt Hacking and Jervis Bay and from PH50/100 stations at 0m (n=263) and 50m (n=170) depths for the period from August 1995 – April 1997
\# typical averages based on NSW EPA data 1995-97.
Notes: I reported as inorganic; NOx = nitrate plus nitrite.

Slope Water

Nutrient rich slope water intrusions (from depths >150-200m) were found to be seasonal (spring/summer peak) and episodic, operating over length scales of hundreds of kilometres and time scales of several days (PRITCHARD et al., 1998). Slope water intrusions delivered mainly dissolved nutrients (nitrate and phosphate) and typically remained submerged, but often penetrated inner shelf waters thus elevating nutrients to the euphotic zone. Association between slope water intrusions and phytoplankton responses were suggested by HUMPHREY (1960, 1963) and have been illustrated by LEE et al. (2001). A standing nitrate load of 2,500 tonnes and corresponding phosphate load of 400 tonnes would be associated with a notional slope water intrusion 200 km in length, 3km in width (inner mid shelf) and 30m in thickness (scale based on PRITCHARD et al., 1998; nutrient concentrations from Table 1). A significant proportion of these loads would be rendered unavailable to phytoplankton by other limiting factors and by finite residence times on the inner-mid shelf.

Coastal Catchments

Many coastal NSW catchments have extensive estuarine systems which act as natural buffers, regulating nutrient exchanges between fresh water and ocean systems. Estuarine discharges were found to be sporadic, with high particulate nutrient loads and were dominated by the two estuaries/catchments (Newcastle/Hunter and Broken Bay/Hawkesbury) which together delivered ~40% and ~60% of catchment derived total nitrogen (TN) and total phosphorus (TP), respectively (SKM, 1997 and Figure 2). Total loads were estimated as 1,600 – 7,400 tonnes/yr TN and 160 – 770 tonnes/yr TP (high ranges indicate total catchment exports while low ranges include an estimate of nutrient buffering). Extreme estuarine plumes have extended tens of kilometres for days to weeks (LEE and PRITCHARD, 1999).

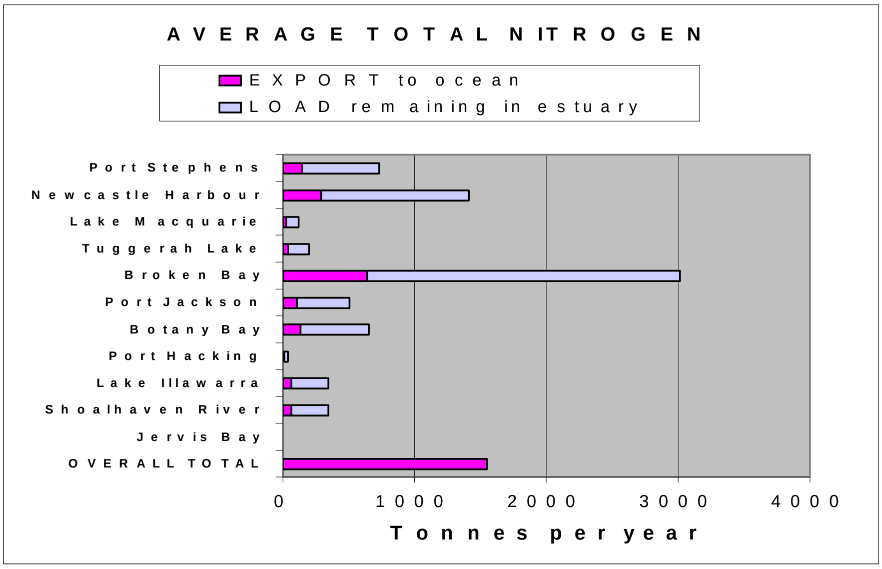


Figure 2a. Indicative total nitrogen loadings from coastal catchments.

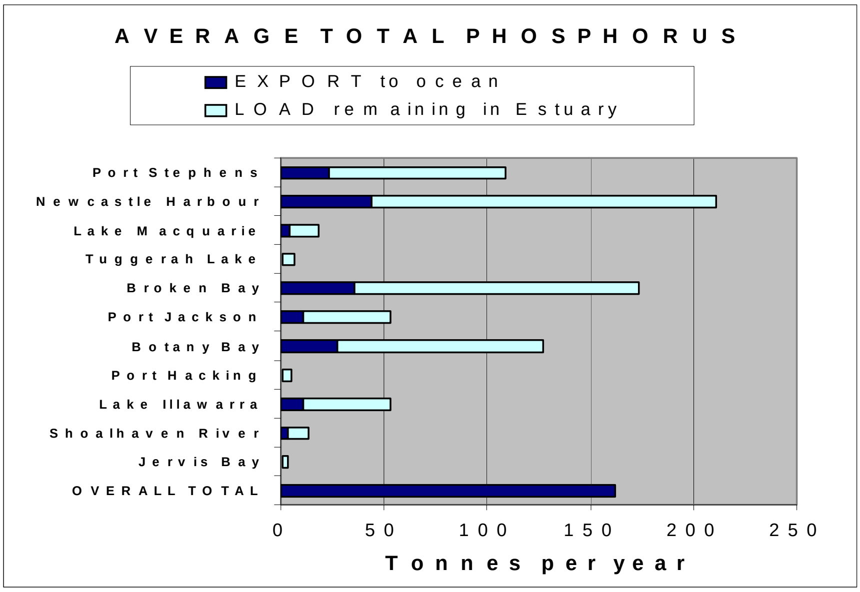


Figure 2b. Indicative total phosphorus loadings from coastal catchments.

Atmospheric and Sediment

Data from AYRES et al. (1987) suggest atmospheric fluxes of total nitrogen of 4.6 kg/hectare/year based on typical (1981/1982) Sydney rainwater concentrations of 170 mg/L nitrate and 210 mg/L ammonia, average rainfall of 1225mm/yr (assuming negligible organic N in air). HARRIS et al. (1996) estimated aerial deposition to Port Phillip Bay (Melbourne) at 2.56 kgN/hectare/yr. These available data may not be representative of NSW coastal waters but indicate potential for significant atmospheric loads. Significant biological nitrogen fixation was unlikely because relevant species such as Trichodesmium were typically present in low densities (AJANI et al., 2001) and only senescent Trichodesmium cells would be expected in our study region (HALLEGRAEFF pers comm., 1997).

Few relevant data were available to indicate nutrient fluxes across the sediment-water interface in our study region (BICKFORD, 1996) and no data were available to characterise exchanges during re-mobilisation (high wave/current) events. Remobilisation effects could be expected to be highly relevant given evidence that the upper 30cm of the mainly sandy sediments may be re-mobilised during events (SCHNEIDER, 1999).

Ocean Outfalls

Figure 1 shows locations of outfalls associated with sewage treatment plants (STPs) within our study region while Figure 3 indicates STP nutrient loadings. Outfalls within the study region, together, contributed 97% of the total sewage effluent discharged to NSW marine waters (~99% of total nitrogen load and ~96% of total phosphorus load). Dominant among them are Sydney's three deepwater outfalls (North Head, Bondi and Malabar) which are located in the centre of the study area. The three deepwater outfalls together contributed about 76% of the total nitrogen and 71% of the total phosphorus.

Ammonia-N was the dominant form of nitrogen (~73% of TN) with subordinate amounts of particulate-N (~18% of TN), dissolved organic-N (~9% of TN) and NOx-N (<0.5% of TN) in primary treated sewage effluent such as that discharged from North Head, Bondi, Malabar, Cronulla, Bellambi and Port Kembla. Table 2 summarises nutrient concentrations observed in effluent from North Head, Bondi and Malabar STPs during 1996/97 – these results are consistent with previous available data spanning 1993-1996 (SYDNEY WATER, 1997).

At Sydney Water outfalls discharging secondary effluent, ammonia-N, or ammonia-N and NOx-N, were the dominant forms. The relative contributions of ammonia and NOx-N varied considerably among these outfalls. Combined, ammonia-N and NOx-N made up greater than 83% of the total nitrogen. Similar results would be expected at the other NSW outfalls discharging secondary effluent.

Much less data is available on the forms of phosphorus. Based on concentration data collected by Sydney Water in 1993/94 we would expect about 60 to 80% of the total phosphorus in primary effluent to be present as dissolved phosphorus (Table 3). The proportion would be expected to be about 85 to 95% at outfalls discharging secondary effluent.

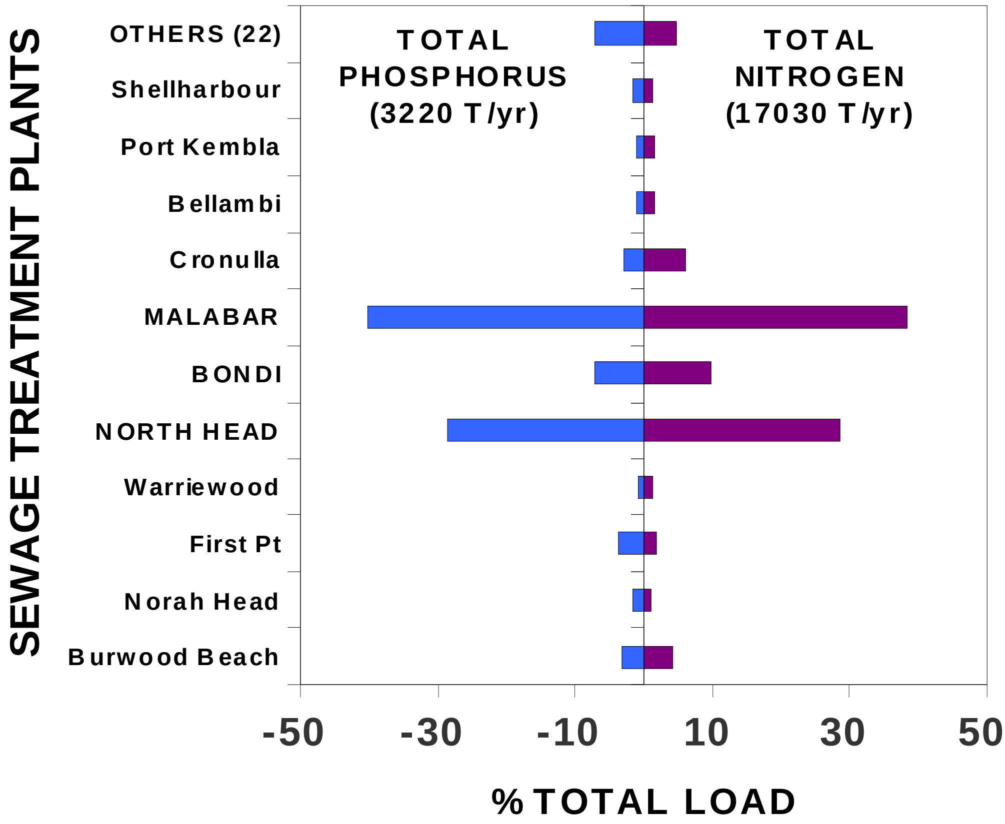


Figure 3. Total nitrogen and total phosphorus loadings from sewage treatment plants to NSW coastal waters. Data compiled for 1996/97 except 'Others' which includes data for 1991.

Load data for non-outfall sources were inadequate to allow statistical evaluation of apparent differences. Despite this, it was clear that nutrient loadings from coastal STPs were large with respect to other discrete sources. Based on the dominance of Sydney's deepwater outfalls and the scale of this study, further consideration of outfall effects focused on these outfalls.

Table 2 Nutrient concentrations in the effluent from Sydney's three deepwater ocean outfalls (1996/97)

Nutrient	**Outfall**	**n**	**Effluent concentration mg/L**	
			Median	**Maximum**
Ammonia N	North Head	38	32.0	37.0
	Bondi	40	27.0	37.0
	Malabar	40	30.0	36.0
Nox	North Head	12	<0.01	0.03
	Bondi	12	<0.01	0.35
	Malabar	12	<0.01	0.07
Total N	North Head	13	44.1	49.9
	Bondi	13	36.0	41.0
	Malabar	13	39.1	44.9
Total P	North Head	12	7.50	8.70
	Bondi	12	4.45	5.80
	Malabar	12	5.40	6.60
Flow (average daily dry weather)	North Head		280ML/d	
	Bondi		130ML/d	
	Malabar		430ML/d	

n = number of samples   Source: Sydney Water (1997)

Table 3 Phosphorus speciation

STP/outfall	**Geometric mean concentration mg/L**		**Dissolved P % of total**
	Dissolved P	**Total P**	
North Head	6.42	8.32	77
Bondi	3.19	4.66	68
Malabar	4.72	7.30	65
Secondary Treatment Plants (4)	4.71-7.76	5.09-8.67	86-93

(15 samples for each STP)

Source: Unpublished data collected by Sydney Water in 1993/94

AMBIENT NUTRIENT PATTERNS

Previous nutrient studies in these waters have generally focused on nitrate and to a lesser extent phosphate and date back to the 1940s (eg NEWELL, 1966; HAHN et al., 1977; ROCHFORD, 1984; TRANTER et al., 1986; CRESSWELL, 1994). These studies, and our characterisation of ambient nutrient distributions prior to the commission of Sydney's deepwater outfalls, were based to varying degrees on data from long term monitoring by CSIRO at station PH50 off Port Hacking, southern Sydney. These ambient nutrient data represent the combined effects of all sources regulated by biological activity.

Seasonal cycles of nutrient enrichment are apparent in Figure 4. The smallest differences between surface and deeper waters tend to occur late in the austral autumn and winter when thermal stratification was absent or weakest. During this period, nutrient concentrations in surface waters tended to be near their highest and nutrient concentrations at depth tend to be at their lowest. Maximum nutrient concentrations in surface waters occurred during July-August whilst maximum nutrient concentrations in bottom waters occurred during the summer months, peaking during February. These general patterns were evident in all percentile plots and have been attributed to winter overturning of shelf waters and episodic slope water intrusions driven by summertime EAC activity and/or upwelling favourable winds together with enhanced biological (phytoplankton) activity in surface waters during the warmer summer months.

Effects of nutrient enrichment events are illustrated in Figure 5. Absolute enrichment (upper plot) due to extreme events (95 percentile ambient concentration), was greatest at mid-depth (about the thermocline) from September through to April. But when enrichment was considered as a fraction of median ('typical') concentrations (lower plot) the effect was generally contained within the upper half of the water column and up to an order of magnitude greater for nitrate than for phosphate.

OUTFALL EFFECTS

Nutrient fluxes across the three open boundaries of the study region remain elusive especially in the absence of comprehensive hydrodynamic data. However, local nutrient enrichment caused by major sewage outfalls can be quantified when ambient nutrient concentration patterns are considered in relation to effluent plume dynamics and known sewage effluent characteristics.

Effluent Plume Characteristics

The locations of the Sydney deepwater outfalls, which were commissioned in 1990/91, are shown in Figure 1. Effluent is discharged at high velocity from "gas burner" like diffusers that are located on the sea floor along the length of a diffuser line. The diffuser lines are orientated in a shore normal direction and range in length from 510 m at Bondi to 765 m at Malabar. Water depth is about 60 m at North Head and Bondi, and 80 m at Malabar. Because ORS data described density and current structure to maximum depths of only 52m, model results were considered to be most reliable for North Head and Bondi.

Initial dilution of effluent occurs rapidly until plumes reach neutral buoyancy (or surface), typically within 500 m of the outfalls. Figure 6 illustrates modelled effluent exposure patterns which mirror those of ambient nutrient concentrations observed prior to the commissioning of deepwater outfalls (Figure 4), and reflect ambient density stratification. Plume surfacing was often associated with short duration (0.5 to 2 days) forcing events such as storms and internal tides. Plumes were typically trapped at about 30m depth with an average thickness of ~20m. Although effluent exposure patterns were similar between all three outfalls, considerably higher dilutions were associated with lower effluent flow rates at Bondi. Initial dilutions were lower for trapped plumes and generally increased with decreasing density stratification and/or increasing current strength.

Nutrient Enrichment due to Effluent Plumes

Further analysis focused on North Head outfall, which discharges larger loads at lower dilutions than Bondi. Figure 7 describes absolute and relative enrichment of dissolved inorganic nitrogen due to the presence of effluent after initial dilution, relative to ambient receiving waters. Dissolved phosphorus enrichment patterns followed a similar pattern to that of nitrogen. Dissolved inorganic nitrogen was calculated as ammonia-N plus NOx-N. The relative bio-availability of ammonia (principal form of N in effluent) and nitrate (principal form of N in slope/bottom water) are discussed later.

Median ('typical') and 95 percentile plume contributions are compared with median ('typical') ambient nutrient concentrations in Figure 7. Likewise, median plume contributions are compared with 95 percentile ambient nutrient concentrations ('high' - including effects of slope water) in Figure 8. The implications of these enrichment patterns are discussed later in relation to potential for algal problems.

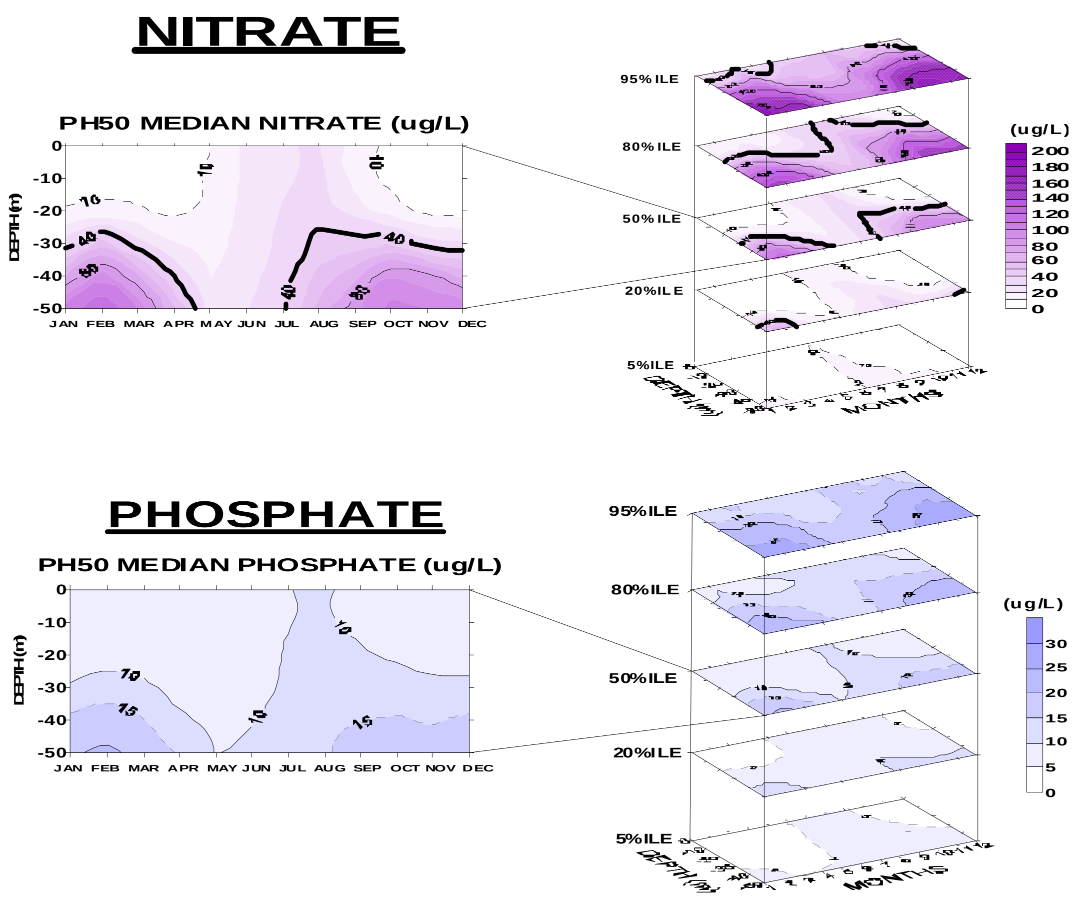


Figure 4. Ambient nutrient patterns at PH50 prior to commissioning of Sydney's deepwater outfalls (NO_3-N and PO_4-P percentile distributions

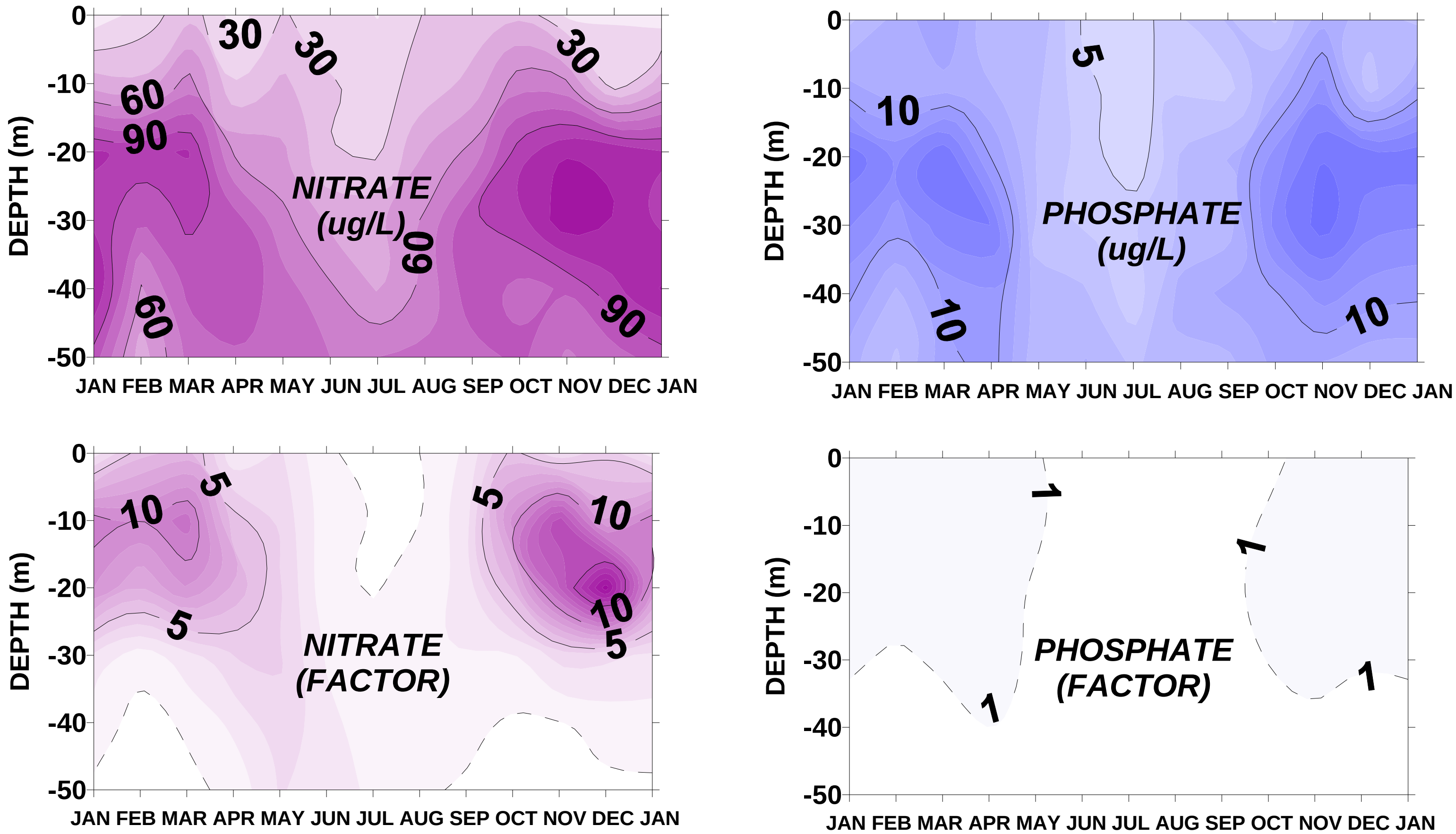


Figure 5. Nutrient enrichment at PH50 for extreme (95 percentile) events expressed as absolute enrichment relative to 50 percentile concentrations (top) and as a factor of 50 percentile concentrations (bottom) [Factor of 1 indicates 95 percentile equals 2 x 50 percentile]

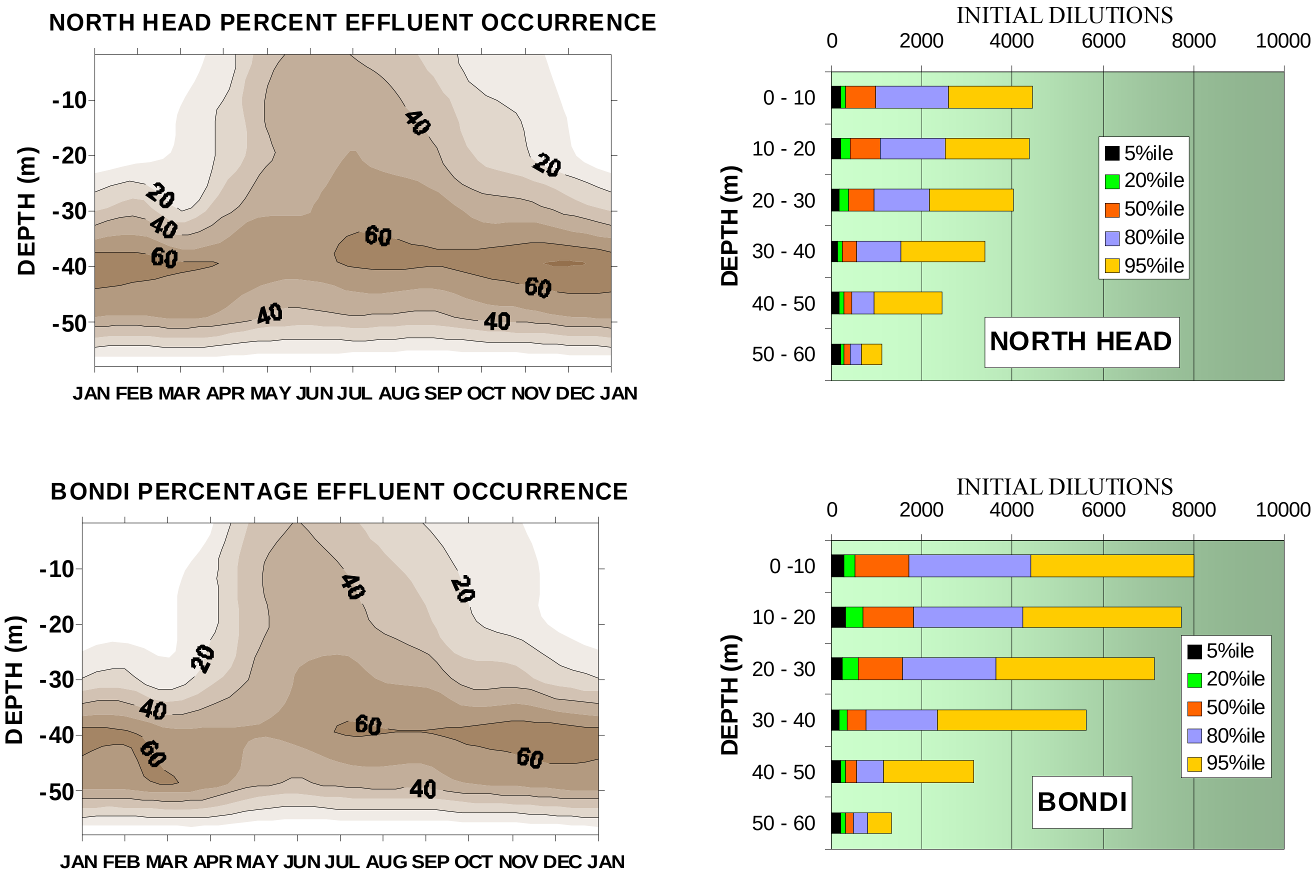
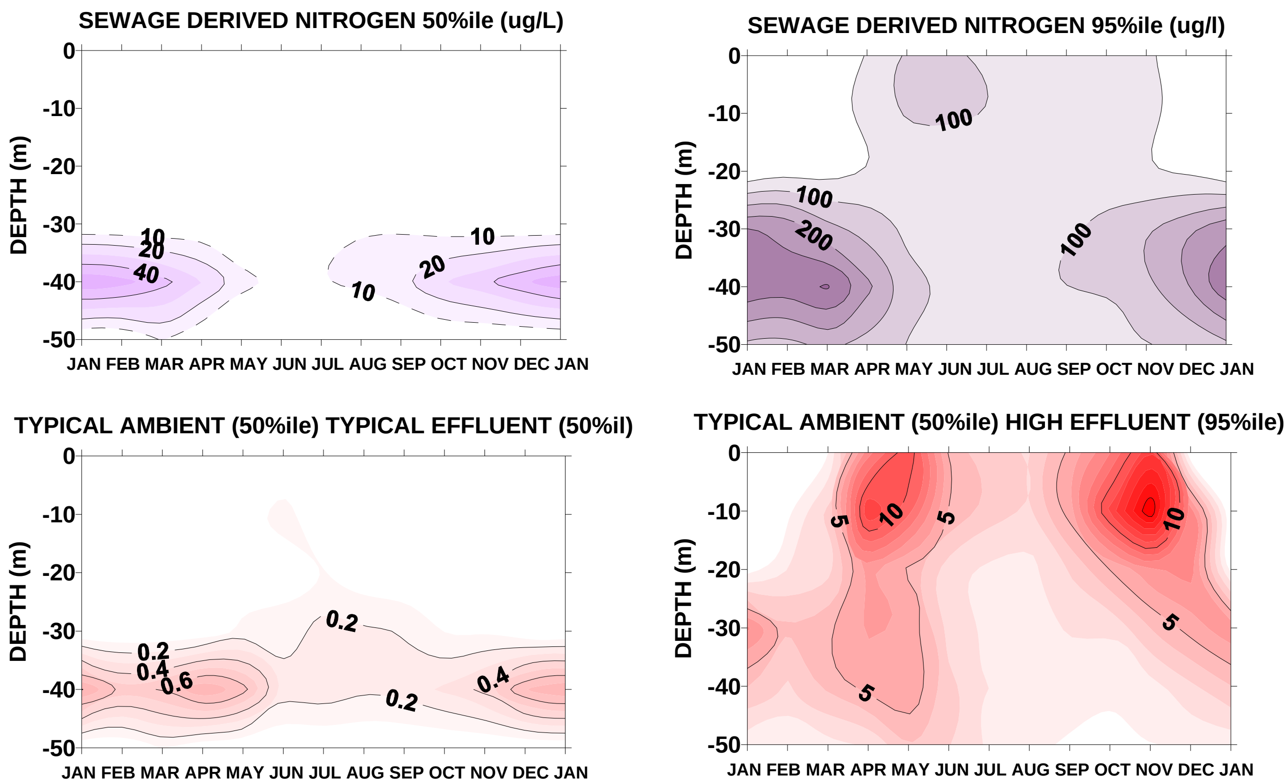


Figure 6. Average annual cycles (1991-1998) of effluent exposure (left) and initial dilutions (right) based on plume model results for North Head (top) and Bondi (bottom)



ENRICHMENT FACTOR = (1/DILUTION) x (EFFLUENT NUTRIENT CONCENTRATION) / (AMBIENT NUTRIENT CONCENTRATION)

Figure 7. Dissolved inorganic nitrogen contribution from North Head effluent plume after initial dilution expressed in absolute terms(top) and relative to ambient concentrations (bottom) for typical plume contributions (left) and extreme plume contributions (right).

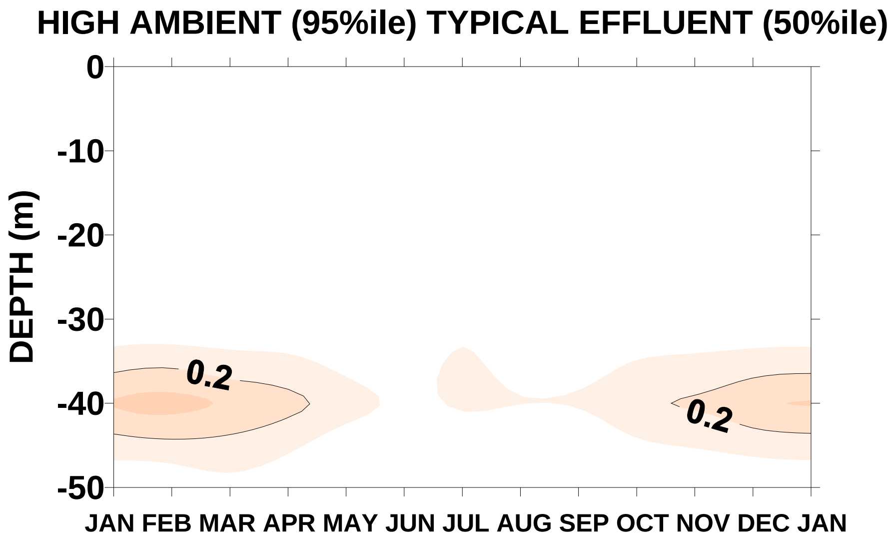


Figure 8. Typical (50 percentile) contributions of dissolved inorganic nitrogen from North Head effluent plume expressed as a fraction of extreme (95 percentile) ambient conditions such as those that may be expected during slope water intrusions.

Spatial Extent of Effluent Plumes

Far-field modelling has shown that, after rapid initial dilution, effluent plumes tend to be advected mainly parallel to isobaths with slow subsequent dilution (WILSON et al. 1995). Figure 9 illustrates results of far field tracer studies conducted at Malabar deepwater outfall where labelled effluent was observed as a 40m thick effluent field trapped below a 1°C thermocline at ~40m depth. Effluent emerged from the diffuser system (720m length) achieving average initial dilutions of 1:1000 within a few hundred metres of the outfall while spreading to form an effluent field which was ~900m wide, about 1km downstream and ~1950m wide, fifteen kilometres downstream the effluent field was advected 15 kilometres in nearly 14 hours but during this time dilution had increased to only 1:2000. Advection rates observed on this occasion were above average when compared to depth averaged ORS current data (i.e. ~15km/day). In contrast, tracer experiments reported by PRITCHARD et al. (1993) under low stratification, indicated a surfacing effluent field that broadened to 2100m at 1km downstream of the outfall.

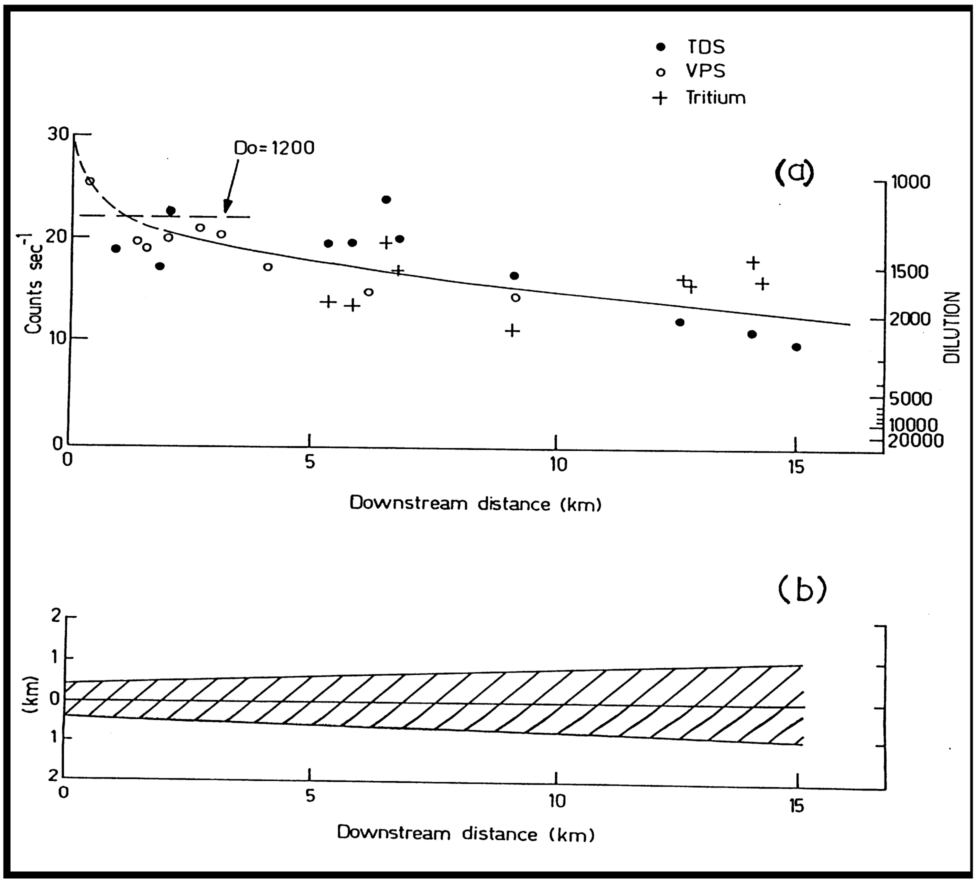


Figure 9. Far field plume dilution and spreading based on radioisotope tracer studies at Malabar ocean outfall on 17/06/92 when the submerged plume was tracked with a vertical triple scintillation detector system (TDS - for Gold198) and a mobile vertical profiling system (VPS) towed at varying depths through and across the plume. Water samples were collected for tritium analysis.

Indirect Factors – Entrainment and Uplift

CTD profiles obtained approximately 500 m downstream from Malabar outfall during the summer of 1992 (Figure 10) illustrates entrainment and uplift of ambient (nutrient rich) bottom waters in the rising plume. On this occasion a near linear temperature gradient (~4°C over 80m) and a salinity peak at about 40m trapped the plume. Salinity differences between essentially 'fresh' effluent (~0.1psu) and receiving ocean waters (~35.4psu) clearly delineate the upper surface of the plume of diluted effluent at ~40 m depth at the downstream (impacted) location. The isothermal profile within the plume (impacted) between 80 and 40 m indicated that cool ambient bottom water (depicted in the lower ~10m of the control profile) dominated the profile/plume up to the trap depth. This suggests that most initial mixing occurred as effluent entered the ocean at 80m depth, presumably during the jet (momentum) dominated phase. Given increasing ambient nitrate (and phosphate) concentrations with depth (Figure 4), it is clear that the physical release of effluent can have an indirect effect on receiving water nitrate concentrations despite the virtual absence of nitrate in primary treated effluent. That is, the entrainment and uplift of nutrient (nitrate) rich bottom waters results in a net upward flux of ambient nutrients irrespective of the contribution from the effluent.

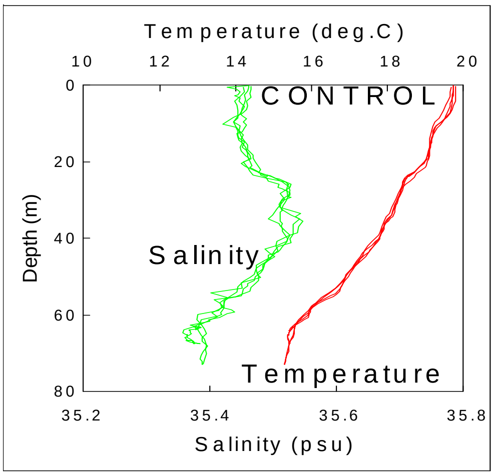
Other features such as a strong effluent concentration gradient (decreasing with increasing depth) to a discrete upper boundary are expressed in Figure 10. In combination with the information from the temperature trace, this suggests variable distributions achieved during chaotic jet dominated dilution occur prior to the rise to a level of neutral buoyancy where the plume stabilises. These observations are however contrary to the near field model simulations which do not accommodate such vertical gradients within the neutrally buoyant plume. However, possible errors in our assessment of enrichment (due to effluent plumes) were minimised by the grouping of average effluent dilutions (in 2m bins) over 10 m depth intervals and mitigated by the fact that JETLAG conserves mass when estimating average dilutions.

POTENTIAL FOR ALGAL PROBLEMS

For the deep water ocean outfalls, a consideration of only the nutrient concentrations and loads would suggest a considerable potential for algal problems. Furthermore, nutrient rich ambient waters from deep in the water column are carried upwards in to the euphotic zone in the rising plume. Furthermore, nutrient rich ambient waters from deep in the water column are carried upwards by the rising plume in to the euphotic zone. The nutrient concentrations in these vertically displaced ambient waters exceeds those typically found in ambient upper water (Table 1) and are generally at or above the concentrations (in surface water) that have been associated with problems elsewhere (ANZECC 1992).

Light and nutrients, particularly nitrogen, have generally been regarded as primary limiting factors for the growth of phytoplankton in the ocean (OVIATT et al. 1989; GABRIC and BELL, 1993; PELLEY, 1998). Observed associations between nutrient enrichment and phytoplankton blooms (e.g. HUMPHREY, 1960; AJANI et al., 2001; LEE et al., 2001) together with observed N:P ratios (Figure11) support the notion that nutrients, especially dissolved inorganic nitrogen, are critical to the development of algal blooms in our study region.

Although high concentrations and loads of nutrients are necessary for excessive growth of phytoplankton, many other factors can limit growth (ANZECC, 1992) including mixing conditions, hydraulic retention time, light, temperature and grazing pressure.



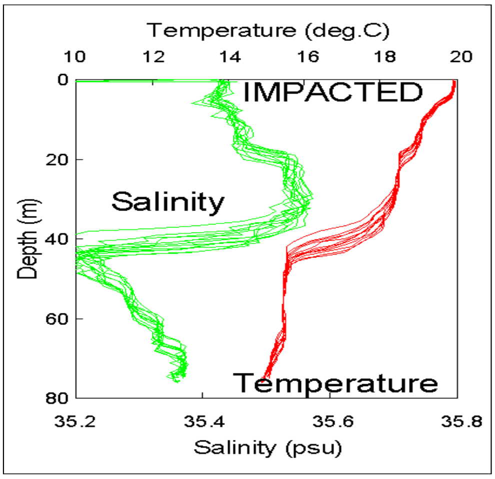
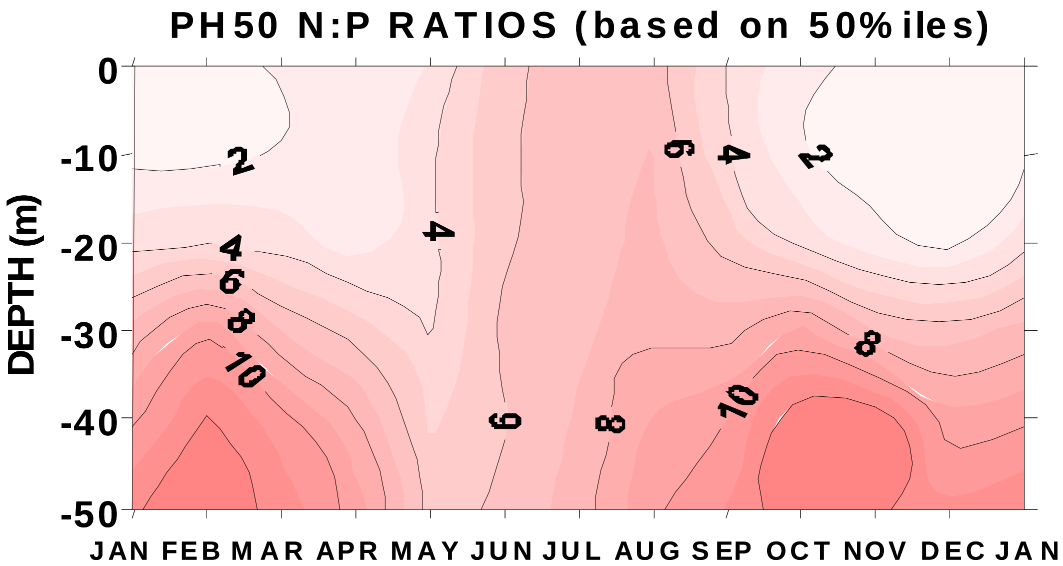


Figure 10. CTD data collected ~200m upstream (CONTROL) and ~500 m downstream (IMPACTED) from Malabar deepwater outfall during summer 1992.

Consistent associations between algal blooms and slope water intrusions and the lack of associations with proximity to major outfalls (e.g. AJANI et al., 2001; LEE et al., 2001 - this volume) led PRITCHARD et al. (1999) to conclude that slope water intrusions were the major factor leading to phytoplankton blooms in our study region. Despite this, potential remains for secondary effects due to sewage derived nutrients.



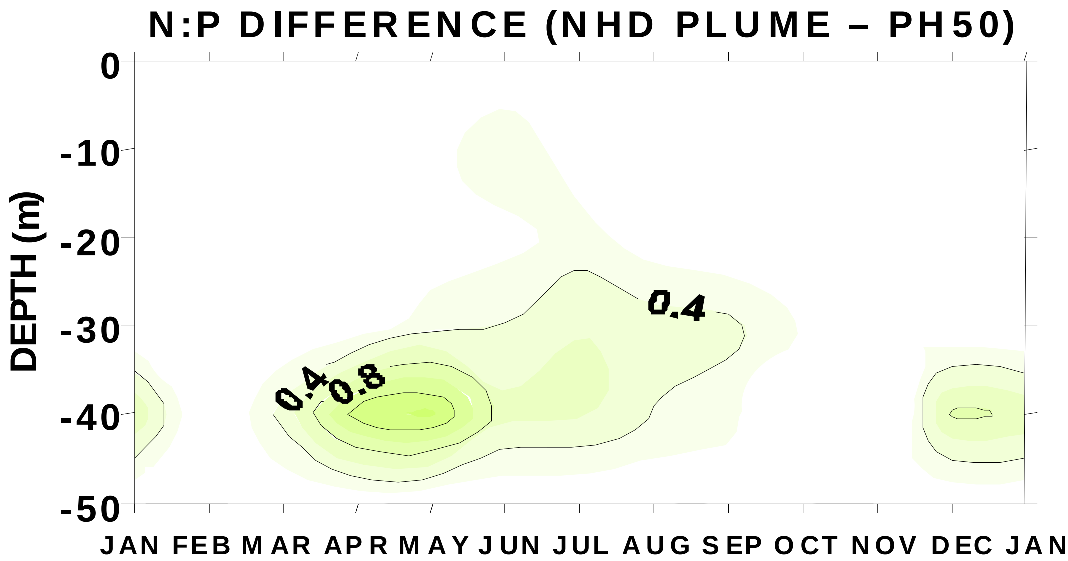


Figure 11. Molar ratios of NOx-N to PO_4-P at Port Hacking site PH50 (top) and residual effect due to North Head (NHD) effluent plume

Phytoplankton Patterns

A range of studies off Port Hacking have found a seasonal pattern with several peaks in phytoplankton activity particularly in late summer and spring (e.g.

HUMPHREY, 1960; JEFFREY and CARPENTER, 1974; AJANI et al., 2001). These correspond to the two nutrient peaks within an annual cycle mentioned earlier. Greater phytoplankton biomass was found at the nearshore (PH50) monitoring station compared to observations at a station in 100-110m water depth off Port Hacking (PH100) (HUMPHREY, 1963). Phytoplankton biomass was found to be about three times that of zooplankton communities (HUMPHREY, 1963) with higher concentrations of phytoplankton in the upper half of the water column than in bottom waters (GRANT and KERR, 1970). Large chlorophyll peaks have been predominantly due to the >15 mm fraction, superimposed upon a nanoplankton fraction (<15 mm) which formed a more constant background level throughout the year and diatoms, coccolithophorids and green flagellates appeared to be the main primary producers at PH100 (HALLEGRAEFF, 1981).

The phytoplankton population was found to consist of mainly neritic species (GRANT and KERR (1970). Three major phytoplankton categories were distinguished at PH100: a large group of species which were present throughout the year; a group of diatom species, which bloomed following episodic nutrient enrichments; and, a group of warm water species associated with tropical water masses (HALLEGRAEFF and REID, 1986)

Studies at PH100 during 1997-98 (AJANI et al., 2001 - this volume) found phytoplankton blooms of similar frequency and magnitude to those seen at this location during 1978-79 (HALLEGRAEFF and REID, 1986). However, the high frequency of occurrence of the chain forming diatom *Thalassiosira spp.* and the 'red tide', heterotrophic, dinoflagellate Noctiluca scintillans observed during 1997-98 was unprecedented in these waters. Any explanation for this change was, however, complicated by the altered physico-chemical conditions associated with the prevailing El Niño conditions that were not present in previous phytoplankton studies at PH100 (LEE et al., 2001).

Nutrient Enrichment

Nutrient enrichment has the potential to affect both phytoplankton biomass and species composition – for example diatoms have high growth rates under nutrient rich-conditions (GRANELI and MOREIRA, 1990) while flagellates do not (OVIATT et al. 1989).

Both slope water intrusions and plume dynamics were strongly influenced by ambient density stratification of the water column. Patterns of exposure to effluent from Sydney's deepwater outfalls (Figure 6), therefore, mimicked seasonal patterns of concentrations of ambient nutrients (Figure 4). Thus, 'natural' enrichment events would appear to be enhanced by contributions from deepwater outfalls. Greatest risk of outfall impacts would be expected when the contribution from outfalls is large with respect to ambient nutrient concentrations especially when ambient concentrations are low relative to saturation levels for phytoplankton growth. Figures 6 and 7 indicate that most of the nutrient loading from Sydney's deepwater outfalls remained submerged in the bottom half of the water column although under extreme (95 percentile) plume conditions effluent enrichment factors (relative to typical ambient concentrations) were greatest in the upper half of the water column during late summer and spring (Figure 7). When compared to enrichment associated with ambient extremes (Figure 5), it would appear that outfalls effects would be most apparent under specific scenarios (low stratification and low current) during late summer.

Nutrient Speciation

Both laboratory and coastal marine mesocosm experiments have demonstrated that different taxonomic groups of phytoplankton may respond to environmental variables in different ways. Competitive differences in the ability of phytoplankton species to respond to sewage derived nutrients may provide the potential to shift phytoplankton species composition. Nitrate was the principal form of 'natural' nitrogen enrichment of ambient waters (associated with slope water) while ammonia (predominantly the ammonium ion) was the principal form of nitrogen in most of the treated effluent. Nitrate and ammonium are the primary forms of nitrogen used by phytoplankton, but nitrite, urea and other forms of organic nitrogen can also be used. Both nitrate and nitrite must be reduced to ammonium before incorporation into amino acids and other organic compounds in a cell. Under conditions of nitrogen excess, therefore, the preferred source is usually the most reduced form, that is the ammonium ion (EPPLEY et al. 1969, SERRA et al., 1978). The ability of a species to utilise organic forms of nitrogen varies with the habitat for which the organism is adapted. For instance, inshore, littoral and benthic species are better able to utilise amino acids and other organic forms of nitrogen than offshore species (WHEELER et al., 1974).

Cellular accumulation of nitrogen in an inactive storage form is limited in comparison to phosphorus, and when nitrogen is deficient, nitrogen compounds in cellular structures may degrade.

Filterable reactive phosphorous (predominantly phosphate) was the principal form of phosphorus in slope/bottom waters, and comprised 60 to 80% of the total phosphorus in primary treated effluent. Phosphorus uptake by algae is almost exclusively as phosphate. When inorganic phosphorus (predominantly phosphate) is low but organic forms of phosphorus are available, algae may excrete phosphatases to break down phosphorous compounds. When phosphate is available in excess amounts, cells may take it up (luxury consumption) and store it as polyphosphates for later use when external supplies are low. Therefore, under certain circumstances, the continuity of supply of phosphorus may be less critical than for nitrogen.

Nutrient Ratios

Ecosystem biomass is limited by the total amount of biochemically available nutrients through the natural stoichiometric ratios between the elements (C, N, P, S, Si, Fe, Cu, etc.) from which all living things are made. Literature cites the Redfield ratio (JUSTIC et al., 1995) of 16:16:1 for bio-available Silica:Nitrogen:Phosphorus as the idealised ratio of nutrients for optimal phytoplankton growth. Discharges of treated sewage can alter both the quantity and relative proportions of various nutrients in coastal waters over time, which numerous studies have indicated can lead to eutrophic conditions or shift the composition and abundance of phytoplankton (OVIATT et al. 1989, GRANELI and MOREIRA 1990, RIEGMAN et al. 1992).

Ratios of dissolved inorganic N:P calculated from long term data collected at PH50 shown in Figure 11 indicate conditions that favour nitrogen limitation prior to the commissioning of Sydney's deepwater outfalls. The time series of N:P ratios showed no clear trend over the period of the data set.

The annual cycle of N:P ratios at PH50 (Figure 11) indicates low ambient inorganic N:P ratios that increase towards optimal 16:1 Redfield Ratios in bottom waters during Spring-Summer, when phytoplankton activity is greatest. Model results suggest that these ratios are relatively unaffected by the discharge of effluent from North Head outfall (after initial dilution), especially during spring/summer in the upper half of the water column when and where phytoplankton activity is greatest (also Figure 11).

Other Considerations

LEE et al. (2001 – this volume) demonstrated the potential for strong El Niño Southern Oscillation (ENSO) signals to affect physico-chemical conditions. Therefore, long term variability must be considered especially for impact assessments when 'before' data are unavailable and/or where relevant control sites are unavailable/impractical. Our investigations were based on ambient conditions defined by data with minimal ENSO bias while effluent plume data may be slightly biased in favour of El Niño, as indicated earlier. No major ENSO bias is expected although El Niño conditions may be associated with decreased thermal stratification during the winter months which promotes a slightly greater frequency of surfacing plumes and associated higher dilutions at these times (LEE and PRITCHARD, 1996).

The continual supply of nutrients from ocean outfalls may sustain background (low level) populations of specific plankton thus maintaining a seed stock which would otherwise be absent during sporadic enrichment events (SUTHERS pers comm). Effluent may be present in surface waters at high dilution for about 20-40% of the time during winter, and over 60% of the time at lower dilutions within the bottom half of the water column (Figure 6). However, when typical (50 percentile) plume nutrient contributions were compared with typical (50 percentile) ambient concentrations, enrichment due to outfalls was generally restricted well within the lower half of the water column - exceptions occur when extreme plume conditions (95 percentile) occur (Figure 7).

CONCLUSIONS

Estimates of various nutrient loadings to NSW coastal waters indicated that loadings from coastal STPs were large with respect to other discrete sources. Furthermore, Sydney's three deepwater outfalls were found to be responsible for the vast majority of sewage contributions to coastal waters. These loadings and a consideration of nutrient concentrations suggested a considerable potential for algal problems.

No new evidence has been presented to contradict previous findings that algal blooms are principally driven by seasonal oceanic nutrient enrichments. But recent studies in southern Sydney offshore waters did observe an unprecedented abundance of the chain forming diatom *Thalassiosira spp*. and the 'red tide', heterotrophic, dinoflagellate *Noctiluca scintillans*, although prevailling El Niño conditions had altered physico-chemical conditions and therefore complicated interpretations.

If there are any undetected outfall impacts, they are likely to be subtle and require more focused investigation. An understanding of physical processes operating on the continental shelf is necessary to focus such investigations because of highly variable ambient nutrient concentrations together with considerable lag times for phytoplankton (and especially heterotroph) responses. By considering simulations of near field effluent plume behaviour in relation to long term ambient nutrient patterns we have identified specific periods of the year and depth intervals when outfalls would have an increased opportunity to influence bloom development, especially the upper half of the water column during late summer.

Discharges from coastal sewage treatment plants were shown to contain large quantities and relatively high concentrations of bioavailable nutrients. However, there is little evidence to suggest that plumes from Sydney's deepwater outfalls result in major shifts in the ratio of dissolved inorganic nitrogen to dissolved phosphorus.

Worthy areas for further research include focused studies during late summer scenarios, more detailed investigations of factors which limit phytoplankton growth, and the role of biological processes (including zooplankton interactions and bacterial processes) in cycling and sequestering nutrients.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Ocean Reference Station data and effluent monitoring data from Sydney Water Corporation and near field modelling undertaken for this project by the Water Research Laboratory. We are also grateful to Dr Matthew England and Dr Klaus Koop for their constructive reviews of this paper. This work was supported by the New South Wales Environment Protection Authority

LITERATURE CITED

AIREY, D. and SANDARS, G., 1987. Automated Analysis of Nutrients in Seawater, CSIRO Marine Laboratories Report 166, 95p.

AJANI, P., LEE, R., PRITCHARD, T. and KROGH, M., 2001. Phytoplankton dynamics at a long-term coastal station off Sydney, Australia. Journal of Coastal Research (this volume).

ANDERSON, D. M., 1995. Toxic red tides and harmful algal blooms: a practical challenge in coastal oceanography. Review Geophysics, Suppl. U. S. National Report to the Int. Union of Geodesy and Geophysics. 1991-1994, pp. 1189-1200.

ANZECC, 1992. Australian Water Quality Guidelines for Fresh and Marine Waters, Australian and New Zealand Environment and Conservation Council, Australia. 148p.

AYRES, C. P., GILLETT, R. W. and CERNOT, U., 1987. Rainwater Acidity in Sydney, An Addendum, Clean Air, Vol. 21(2), 8p.

BICKFORD, G. P., 1996. The effects of sewage organic matter on biogeographical processes within mid-shelf sediments offshore Sydney, Australia. Marine Pollution Bulletin, 33 (7-12), 168-181.

CATHERS, B. and PEIRSON, W. L., 1991. Verification of Plume Models Applied to Deepwater Outfalls. In LEE, J. H. W. and CHEUNG, Y. K. (Eds) Environmental Hydraulics, Proceedings of International Symposium on Environmental Hydrology, Hong Kong, 16-18, December 1991, pp. 261-266.

CHURCH, J. A., FREELAND, H. J. and SMITH, R. L., 1986. Coastal trapped waves on the east Australian continental shelf Part I: propagation of modes. Journal of Physical Oceanography, 6, 1929-1943.

CRESSWELL, G., 1994. Nutrient enrichment of the Sydney continental shelf. Australian Journal of Marine and Freshwater Research, 45, 677-691.

CRESSWELL, G. R. and LEGECHIS, R., 1986. Eddies off southeastern Australia. Deep Sea Research, 33, 1527-1562.

EPPLEY, R. W., COAYSWORTH, J. L. and SOLORZANO, L., 1969. Studies of nitrate reductase in marine phytoplankton. Limnology and Oceanography 14, 194-205.

GABRIC, A. J., and BELL, P. F. R., 1993. Review of the effects of non-point source loading on coastal ecosystems. Australian Journal of Marine and Freshwater Research. 44 (2), 261-283.

GIBBS, M. T., MIDDLETON, J. H. and MARCHESIELLO, P., 1998. Baroclinic responses of Sydney Shelf Waters to Local Wind and Deep Ocean Forcing. Journal of Physical Oceanography, 28, 178-190.

GRANELI, E. and MOREIRA, M. O., 1990. Effects of river water of different origin on the growth of marine dinoflagellates and diatoms in laboratory cultures. Journal of Experimental Marine Biology and Ecology 136, 89-106.

GRANT, B. R. and KERR, J. D. 1970. Phytoplankton numbers and species at Port Hacking station and their relationship to the physical environment. Australian Journal of Marine and Freshwater Research, 21, 35-45.

GRIFFIN, D. A. and MIDDLETON, J. H., 1991. Local and Remote wind forcing of New South Wales inner shelf currents and sea level. Journal of Geophysical Research, 21, 304-322.

GRIFFIN, D. A. and MIDDLETON, J. H., 1992. Upwelling and internal tides over the inner New South Wales continental shelf, Journal of Geophysical Research, 97(C9), 14389-14405.

HAHN, S. D., ROCHFORD, D. J. and GODFREY, J. S., 1977. Long-term variability of oceanographic data at the Port Hacking 50-metre station. Australian Journal of Marine and Freshwater Research, 28, 57-66.

HALLEGRAEFF, G. M., 1981. Seasonal study of phytoplankton pigments and species at a coastal station off Sydney. Marine Biology, 61, 107-118.

HALLEGRAEFF, G. M. and REID, D. D., 1986. Phytoplankton species successions and their hydrological environment at a coastal station off Sydney. Australian Journal of Marine and Freshwater Research, 37, 361-377.

HALLEGRAEFF, G. M., 1993. Assessment of the Impact of Algal Blooms on the Water Quality of Sydney Coastal Waters. Report to the Sydney Water Board, University of Tasmania, Hobart. 49p.

HARRIS, G., BATLEY. G., FOX, D., HALL, D., JERNAKOFF, P., MOLLOY, R. MURRAY, A., NEWELL, B., PARSLOW, J., SKYRING G. and WALKER, S., 1996. Port Phillip Bay Environmental Study Final Report. CSIRO, Canberra Australia, 239p.

HUMPHREY, G. F., 1960. The concentration of planktonic pigments in Australian waters, CSIRO Division of Fisheries and Oceanography Technical Paper No. 9, pp. 1-27.

HUMPHREY, G. F., 1963. Seasonal variations in plankton pigments in waters off Sydney. Australian Journal of Marine and Freshwater Research, 14 (1), 24-36.

JEFFREY, S.W. and CARPENTER, S. M., 1974. Seasonal succession of phytoplankton at a coastal station off Sydney. Australian Journal of Marine and Freshwater Research, 25, 361-369.

JUSTIC, D., RABALAIS, N. N. and TURNER, R. E., 1995. Stochiometric nutrient balance and origins of coastal eutrophication, Marine Pollution Bulletin, 30(1), 41-46.

LEE, L. H. W. and CHEUNG, Y. K., 1990. Generalised Lagrangian model for buoyant jets in a current. Proc. ASCE, Journal of Environmental.Engineering, 116(6), 1085-1106.

LEE, R. S., AJANI, P. A., KROGH, M. and PRICTHARD, T. R., 2001. Resolving climatic variance in the context of retrospective phytoplankton pattern investigations off the east coast of Australia. Journal of Coastal Research (this volume).

LEE, R. S., and PRITCHARD, T. R., 1999. Extreme discharges into the coastal ocean: A case study of August 1998 flooding on the Hawkesbury and Hunter Rivers. 14th Australian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference – Coasts and Ports 1999, pp. 341-346.

LEE, R. S., and PRITCHARD, T. R., 1996. Dispersion of Effluent from Sydney's New Deepwater Outfalls. Part 1: Ocean Processes. In Mixing Processes in Estuaries and Coastal Seas (C.PATTIARATCHI, ed), American Geophysical Union, Washington, pp. 430-438.

LEE, R. S., and PRITCHARD, T. R., 1996. How do long-term patterns affect time-limited environmental monitoring programmes? Marine Pollution Bulletin, 33(7-12), 260-268.

NEWELL, B. S., 1966. Seasonal changes in the hydrological and biological environments off Port Hacking, Sydney. Australian Journal of Marine and Freshwater Research, 17, 77-91.

MAJOR G. A., DAL PONT G., KYLE J., and NEWELL B., 1972. Laboratory Techniques in Marine Chemistry - A Manual, CSIRO Division of Fisheries and Oceanography, Report 51, Sydney, 60p.

MHL, 1997. Review of Sewage Effluent Ocean Outfall Performance in NSW. Manly Hydraulics Laboratory Report MHL769, 65p.

OKE, P. R. and MIDDLETON, J. H., 1999 Nutrient enrichment off Port Stephens: the Role of the East Australian Current. Continental Shelf Research, 21(6-7), 587-606.

OVIATT, C., LANE, P., FRENCH, F. and DONAGHAY, P., 1989. Phytoplankton species and abundance in response to eutrophication in coastal marine mesocosms. Journal of Plankton Research, 11(6), 1223-1244.

PAERL, H., 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnology and Oceanography, 42(5), 1154-1165.

PAN, Y. and RAO, S., 1997. Impacts of domestic sewage effluent on phytoplankton from Bedford Basin, Eastern Canada. Marine Pollution Bulletin, 34(12), 1001-1005.

PELLEY, J., 1998 ‘Is Coastal Eutrophication Out of Control?’ Environmental Science and Technology, October 1998, 462-466.

PRITCHARD, T., AJANI P., ANDREW, D., CALFAS, M., HOLDEN, C., LEE. R., LINFORTH, S. and RENDELL, P., 1998. Relative significance of slope water, estuarine discharges and sewage outfalls for nutrients in offshore coastal waters. Coastal Nutrients Conference Proceedings, Australia, 1998. Australian Water and Wastewater Association Inc. pp. 44-50.

PRITCHARD, T., LEE, R. and AJANI, P., 1999. Anthropogenic and oceanic nutrients in NSW’s dynamic coastal waters and their effect on phytoplankton populations. 14th Australian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference – Coasts and Ports 1999. pp. 537-543.

PRITCHARD, T. R. LEE, R. S. and DAVISON, A., 1996. Dispersion of effluent from Sydney's new deepwater outfalls Part 2: Observations of Sewage Plume Behaviour: Winter and Summer Examples. In Mixing Processes in Estuaries and Coastal Seas (C.PATTIARATCHI, ed), American Geophysical Union, Washington, pp. 439-452.

PRITCHARD, T., RENDELL, P., SCANES, P. and PHILIP, N., 1996. Assessment of the Deepwater Outfalls. Vol 1. EMP Final Report Series. Environment Protection Authority, Sydney, 194p.

PRITCHARD, T.R., LEE, R.S. and DAVISON, A., 1993. Sydney’s Deepwater Outfalls. In situ Observations of Plume Characteristics. In:Proceedings of 11th Australasian Conference in Coastal and Ocean Engineering, Townsville, 23-27 August 1993. Institute of Engineers, Australia.

RIEGMAN, R., NOODELOOS, A. M. and CADEE, G. C., 1992. Phaeocystis blooms and eutrophication of the continental coastal zones of the North Sea. Marine Biology, 112, 479-484.

ROCHFORD, D. J., 1984. Nitrates in eastern Australian coastal waters. Australian Journal of Marine and Freshwater Research, 35, 385-397.

SCHNEIDER, P. M., 1999. Offshore Sydney Contaminants – Their Distribution and Associations. PhD Thesis, Dept. Geology and Geophysics, University of Sydney, Australian, 344p.

SERRA, J. L., LLAMA, M. J. and CADENAS, E., 1978. Nitrate utilisation by the diatom Skeletonema costatum. II. Regulation of nitrate uptake. Plant Physiology, 62, 991-994.

SINCLAIR KNIGHT MERZ (SKM), 1997. Nutrient Discharges from Estuaries, Report to NSW EPA, 28p.

SMAYDA, T. J., 1990. Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic. In: OKAICHI, T., ANDERSON, D., NEMOTS, T., (eds). Red tides – Biology, Environmental Science and Toxicology. Elsevier, New York, pp. 29-39.

SMAYDA, T. J., 1997. Harmful algal blooms: Their ecophysiology and general relevance to phytoplankton blooms in the sea. Limnology and Oceanography, 42(2), 1137-1153.

SYDNEY WATER, 1997. Environmental Indicators Monitoring Report and Special Objectives Statement, Sydney Water Annual Environment Report Auxiliary volume. Sydney Water Corporation, 133p.

TRANTER, D. J., CARPENTER, D. J. and LEECH G. S., 1986. The coastal enrichment effect of the East Australian Current eddy field. Deep-Sea Research, 33, 1705-1728.

WHEELER, P. A., NORTH, B. B. and Stephens, G. C., 1974. Amino acid uptake by marine phytoplankters. Limnology and Oceanography, 19(2) 249-259.

WILSON, J. R., COX, D. R., WALKER, J. W., HOWDEN, M. I., COURIEL, E. D. and LEE, R. S., 1995. Sydney Deepwater Outfalls Environmental Monitoring Program: Final Report Series: Volume 2: Sewage Plume Behaviour, NSW EPA Publication, 227p.

ZANN, L., 1995. Our Sea, Our future. Major findings of the state of the Marine Environment report for Australia, Great Barrier Reef Marine Park Authority (Australia) for Ocean Rescue 2000, 112p.

6.5 Summary and Outcomes

Analysis of extensive current meter and temperature time series data revealed the dominant driving mechanisms, which are different to those within near shore coastal boundary layer features observed off Coffs Harbour (Chapter 8). Furthermore, the deepwater locations of effluent discharge off Sydney appears to mitigate many of the risk factors that lead to environmental impacts; initial dilutions are high and pollutant residence times are low in this high energy environment with limited flow disruption due to local bathymetric features. At the extremities of the inner shelf off Sydney, broad coastal boundary layer effects dominate such as the manifestation of a western boundary current in the form of the EAC and its eddies, associated bottom (and wind) stresses which promotes cross-shelf transport and upwelling/downwelling dynamics (an inevitable consequence of a closed western boundary). The bathymetry of the continental shelf also has a broad effect in constraining the passage of coastal trapped waves.

Differences between the dominant drivers at Coffs Harbour and Sydney and various scales of coastal boundary layer effects are discussed further in Chapter 9.

Nutrient loadings from Sydney's coastal sewage treatment plants were large with respect to other discrete sources. These loadings and a consideration of nutrient concentrations suggested a considerable potential for algal problems. However, significant outfall impacts remain undetected and, if present, are likely to be subtle. By considering simulations of near field effluent plume behaviour in relation to long term ambient nutrient patterns specific periods of the year and depth intervals have been identified when outfalls would have an increased opportunity to influence bloom development, especially the upper half of the water column during late summer. However, algal blooms appear to be principally driven by seasonal oceanic nutrient enrichment.

Key findings include:

- broad coastal boundary layer effects were observed at the ORS including: EAC influences; upwelling dynamics; coastal trapped waves; and, bottom (and surface wind) stress promoting cross shelf transport evident as

- ORS data indicate prevailing southward transport punctuated by a number of ‘events’ when rapid accelerations and/or flow reversal interrupted the southward trajectory. This supports the assumption that long-term CSIRO sampling stations off Port Hacking are typically downstream of Sydney’s deepwater outfalls.

- high energy coastal waters off Sydney exhibit dynamic variability across a range of scales which can affect pollutant impacts:
  - high frequency internal waves are evident in the ORS record: buoyant plumes rising through internal wave fields may differ significantly in height of rise and dilution compared to plume behaviour under mean stratification; likewise, biological and water quality sampling designs must recognise variability associated with these vertical displacements.
  - de-stratification can occur over time frames of hours promoting vertical mixing of nutrient rich bottom waters and allowing effluent plumes to reach the surface.
  - temperature stratification exhibits seasonal and inter annual variability: peak stratification ranges from ~7°C in summer 1993 to ~4°C in summer 1994.
  - plumes generally surface (and achieve high effluent dilutions) when stratification is less that 1°C as exemplified by winter 1993.
  - stratification minima and associated high plume surfacing frequencies were generally confined to El Niño (warm) episodes

- power spectra for Sydney inner-mid shelf water are available for comparison with Coffs Harbour coastal waters (in Chapter 8):
  - semi-diurnal tides are prominent but relatively low energy.
  - strong, coincident (wind and current), diurnal energy peaks represent sea/land breeze effects, transient weather systems and inertial motions (inertial period 23.6hrs at ORS).

- synoptic weather band energy dominates the signal driven by local weather systems (several days as shown in the wind spectra), distant weather systems (e.g. coastal trapped waves) and EAC effects which can span weeks.
- both winds and currents show prominent seasonal peaks due to latitudinal shifts in atmospheric pressure systems and seasonal differences in EAC effects.
- the annual cycle is subtle in the current meter record and virtually absent in the wind record.
- a low frequency signal is apparent when the directional current displacements are plotted for entire ORS time series; eastward deviations are apparent in the upper current meter record for events centred on 1996 and 2001.

- Long term nutrient patterns prior to the commissioning of deepwater outfalls were consistent with winter overturning of shelf waters and episodic slope water intrusions and enhanced biological (phytoplankton) activity in surface waters during the warmer summer months. That is:
    - minimum nutrient (and thermal) stratification occurred late in the austral autumn and winter: at this time surface water nutrient concentrations tended to coincide with minimum deepwater nutrient concentrations.
    - maximum surface waters nutrient concentrations occurred during July-August
    - maximum deep waters nutrient concentrations occurred during spring and summer, peaking in February.
    - absolute enrichment due to extreme 'natural' events (95%ile minus 50%ile) was greatest at mid-depth (about the thermocline) from September through to April.
    - relative enrichment due to extreme 'natural' events (95%ile divided by 50%ile) was most marked within the upper half of the water column and up to an order of magnitude greater for nitrate than for phosphate.

    - ambient nutrient ratios suggest that nitrogen is the limiting nutrient; effluent discharged from the deepwater outfalls carries nitrogen mostly as ammonia which is available to algae

- nutrient concentration data indicate the potential for enrichment of surface waters due to estuarine discharges (especially nitrate and ammonia) and outfalls (especially ammonia) on those occasions when sewage effluent plumes surface. Bottom waters may be enriched by slope water intrusions (especially nitrate and phosphate) and by outfalls (especially ammonia).

- Sydney's three deepwater ocean outfalls were found to be the principal, continuous, anthropogenic source of nutrients to NSW coastal waters:
    - together they contribute nearly 75% of the nutrient loading to NSW waters from coastal sewage treatment plants
    - clear nutrient enrichment due to sewage discharges
    - effluent plumes (~30m thick) typically remain submerged, broadening to 1-2 kilometers by about 10 kilometers downstream of the outfall (predominantly southward)
    - sewage effluent typically remains submerged especially during spring and summer which is when algal blooms typically occur; maximum effluent dilutions occur when sewage effluent surfaces

- ADCP data are vastly superior to extrapolation below the bottom ORS current meter which until recently was used for plume model simulations. This is a critical finding given that investigations of plume behaviour (**Pritchard** et al., 2001) suggest that most initial mixing can occur within the bottom 10-15 m of the water column (i.e. below the bottom ORS current meter).

- density stratification (of ambient waters) was a critical factor in determining the vertical movement of both oceanic and sewage derived nutrients into the euphotic zone (where light is available for algal growth):
    - the entrainment and uplift of nutrient (nitrate) rich bottom waters in buoyant plumes results in a net upward flux of ambient nutrients irrespective of the contribution from the effluent.

- for the deepwater outfalls, a consideration of nutrient loads and concentrations alone would suggest a considerable potential for algal blooms although many other factors can limit algal blooms.

- consistent associations between algal blooms and slope water intrusions and the lack of associations with proximity to major outfalls led **Pritchard** et al. (1999) to conclude that slope water intrusions were the major factor leading to phytoplankton blooms in our study region but raised the possibility of secondary effects due to sewage derived nutrients. For example:
  - competitive differences in the ability of phytoplankton species to respond to sewage derived nutrients may provide the potential to shift phytoplankton species composition. Studies have shown that under conditions of nitrogen excess the preferred source of nitrogen is usually the most reduced form, which is the ammonium ion. Results in this chapter show that nitrate was the principal form of ‘natural’ nitrogen enrichment of ambient waters (associated with slope water) while ammonia (predominantly the ammonium ion) was the principal form of nitrogen in most of the treated effluent.
  - patterns of nutrient delivery have the potential to affect both phytoplankton biomass and species composition. Results in this chapter indicate that the greatest risk of outfall impacts would be in surface waters during late summer when the contributions from outfalls are large with respect to ambient nutrient concentrations, and especially when ambient concentrations are low relative to saturation levels for phytoplankton growth.
  - continual supply of nutrients from ocean outfalls may sustain background (low level) populations of specific plankton thus maintaining a seed stock which would otherwise be absent during sporadic enrichment events (Suthers pers comm). Effluent may be present in surface waters at high dilution for about 20-40% of the time during winter. However, when typical (50 percentile) plume nutrient contributions were compared with typical (50 percentile)

- changed nutrient ratios (Si:N:P) can change algal species compositions although analysis in this chapter suggests that nitrogen to phosphorus ratios (N:P) are typically little changed after initial dilution

The research presented in this chapter, together with companion research (e.g. **Pritchard**,1997; **Pritchard** et al., 2003) and routine ongoing monitoring, indicate the viability of disposal of the vast majority of Sydney's sewage effluent via existing deepwater outfalls. However, on going vigilance is required due to increasing loads and changing ambient conditions associated with global warming and cumulative impacts. Furthermore, long-term variability must be considered in order to extrapolate (generalise) outcomes of impact assessments to other times because variability in hydrodynamic factors can change the sensitivity to, and nature of ecological impacts.

A consideration of increasing human demands on resources in the context of the whole water cycle leads to the inevitable conclusion that water and nutrients in sewage are a valuable resource, which we must make concerted efforts to recover. As such discharges to the ocean and other waters are not appropriate until other options such as source control and re-use have been exhausted.

6.6 References

Ajani, P., Ingleton, T., **Pritchard, T.** and Armand, L. (2011) Microalgal blooms in the coastal waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales 133, 15-31.

Ajani, P.A., Hallegraeff,G. and **Pritchard,T.R.** (2001a) Historic Overview of Algal Blooms in Marine and Estuarine Waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales, 123, pp. 1-22

Ajani,P., Lee,R., **Pritchard,T.R**. and Krogh,M. (2001b) Phytoplankton patterns at CSIRO's long-term coastal station off Sydney. Journal of Coastal Research, 34, 60-73.

Philip, N.A. and **Pritchard, T. R.** (1996) Australia's First Deepwater Sewage Outfalls: Design Considerations and Environmental Performance Monitoring. Mar. Pollut. Bull. 33, 132-139.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T.R, Lee,R.S., Ajani,P.A., Rendell.P.S., Black,K & Koop,K. (2003) Phytoptoplankton responses to nutrient sources in coastal waters off southeastern Australia. Aquatic Ecosystem Health and Management, 6(2): 105-117.

Pritchard, T. R., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Affect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.

Pritchard, T.R. , 1997. Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, Vol 24, No.1. March/April 1997.

Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N., 1996 .Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

Pritchard, T. R., Lee, R. S. and Davison, A. (1996) “Dispersion of effluent from Sydney’s new deepwater outfalls Part 2: Observations of Plume Behaviour: Winter and Summer Examples” In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), pp. 430-438. American Geophysical Union, Washington.

Pritchard, T.R., Lee, R.S. and Davison, A. (1993). Sydney’s Deepwater Outfalls. In situ Observations of Plume Characteristics. In:Proceedings of 1th Australasian Conference in Coastal and Ocean Engineering, Townsville, 23-27 August 1993. Institute of Engineers, Australia.

Roughan, M. and Middleton, J.H. (2002) A comparison of observed upwellingmechanisms off the east coast of Australia. Continental Shelf Research 22, 2551–2572.

7 A MORPHOLOGICAL CLASSIFICATION OF NSW HEADLANDS, BAYS AND ISLANDS

The purpose of this chapter is to develop a hydrodynamically relevant morphological classification of bays, headlands and islands for NSW, and to characterise observed morphologies within each of the classes.

In this way NSW coastal morphologies can be quantified to identify potential coastal boundary layer effects. This provides a framework to assess the general significance of findings from specific case studies such as dispersion in the lee of Corambirra Point, Coffs Harbour in Chapter 8. It also provides a spatial dimension to the classification of *Inner Coastal Boundary Layer* types developed in Chapter 4. Ultimately, this morphological classification of bays, headlands and islands provides the foundation for a risk based hydrodynamic assessment of near shore NSW (and other) waters. Prospects for further research and development of this type are outlined in Chapter 10. This includes discussion on specific targets for research emerging from this morphological classification such as observation-based investigations and hydrodynamic modeling that falls outside the scope of this thesis.

Various techniques have been employed to characterise coastal roughness such as fractal analysis (e.g. Wessel and Smith, 1996) and various classification systems exist for other coastal environments such as estuaries (e.g Roy 2001), beaches (e.g. Short 1993), coastal depositional environments (Harris et al., 2002) and sandbanks (e.g. Dyer and Huntley, 1999). NSW bay shapes have been characterised in relation to likely differences in tsunami amplification and dissipation (Baldock, et al., 2007). However, this author is unaware of any previous morphological classification of bays and headlands based on potential for retention and dispersion of pollutants.

7.1 Introduction

The general criterion for the usefulness of classification systems is that they identify coherent groups with similar properties that inform or simplify a management question (Kurtzi et al., 2006).

In this chapter fundamental coastal morphologies are classified for New South Wales in relation to the key physical processes responsible for mixing, retaining and dispersing particles across the *Inner Coastal Boundary Layer*. Clear definitions and simplified assumptions based on key geometric attributes form the basis of this classification scheme.

In NSW pollutants typically originate from coastal catchments and are discharged to the coastal waters directly via regulated outfalls and unregulated stormwater drains, or indirectly via estuaries, as discussed Chapter 2. These pollutants enter the coastal boundary layer where complex flow fields comprising eddies, jets and stagnation zones occur due to interactions of flows with coastal morphology (as detailed in Chapter 4).

The NSW coastal and shelf morphology is the product of past and present forces acting on its geology. The NSW coastline has been shaped by repeated fluctuations of sea level, especially the 120m rise that occurred during the most recent postglacial period. The current coastline was established when sea level reached its current level about 6,500 years ago so it is a relatively young coastline in geological terms (Short, 1993).

Numerous headlands and small bays along much of the north and south coasts of NSW are associated with the hard metamorphic rocks of New England Fold Belt and the Lachlan Fold Belt (respectively) (Short, 1993; Branagan and Packham, 2000). Broader bays and fewer headlands exist along the coast between these fold belts and to the north where softer, mostly sedimentary rocks outcrop on the coastal fringes of the Sydney Basin and the Clarence-Morton Basin. Harder Hawkesbury sandstones in the centre of the coast of the Sydney Basin have resulted in headland–bay topography that is characteristic of Central-Sydney-Wollongong coastal areas.

Unconsolidated coastal sediments of NSW are dominated by quartz rich sands, especially in northern NSW (Short and Woodroffe, 2009). Indeed the largest area of sediment accumulation in Australia is along northern NSW and southeast Queensland where almost pure quartz sand eroded from extensive granite rocks of the New England fold belt have been transported to the coast by the Hastings, Macleay, Richmond, Clarence, Brunswick and Tweed rivers before being transported northward by waves. These vast sand deposits tend to migrate northward (~500,000m^3yr^{-1} at the NSW – Queensland border) and have the potential to affect shelf bathymetry as well as shaping coastal features. This is evident off northern Fraser Island (Queensland) where the final terminus (Breaksea Spit) of this sand system extends across the continental shelf, spilling sand down the continental slope (Short and Woodroffe, 2009). Abundant mobile sand together with a southerly bias in wave direction gives rise to iconic asymmetric headland forms, especially in northern NSW, as illustrated below (Figure 7.2). South of Port Macquarie headlands essentially stop the northward transport of sand, particularly south of Newcastle, and few rivers presently supply sand to the coastal systems along the south coast. Instead sand from coastal catchments is deposited in the estuaries and coastal lakes.

In the absence of high resolution near shore bathymetry analysis of coastal roughness has focused on coastlines. Fractal characterisation of rocky coastlines has been used elsewhere to predict the spatial distribution of the flux of pollutant diffusing ashore (Boffetta et al., 2008). That is, rocky shorelines with a fractal dimension of 4/3 were shown to be conformally invariant (an expression of rich symmetry) which allowed efficient computation of pollutant fluxes from offshore to the coastline using techniques borrowed from theoretical physics. In this case the pollutant flux scaled exactly as $R^{\pi/\theta}$, where R can be interpreted as the length of a wedge (ie headland/bay) with an opening or apex angle of θ (Duplantier, 2000 in Boffetta et al., 2008). These parameters (length and apex angle) were included as descriptors in the morphological classification proposed here for the NSW shoreline. However, a fractal approach was not adopted. A stochastic analysis based on specific fractal characteristics has the potential to provide a general description of possible dispersion characteristics but is fundamentally limited by its lack of explicit representation of physical processes and uncertainties about its general applicability to New South Wales.

The morphological classification developed in this chapter is designed to combine coastal geometry with regional hydrodynamics to inform a risk based assessment of potential dispersion/retention. This forms an appropriate first step to inform management decisions relating to specific pollutant discharges. The full risk assessment approach is likely to require subsequent more detailed process based assessments (including modeling) for 'high risk' morphological settings that have been prioritised by this method. Therefore, fundamental morphologies are identified here and their parameterisation and context is discussed later in relation to hydrodynamic and dispersion processes.

7.2 Morphological Types

For the purpose of this classification for NSW coastal waters, the following bay characteristics distinguish *Bays* (in scope) from *Estuaries* (which are out of the thesis scope):

- permanently open to pervasive influences of ocean currents and ocean waves
- tidal phase lag within bays indistinguishable from that of the open coastline
- generally bounded by identifiable headlands

The development and application of quantitative criteria to implement this definition was limited by available data. However, the above qualitative criteria served well in the implementation of this classification to NSW bays in Section 7.4.

Headlands can occur in the absence of *Bays* so a working definition is also required to distinguish *Bays* from individual adjacent *Headlands*. For the purpose of this classification:

- the area between adjacent headlands constitute a bay when the distance between adjacent headlands is less than twice the average length of headlands.

This working definition can be tested and refined when field observations and model simulations are available to rigorously determine relevant length scales at which hydrodynamic characteristics are principally determined by the interacting effects of adjacent headlands rather than the individual effects of two single headlands.

Bays could have been parameterised as inverse headlands for the purpose of classification, as is the case in fractal analysis of coastlines. However, initial attempts to develop a generalised classification (for the NSW coast) based on roughness (i.e. a single paramterisation for both bays and headlands) were problematic due to the extensive and complex nature of many NSW bays.

Two simplified headland types were evident from NSW coastal maps, aerial photography and bathymetric charts: ***Triangular*** and ***Coastal Step***, as shown with case examples in Figure 7.1.

Triangular Headlands (Figure 7.2) in NSW have been parameterised in the simplest way possible by assuming triangular form and defining headland length (L), the apex angle (Ω), and the orientation of the headland with respect to regional isobaths (θ). This simple typology captures most salient features of NSW headlands although the representation of the classic NSW asymmetrical cusp headlands (Figure 7.2), required additional parameterisation. These iconic north facing cusp headlands are particularly prominent in sand dominated northern NSW. Variations to the idealized triangular headland form were parameterised by quantifying the convex or concave deviations (Δ) of the limbs of the headland as shown in Figure 7.2.

Coastal Step Headlands (Figure 7.1) are effectively discontinuities in the coastline, or one-sided headlands, with extreme asymmetry generally caused by the northward longshore transport of sand. A *Coastal Step* links two parallel stretches of coastline, with clearly identifiable break points at both ends of the 'step'. Major, broad scale, shifts in the orientation of the regional coastline, such as is evident in the Port Stephens/Stockton Bight area, are not included as Coastal Step 'headlands'. The hydrodynamic significance of these regional shifts in the orientation of the coastline and continental shelf on larger scale coastal boundary layer effects is discussed in Chapter 9.

A practical, hydrodynamically relevant, morphological classification of coastal protrusions (headlands and islands) logically includes parameters relating to:

- Headland or Island dimensions (length & width or length and apex angle of triangular headlands)
- Water depth
- Regional flow incident on the long axis of the headland or island
- Local features such distance from adjacent headlands and nearest islands.

Offshore Islands (Figure 7.1) also act as obstacles to regional flows and affect hydrodynamic processes of dispersion and accumulation in similar ways to headlands. Indeed nearshore islands may become permanent or transient headlands due to the formation of tombola in the low wave energy, depositional, zone behind (shoreward of) the island. The charcteristics of offshore islands were parameterised by simplified measures of island width (X), length (Y) and distance from shore (D), with salient widths (S) recorded when present.

Simplification was an essential design principle in the development of this morphological classification. However, individual morphological features cannot always be considered in isolation because upstream turbulence caused by another morphological feature can effect the formation of wakes and thus affect dispersion potential at the site of interest. For example, anomalously high turbulence near Bass Point (a 4 km wide headland near Sydney, Australia) was found to prevent the formation of a single narrow shear layer and limited large scale re-circulation (Middleton et al., 1993). Instead a broad shear zone formed and the separation point was pushed far downstream.

Upstream morphological features such as islands, headlands and shoals can generate turbulence.

Four simplified bay morphological types were evident from NSW coastal maps, aerial photography and bathymetric charts: ***Open Sweep***, ***Open Triangular***, ***Open Rectangular***, and, ***Semi Enclosed*** as shown with case examples in Figure 7.3.

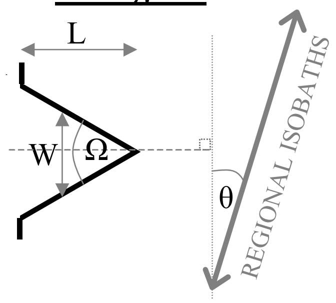
Here a special case morphology consisting of a ***Chain*** of adjacent headlands and bays is defined for completeness (Figure 7.4).

Likewise, engineered ***Training Walls***, warrant special consideration (Figure 7.4). Training walls were commonly constructed in NSW for estuary or harbour entrance management. Indeed, most major rivers in northern New South Wales have training walls. These structures present an obstacle to shore parallel flows and can introduce vorticity to coastal waters through tidal exchanges and continuous or sporadic outflows of run-off from coastal catchments.

A process based rationale for parameterisation of these headland and bay morphological types is provided below in Section 7.3, together with relevant contextual data to inform a risk based assessment of potential pollutant dispersal characteristics. The implementation of this classification to NSW bays and headlands is described in Section 7.4.

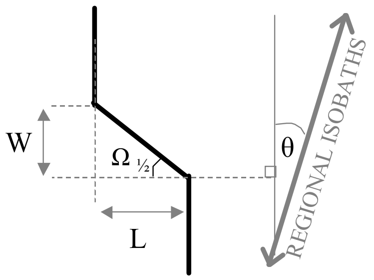
COASTAL MORPHOLOGIES: HEADLANDS & ISLANDS

Triangular



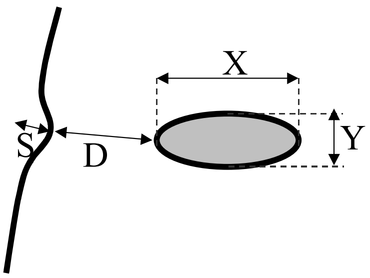
e.g. Bass Pt

Coastal Step



e.g. Diamond Head ($N_{step}E$)

Offshore Island



e.g. Broughton Island

Defining Parameters:

L = headland length
W = headland width
Ω = headland apex angle
θ = orientation w.r.t. isobaths
$N_{step}E$ = step east traveling N to S
$N_{step}W$ = step west traveling N to S
X,Y = island dimensions
D = minimum distance to shore
S = salient width (if present)
H = water depth at L 'upstream' & 'downstream' from headland tip (oriented along regional isobaths)

Figure 7.1 Morphometric classification for NSW headlands and islands (images courtesy Google Earth).

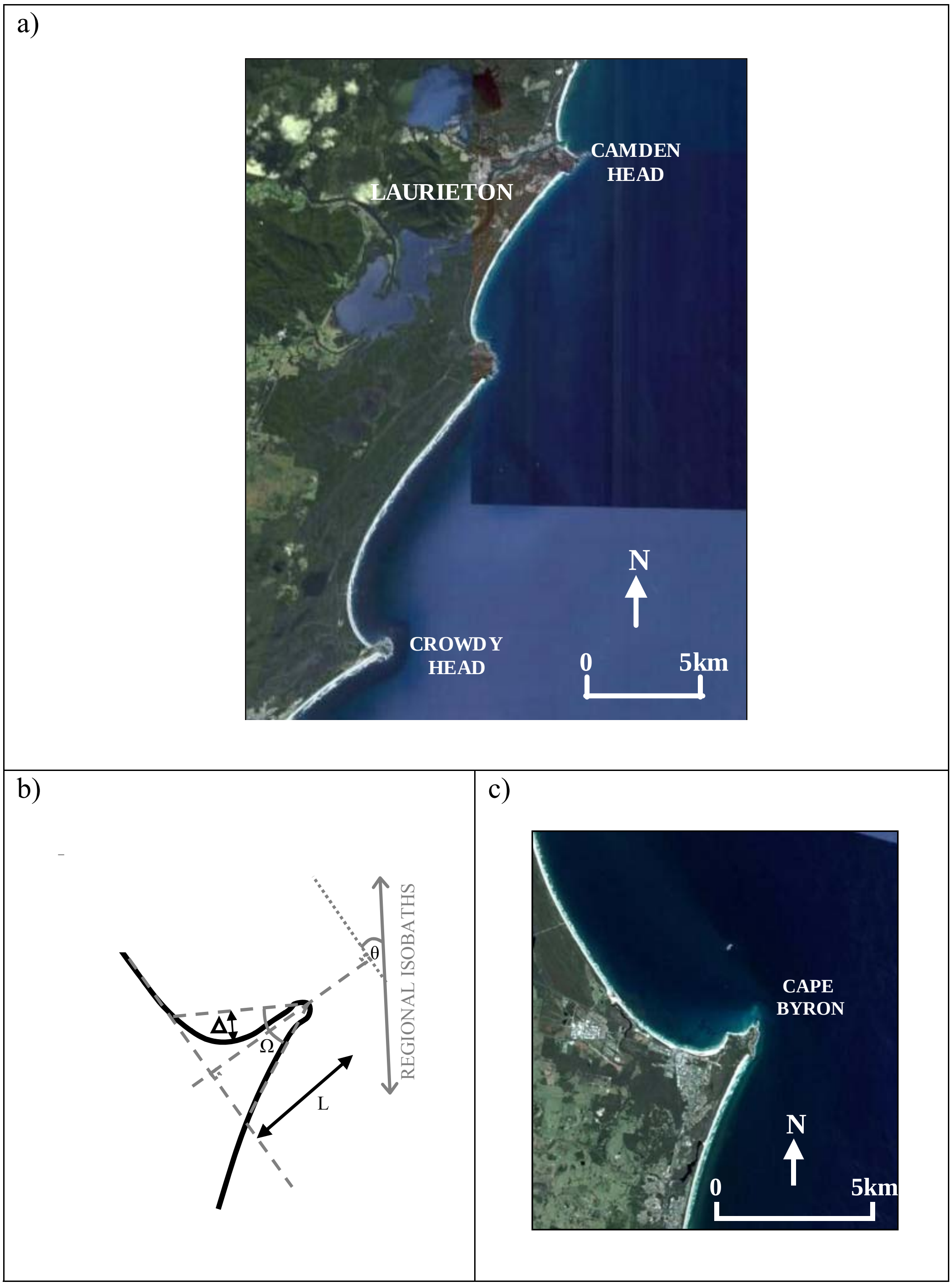
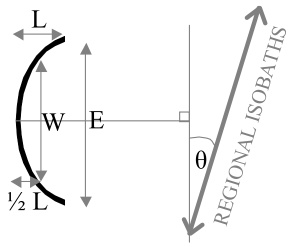


Figure 7.2 a) iconic northern NSW headlands exhibiting north facing cusp asymmetry. b) schematic parameterization of a north facing cusp headland with deviation from standard triangular headland parameterised by Δ ; and, c) Cape Byron, the most prominent north facing cusp headland in NSW (images courtesy Google Earth).

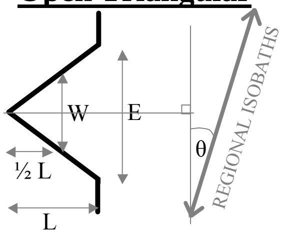
COASTAL MORPHOLOGIES: BAYS

Open Sweep



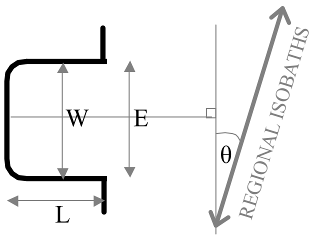
e.g. Merimbula Bay

Open Triangular



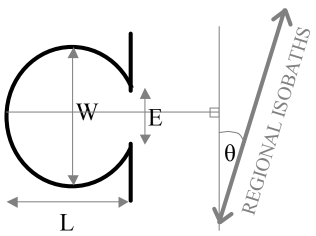
e.g. Batemans Bay

Open Rectangular



e.g. Disaster Bay

Semi Enclosed



e.g. Jervis Bay

Defining Parameters:

L = Length	W = Width
E = width at Entrance	θ = orientation w.r.t. regional isobaths
$H_{½}$ = water depth at ½ L	H_{max} = maximum water depth
H_E = average water depth at entrance	

Working definition: a Bay exists when the separation between headlands is less than twice the average length of the headlands (i.e. W<2L)

Figure 7.3 Morphometric classification for NSW bays (images courtesy Google Earth).

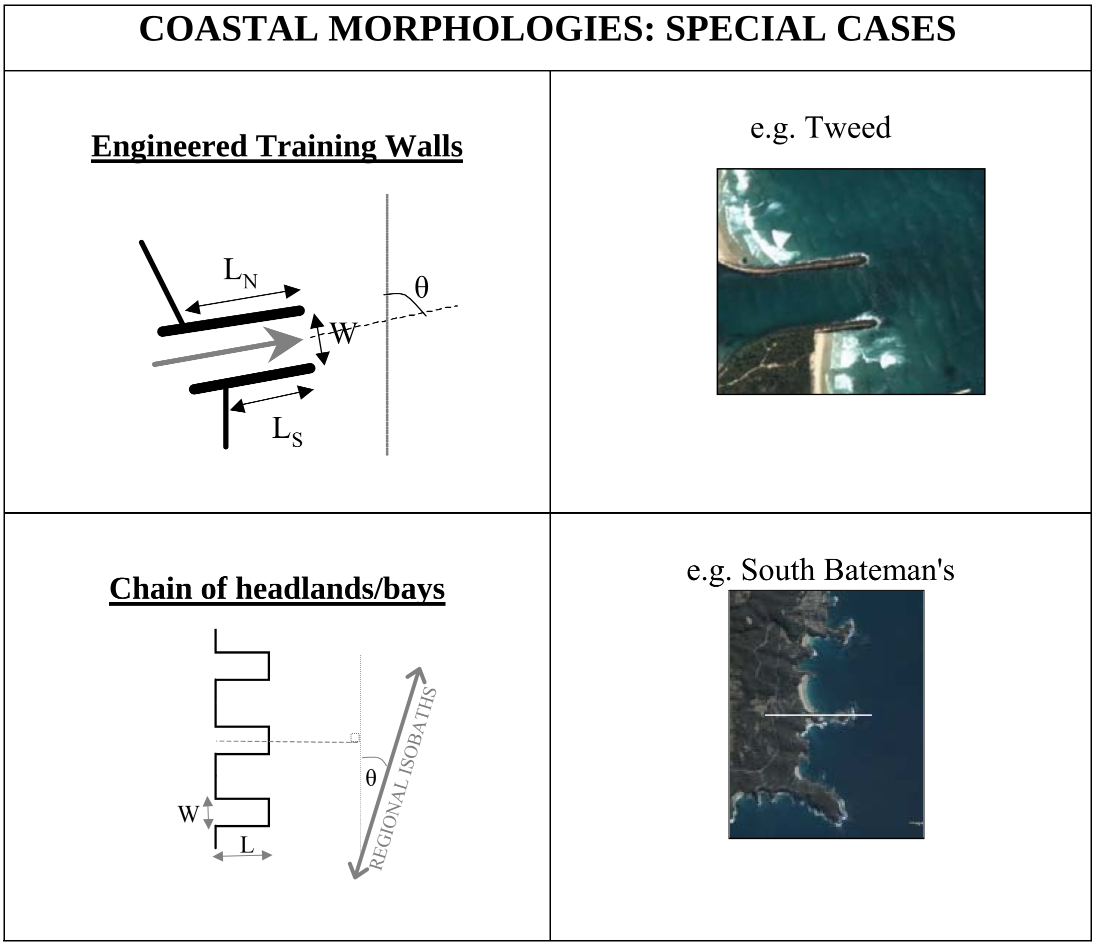


Figure 7.4 Morphometric classification for NSW special cases: engineered training walls; and, chains of headlands/bay. Protrusion lengths are given for both north (L_N) and south (L_S) engineered training walls (images courtesy Google Earth).

7.3 Contextual Data related to Hydrodynamic Processes

Processes affecting retention and dispersion of pollutant in the vicinity of headlands, bays and islands include local currents, waves, winds, riverine inflows, tides, and other system specific processes. Bay and headland circulation patterns and dispersion characteristics exhibit spatial and temporal variability at various scales due to a range of periodic and episodic phenomena such as: regional current reversals (e.g. affecting headland wakes), episodic freshwater discharges (e.g. affecting bay flushing), transient high wave events and differential seasonal cooling (e.g. affecting bay wide circulation). Simplified representation of morphological features related to these processes is critical to a hydrodynamically relevant morphological classification of bays and headlands.

Local currents incident on headlands, bays and estuaries determine wake effects and drive advection and dispersion processes.

Although few data exist to describe local area currents in NSW coastal waters, broad scale regional circulation and the driving processes are well described for NSW shelf waters (see Chapter 2).

Accurate representation of flow regimes at the scale of headlands and bays would enhance the classification of NSW coastal features. However, insufficient data are available for a classification system incorporating all complex hydrodynamic processes to be broadly applied to NSW coastal waters. A simplified morphological classification, commensurate with available data, is necessary and appropriate, especially for shallow coastal water and screening level applications. Such a classification can focus subsequent studies to resolve more complex three dimensional flows interactions between regional currents and bathymetry in the coastal boundary layer which can be physically and ecologically important (e.g. Black et al., 2005; Berthot and Pattiaratchi, 2006).

Well validated hydrodynamic model simulations are not currently available to provide comprehensive coverage of near shore currents incident on headlands, islands and bays for near-shore NSW coastal waters. Recent initiatives such as the Australian Integrated Marine Observing System (IMOS) (Suthers et al., 2010) together with re-analysis products such as the Bluelink ReANalysis (a multi-year model integration with data assimilation described by Oke et al., 2005), and regional modeling (Roughan, et al., 2011) have improved coverage of coastal hydrodynamics but are as yet too coarse and lack extensive nearshore validation. Encouraging developments include the immanent deployment of an IMOS high frequency coastal radar WERA system (http://ifmaxp1.ifm.unihamburg.de/WERA.shtml) off Coffs Harbour to map surface current velocities from 2011, and further high resolution coastal hydrodynamic modeling is underway (Roughan, pers comm., 2010)

Until near shore circulation patterns have been mapped and quantified at an appropriate resolution there is little justification to impose current regimes over the morphological classification of NSW headlands, bays and islands. However, simple flow scenarios can be constructed from observations of *Outer CBL* processes together with the sparse existing near shore current time series data. For example, observed offshore Sydney mean upper current speed was 0.22 m/s (Chapter 6; **Pritchard** et al., 1996) while mean depth averaged current speed at the outer Coffs Harbour site (Site D) was 0.19 m/s (Chapter 8; **Pritchard** et al., 2001 and 2007).

Sydney's Ocean Reference Station (ORS) has captured the longest time series of high frequency flow observations in Sydney offshore waters, now spanning nearly two decades. **Pritchard** et al., (2005) analysed these data to describe temporal variability including:

- prominent but relatively low energy semi-diurnal tides
- strong diurnal energy peaks represent sea/land breeze effects, transient weather systems and inertial motions (inertial period 23.6hrs at ORS).
- dominant synoptic weather band energy driven by local weather systems, distant weather systems (e.g. coastal trapped waves) and East Australian Current effects which can span weeks.
- prominent seasonal peaks due to latitudinal shifts in atmospheric pressure systems and seasonal differences in EAC effects.
- subtle annual cycle

The orientation of morphological features with respect to regional flows has the potential to affect the location and extent of wakes and associated dispersion potential. Previous studies, such as those reported in Chapter 6 of this thesis (**Pritchard** et al., 2001 & 2007) indicate that regional current vectors on the NSW inner continental shelf tend to follow isobaths. In the absence of site specific current data, critical contextual data include:

- ❖ Orientation of morphological features (headland axis and orientation of bay entrance) with respect to alignment of regional isobaths (surrogate for regional flow axis)

Local winds are major drivers of inner shelf currents (**Pritchard** et al., 2001), they promote vertical mixing of the water column (**Pritchard** et al., 2005), and contribute to mixing within bays and estuaries (Wolanski, 2007) which increases potential for exchange of particles across bay entrances.

Wind patterns across NSW coastal waters have been described in Chapter 2. That is, afternoon northeasterly seabreezes are typically observed in summer across the coastal observing network although easterly or southeasterly winds dominate at Williamstown (north of Newcastle) and Nowra (south of Sydney). Morning westerlies, ranging from southwest to northwest, frequently occur during winter, while extreme events are often associated with southerly and south-easterly winds. Important morphologic parameters affecting mixing and exchanges with offshore waters are the length and orientation of long axes of bays (and headlands) relative to dominant wind vectors. This could not be applied across the NSW coast due to significant temporal and spatial variability of coastal winds and limited observations of local winds across relevant coastal features, but is an important next step when assessing a prioritized coastal site for further investigation. For this broader assessment, a more simplistic approach is appropriate for the preliminary classification presented here, whereby internal bay dimensions are considered in relation to entrance dimensions to indicate relative clearance potential for bays, using:

- ❖ Bay Centerline Length: distance to entrance (m)
- ❖ Bay Entrance Area/Bay Volume: exchange potential at entrance (m^{-1})

Breaking waves have the potential to increase vertical mixing, re-suspend particles and drive circulation in bays (e.g. Bate Bay – Large et al., 1994).

Most bays encompass beaches and all beach morphologies observed in NSW have been classified as wave-dominated (transverse bar and rip/reflective/low tide terrace/rhythmic bar and beach) (Short, 1993). Thus the fine scale morphology of bays is often dominated by bars and rips, which are often regularly spaced at typical intervals of about 250m (Short and Woodroffe, 2009). However, the hydrodynamically relevant morphological classification of bays and headlands developed here focuses on broader scale wave induced mixing and potential for wave induced pollutant transport.

NSW wave data collected at seven locations over periods of up to 28yrs indicate average significant wave heights of ~1.6m, spectral peak periods of ~9.6s and maximum wave heights of ~7.1m (see Chapter 2). Directional data are available from three of these locations for lesser durations, exhibiting predominantly south-south-easterly wave directions. The NSW waverider network is currently being upgraded to include directional observations across all seven observing stations. Based on available data there is some evidence for more intense extreme wave events in central NSW (Sydney and Pt Kembla) but little justification to impose latitudinal wave zonation over the morphological classification of bays and headlands. However, the following morphological parameters determine penetration of wave energy into bays or indicate finer scale variability in dispersion characteristics:

- ❖ entrance width and depth; and,
- ❖ entrance orientation with respect to dominant wave directions
- ❖ orientation of headlands (and islands and reefs) with respect to dominant wave directions and major rips (often reflected in headland morphologies)

Tidal currents are generally minor in open coastal waters of NSW because of the micro-tide range (mean ~1.3m; maximum ~2m) combined with little tidal phase difference along the coast. By definition tidal currents within *Bays* are minimal (Section 7.2) although the entrances of some *semi-enclosed Bays* and *Training Walls* may exhibit tidal flows. Entrance tidal exchange observations from the Sydney region (Fig 4.11 in Chapter 4) show ebb jets extending 4km offshore and buffering alongshore flows.

Riverine (freshwater) outflows have the potential to drive or influence circulation within bays and therefore affect pollutant retention/flushing.

River inflows were derived from 2CSalt modeling undertaken by Littleboy et al. (2009) and Roper, et al. (2011) for all NSW coastal catchments: 198

catchments covering a total area of ~130 000 km^2. Flows were simulated for the period from 1975 to 2007 using daily weather data together with hydrologic soil data, land use data (1:25,000), topography (100m DEM), and groundwater attributes. S2CSalt quantifies monthly surface and subsurface contributions of water (and salt) exports at a catchment scale, based on monthly groundwater time steps and daily surface hydrology time steps, which were summed to monthly totals. Annual averages were calculated from the monthly times series and river inflows were estimated by summing average annual exports from all relevant sub-catchments.

River inflows from all subcatchments are not necessarily equal to freshwater outflows to coastal waters or bay flushing because estuarine processes and bay entrance conditions regulate the connection between catchments and offshore waters and mixing within the bay (e.g. retention within estuarine systems and evaporation). However, for the purposes of this classification river inflows were used as a surrogate for potential freshwater outflows. This is a reasonable first approximation given that it favours a conservative evaluation that would trigger more detailed investigation within a risk assessment framework.

- A *Fluvial Factor* was estimated for bays as the ratio of *long term daily average freshwater inflow (m^3 day^{-1}) multiplied by the flushing time (day) to the estimated volume of the bay (m^3).*

Volume was calculated from the bay Length, Width and Average Depth. This provided a reasonable representation of bay volume for most bay types but may tend to over estimate bay volumes for semi-enclosed (SE) bay types resulting in under estimation of the flushing potential. SE bay types are often inherently less well flushed than open bay types so this is an appropriate conservative approach for a risk based assessment to flag potential pollutant impacts for further investigation (an intended use of this classification). In the absence of bay residence flushing times, and for the purpose of this NSW assessment only, the bay residence time was set at 1 day for comparative purposes.

By necessity morphological classifications seek to simplify often-complex real world morphologies and interacting processes. A process based understanding (outlined above) informs the limitations of this simplification and examples provided below illustrate how the specific configuration of key morphological features can affect circulation patterns.

Discussions and specific case studies in Chapter 9 illustrate the hydrodynamic importance of various morphologies and demonstrate how hypotheses about pollutant dispersal developed using this classification can be tested and refined by direct observations and validated model simulations.

7.4 Implementing Morphological Classification of NSW Headlands, Bays and Islands

Existing NSW near shore bathymetry is inadequate to determine sub-tidal bathymetric expressions of most *Headlands* and *Bays* across all NSW coastal waters so this classification is biased by the morphological expression of the coastline.

Fractal considerations introduced in Section 7.1 (above) require definition of a scale or lower length threshold for coastal roughness. This classification was based on parameterisation of *Headlands* and *Bays* at a scale of 1:25,000 which resulted in headland length scales greater than 185m and internal bay dimensions greater than 120m.

Training walls and *Offshore islands*, were included in this classification for completeness because they operate as obstacles to regional flows in similar ways to headlands. However, these features introduce hydrodynamic complexity which required special consideration, which is beyond the scope of this thesis. Near-shore islands with dynamic salient/tombola features have not been parameterised in this classification because of the highly variable passage of water between the island and the shore due to tidal extremes and sand movements. These features are flagged for case specific consideration rather than generalised within the classification because variable 'leakage' through these ‘transient headlands’ has the potential to profoundly affect pollutant residence times.

Oceanic islands such as Lord Howe Island that cause no expression on the mainland coastal boundary layer are not included in this classification due to their uniqueness and distance from mainland Australia.

Simple prescriptive methodologies were developed to interrogate the following morphological data sources in developing this morphological classification of NSW bays and headlands: GoogleEarth (2009) at view altitude of ~4km and associated measurement tools, NSW Department of Environment and Climate Change bathymetric database and associated ArcMap Fieldmap and measurement tools, and Admiralty Charts (Australian Hydrographic Office, 1962). Contextual data sources have been described above.

Parameters used to classify hydrodynamically relevant NSW coastal morphologies are listed in Table 7.1, and illustrated in Figure 7.2, 7.3, 7.4 and 7.5.

Table 7.1 NSW Headland parameters

HEADLANDS	Observed and Calculated Parameters
Name	Headland name
Location	Latitude, Longitude, Distance south of Queensland border (km)
Type	Triangular Headland (H), Southward step East or West (S_{step}E or S_{step}W) - see Section 7.2
Centerline	Length (m) Orientation wrt true north (assumes idealised triangular form for both *Triangular* and *Step* headlands)
Width & Apex Angle	Width at 1/2L Apex Angle is the internal angle at the tip of the idealised headland triangular calculated from measured *Length* and *Width* of the headland
Triangular Deviation & Cusp Parameter	Concave/convex/straight morphologic type of North and South limbs of the headland (S_{cv}/S_{cx}/S_{st}/N_{cv}/N_{cx}/N_{st}) . Maximum deviation from each of the ocean facing sides of an idealised triangular headland (negative concave, positive convex). 'Cusp Parameter' = radius of curvature (m) of an arc passing through end points of an ocean facing side of the idealised headland triangle plus the central point of deviation (note that the maximum deviation' (above) is the perpendicular distance from the centre of the side of the triangle to the arc). (applied to both *Triangular* and *Step* headlands)
Depth	Water depth one headland length north (D_N) and south (D_S) of tip of the headland in a direction parallel to regional isobaths and regional coastline (generally perpendicular to headland centreline), Average depth (D_N + D_S)/2 for triangular headlands.
'Flow' Orientation	Orientation of an isobath (default 60m) which charcterises regional inner and mid shelf orientation (indicative of regional flows) w.r.t. true north Orientation of headland w.r.t. regional isobaths
Cross shelf profile	Distances (km) from shore to 25m, 40m, 60m, 100m, 200m isobaths
Nearest island	Name, Distance from headland (km)
Comments	Site specific characteristics and notable features

Table 7.2 NSW Bay parameters

BAYS	Observed and Calculated Parameters
Name	Bay name
Location	Latitude & Longitude at intersection of bay centreline and shore; plus calculated distance south of Queensland border (km)
Type	Open Rectangular (OR), Open Sweep (OS), Open Triangular (OT), Semi enclosed (SE) - see Section 7.2
Entrance	Width (head to head) (m) Average depth (m) Calculated cross sectional area (W x D) Orientation w.r.t. true north and w.r.t. regional isobaths Orientation w.r.t. dominant south-south-easterly waves
Centreline	Length from shore to mid point of entrance (m) Orientation wrt true north
Width	Width at 1/2L at right angle to centreline (m) Maximum width at right angle to centreline (m)
Bay Volume	Approximated as Width x Length x Average Depth (m^3)
Depth	Average water depth in bay (m)
'Flow' Orientation	Orientation of an isobath (default 60m) which characterises regional inner and mid shelf orientation w.r.t. true north (indicative of regional flows) Calculated orientation of bay entrance w.r.t. regional isobaths
Coastline Orientation	Regional orientation of the coastline Orientation of bay entrance w.r.t. regional coastline
Fluvial Input	Name of river discharging to Bay Average annual discharge (ML/yr) derived from Roper, et al. (2011) based on the methodology described in Littleboy et al. (2009)
Cross shelf profile	Distances (km) from shore to 25m, 40m, 60m, 100m, 200m isobaths
Indicative clearance factors (calculated) Comments	Centreline Length: distance to entrance (m) Entrance Area/Bay Volume: exchange potential at entrance (m^{-1}) Fluvial Factor (d^{-1}) = 100% x (average annual freshwater input/365 (m^3d^{-1}) / (Bay Volume (m^3)) which is a first order approximation of the percent ratio of bay volume to daily freshwater input Effective entrance width facing SSE vs maximum bay width: relative wave penetration assuming no breaking (m) Effective entrance aspect w.r.t. regional isobaths: entrance exposure to regional flows (m) Site specific characteristics and notable features

Table 7.3 NSW Island Parameters

ISLANDS	Observed and Calculated Parameters
Name	Island name
Location	Latitude, Longitude, Distance south of Queensland border (km)
Distance from shore	Shortest distance to mainland (m)
Dimensions	East-West extent (km)
	North-South extent (km)
	Maximum dimension (E-W or N-S) (km)
Depth	Estimated from regional along shelf isobaths (m)
Salient width	Estimated maximum departure from regional coastline between island and shore (m)
Comments	Site specific characteristics and notable features

Table 7.4 NSW Training Walls parameters

TRAINING WALLS	Observed and Calculated Parameters
Name	Location name
Location	Latitude, Longitude, Distance south of Queensland border (km)
Wall length	North wall protrusion (m) South wall protrusion (m) Average protrusion (m)
Freshwater outflow	River name Average annual discharge (ML/yr) derived from Roper, et al. (2011) based on the methodology described in Littleboy et al. (2009) expressed as High/Medium/Low
Entrance Width	Width between walls at mouth (m)
Wall Orientation	Wall orientation w.r.t. true north
Coastal discontinuity	Shoreline discontinuity across walls (m) Southward step East or West ($S_{step}E$ or $S_{step}W$) if applicable
Normalised flow factor (calculated)	Flow/Entrance width categorised as High/Medium/Low
Comments	Site specific characteristics and notable features

7.5 Results: coastal morphologies of NSW

Headland morphologies ranged from sand dominated asymmetric cusp shaped headlands such as near Crowdy Head to rocky headlands with conspicuously fractal characteristics near Batemans Bay. One hundred and forty four NSW headlands were classified, from Fingal Head just south of the Queensland border to Green Cape near the border with Victoria. Of these one hundred and fourteen (~80%) were identified as *Triangular* headlands and thirty as *Coastal Step* (one-sided) headlands.

Triangular headlands in this NSW classification ranged up to 5768m in length (Green Cape) with a median length of 624m (Table 7.5). The distribution was skewed towards short (39 or 26.4%) and medium length headlands with just 14 (20.1%) headlands greater than 1500m in length and most (63 or 53.5%) falling with the range from 500m to 1500m. The shortest *Triangular* headland to be classified was 186m joining 36 other short headlands spanning the NSW coastline (Figure 7.5). The triangular representation captured a broad range of headland shapes with standardised apex angles varying from 20° to 119° (mean 70°; standard deviation 24°).

Table 7.5 NSW Headland Statistics (lengths in meters)

HEADLANDS	Count	Minimum	Maximum	Mean	Standard Deviation
Triangular	114				
Length (L)		186	5,768	857	740
Width (W)		110	2,338	572	422
Apex Angle (Ω)		20	119	70	24
Coastal Step	30				
Length (L)		230	13,980	1,324	1,879
Width (W)		113	8,800	875	1,206
Apex Angle (Ω)		23	102	65	19

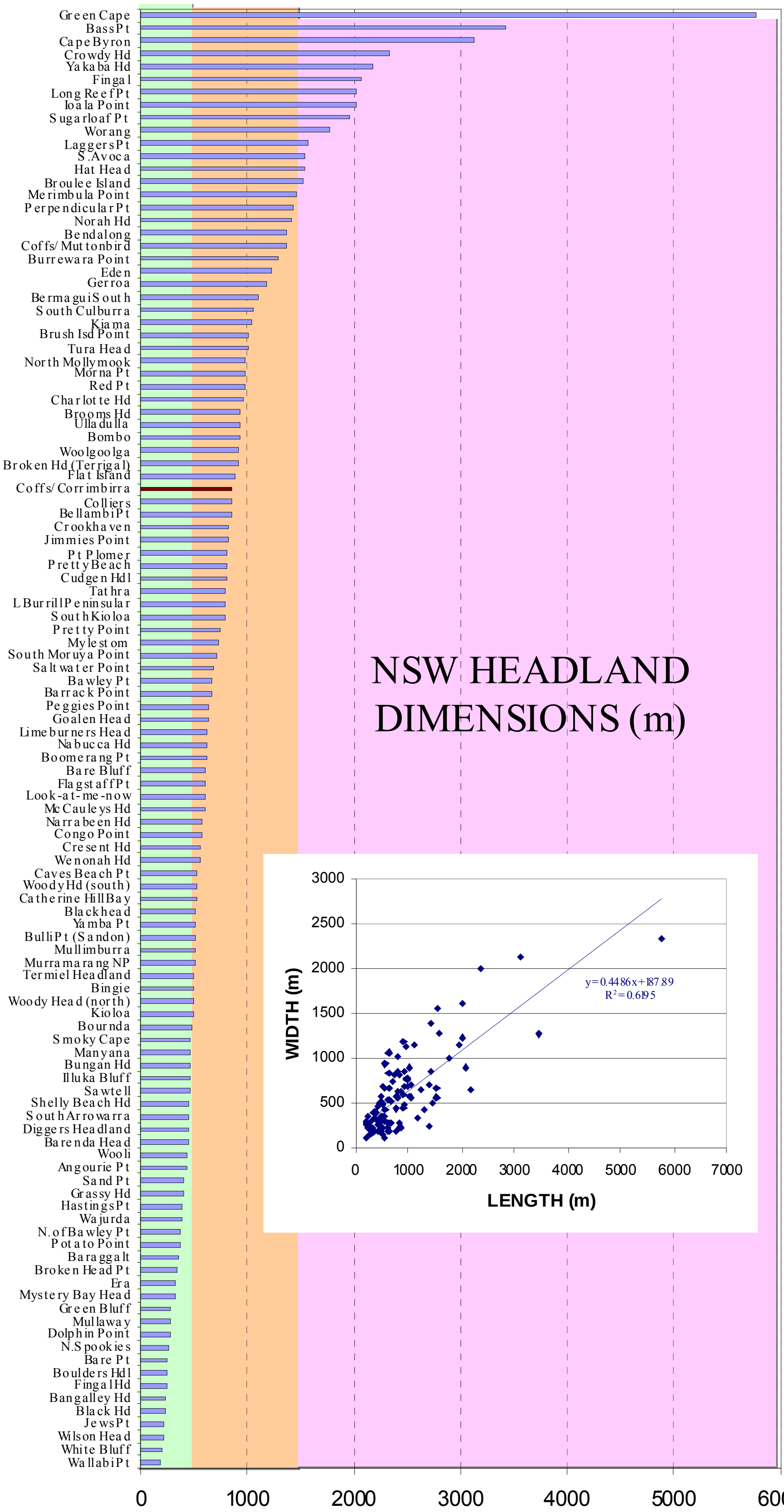


Figure 7.5 NSW Triangular headland lengths (Short in green <500m; Medium in orange 500>L1500m; and, Long in red (>1500m) and width to length ratios.

The nature of headland (and island) wake effects is determined by the relative importance of inertial forces and frictional forces, which can be expressed in terms of a *Wake Parameter* (Wolanski et al, 1984). Although the *Wake Parameter* (P) is a simple representation of often-complex natural morphologies it serves well to indicate the relative importance of morphological parameters (water depth and headland length) in determining turbulent characteristics in the wakes of headlands. The *Wake Parameter* has been shown to work well in the description of re-circulation in two dimensional steady flows (Wolanski et al., 1984; Pattiaratchi et al., 1986; Denniss and Middleton, 1994).

Here unknown variables needed to calculate the *Wake Parameter* are held constant at 'typical' values (current velocity = 0.2 m/s; and, vertical eddy diffusion coefficient = 0.1 m^2/s) in order to indicate the relative propensities for flow separation and re-circulation for triangular headlands in NSW (Figure 7.6). A curve corresponding to P=1 on Figure 7.6 shows the theoretical threshold for flow separation and re-circulation.

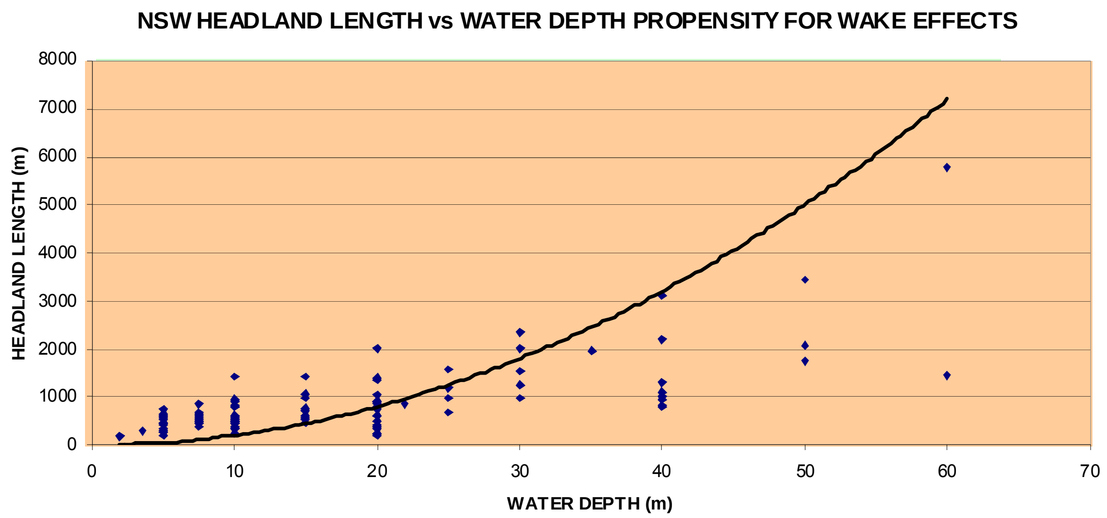


Figure 7.6 Headland length-depth distributions shown in relation to *Wake Parameter*, P =1, which is the threshold above which inertial forces dominate over frictional forces. Below P=1 (tan colour zone) flow separation and wake features such as re-circulation cells are favoured whereas above P=1 (green colour zone) frictional forces dominate to limit flow separation.

The propensity to develop wakes, as indicated by the *Wake Parameter* (and many other similar dimensionless indices), is proportional to the square of the water depth and inversely proportional to the length of the headland (Figure 7.6). Therefore, headlands protruding across steeply shelving inner shelf bathymetries are predisposed to wakes effects. In NSW, wakes effects are predicted by the *Wake Parameter* for headlands in water depths greater than 35m. Conversely, NSW headlands in water depths less than 15m are unlikely to be associated with prominent wake effects.

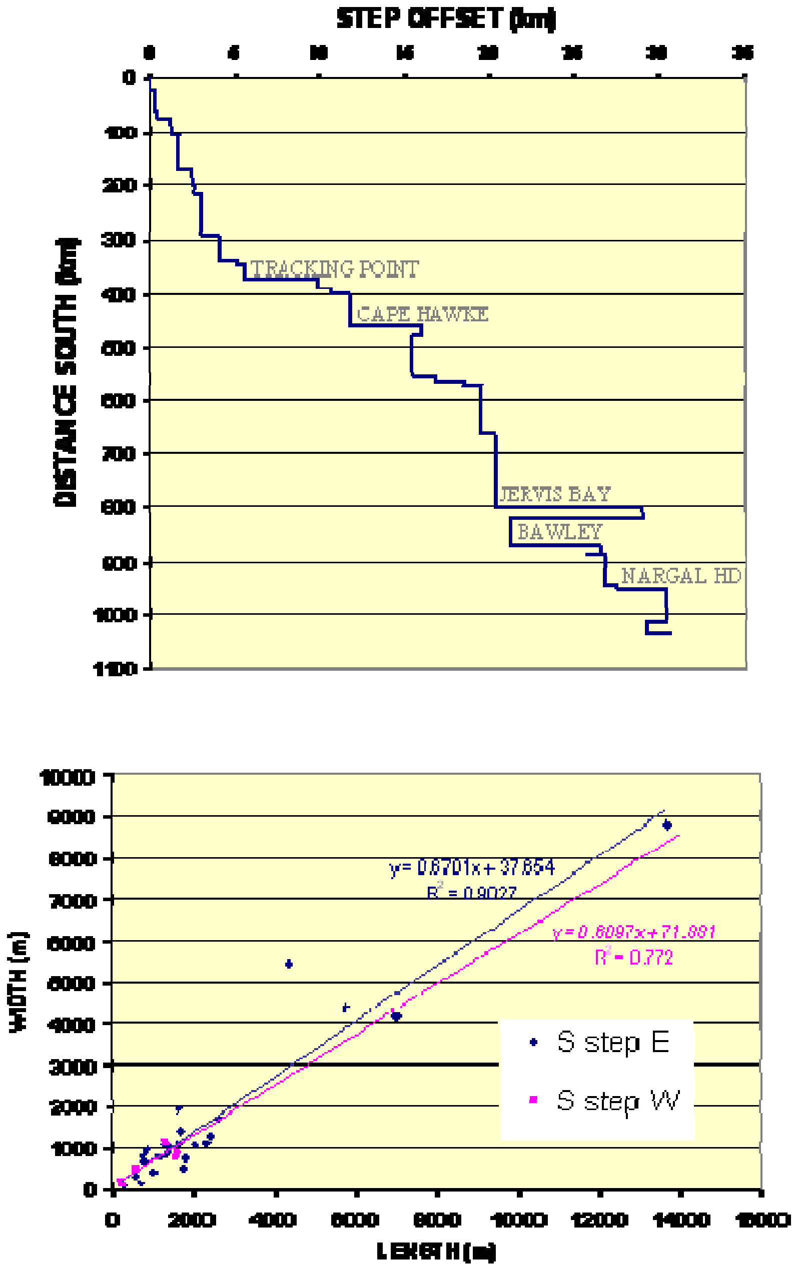


Figure 7.7 Cumulative offsets of NSW *Coastal Step* 'headlands' plotted against distance south of Queensland border with major coastal offsets as labeled (top). *Coastal Step* headland width-to-length ratios indicate consistent step angles (as defined in Figure 7.1).

The *Coastal Step* headland type captured 'one-sided' headlands on otherwise straight stretches of coastline. Although the general orientation of the NSW coastline is NNE – SSW (~200˚N) there is a net eastward cumulative offset associated with *Coastal Step* headlands, as shown in Figure 7.7, due to underlying geology combined with northward sediment transport favouring infilling of bays on the southern side of headlands, thus forming iconic NSW headlands shown in Figure 7.2.

The standardised *Apex Angle* of both *Triangular* and *Coastal Step* headlands was remarkably consistent with mean apex angles of 70° (SD 24°) and 67° (SD 22°), respectively, and identical ranges (20°to119°).

Offshore Islands have the potential to disrupt regional flows and express wake effects. Few large islands exist close to mainland NSW. Two large oceanic islands - Lord Howe Island and Norfolk Island – lie within NSW coastal waters but do not interact with mainland coastal boundary layer effects so they are excluded from this classification.

Forty-three offshore islands were identified. Other islands attached to the mainland by quasi-permanent tombola, such as Fingal Island (near Port Stephens), Broulee Island, Windang Island, Green Island (Manyana), O'Hara Island, and Bournda Island, were identified but omitted from the island classification because of their hydrodynamic complexity. These 'islands' generally operate as atypical headlands.

Twenty four islands are located within one kilometer from shore, mostly too small or in water too shallow for large scale re-circulation wake features to develop (see Figure 7.8). Most major offshore islands occur within NSW marine parks, especially Solitary Islands Marine Park (North Solitary Island), Port Stephens Great Lake Marine Park (e.g. Broughton Island) and Batemans Marine Park (e.g. Montague Island)

Of the remaining nineteen islands, Broughton Island, within the Port Stephens Great Lakes Marine Park, is the largest of NSWs offshore islands (Table 7.6 and Figure 7.8).

This classification was focused on hydrodynamic effects and as such some islands were more appropriately regarded as single entities. For example the two Tollgate islands off Batemans Bay are effectively a single obstacle to regional flows and are classified as such.

Islands affect dispersion and retention characteristics due to wake effects but they can also affect shoreline morphology by creating wave shadows and forming salients between the islands and the shoreline. Analysis of aerial and satellite photography revealed that the formation of salients is common between the mainland and islands for islands located less than 200m from sandy shorelines. However, most NSW offshore islands are generally too small or too far offshore to result in the formation of major salients. Emergent reefs (with no terrestrial vegetation) were not included in this classification but have significant potential for the formation of salients. Both emergent and submerged reefs have potential to develop turbulence in flows.

The largest salient in NSW extends nearly 1.7km towards NSWs largest near shore island - Broughton Island - which is located just 2.3 km from shore (see Figure 7.1). However, based on the indicative *Wake Parameter*, Broughton Island is unlikely to be associated with prominent large scale re-circulation in its wake because it is located in relatively shallow waters.

Montague Island and North Solitary Island stand out from NSWs five largest offshore islands as targets for more detailed evaluation of wake effects as they appear most likely to be associated with wake effects such as re-circulation cells. Most of the smaller offshore islands shown in Table 7.6 also appear to be pre-disposed to wake effects (*Wake Parameter* >1).

The island with the highest Indicative *Wake Parameter* was Fish Rock, a small island about 2km offshore from Smoky Cape. Interestingly, recent high resolution swath bathymetry has revealed scour channels on the flanks and to the south of Fish Island in a pattern consistent with convergence of the strong southward flowing EAC and flow separation in the lee of the island (Figure 7.9). An elongated scour channel 7-8 m deep (15 m at its deepest) almost 1 km long and up to 200 m wide runs southwest across soft sediments off the western side of the island. A similar scour channel is also evident east and southeast of Fish Rock (7 -10 m increase in depth over 100 m). Slightly higher backscatter intensity, within the depressions, indicated the scour around Fish Rock contained a comparatively coarse sandy substrate which is consistent with flow acceleration. Clearly benthic habitats have been profoundly affected by island wake effects in the vicinity of Fish Rock.

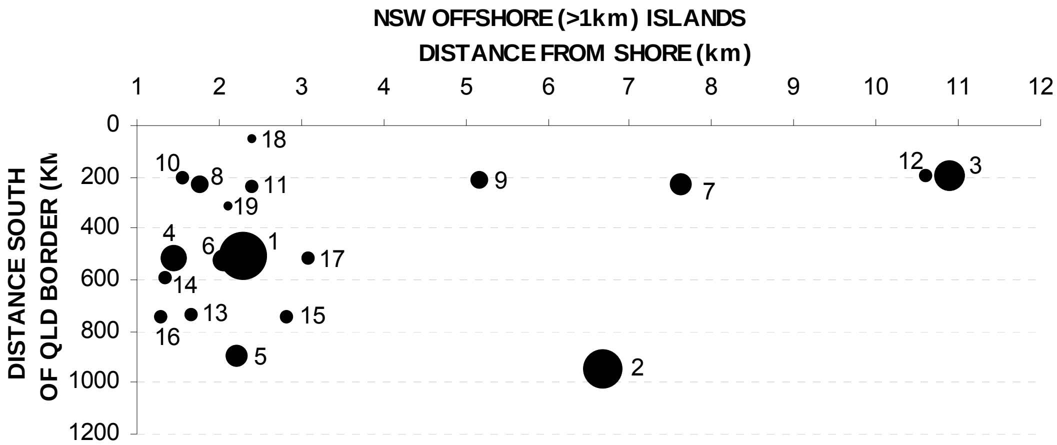


Figure 7.8 NSW islands located >1km from shore showing north-south distribution (from Queensland border), distance offshore, and size (maximum dimension proportional to area). See Table 7.6 for numeric island codes.

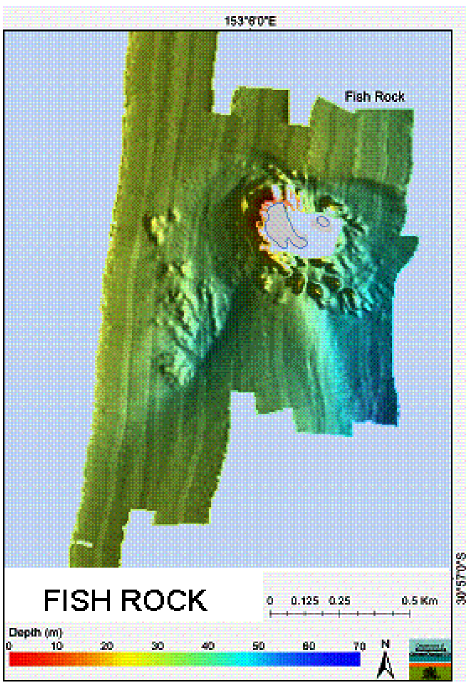


Figure 7.9: Hill-shaded bathymetric model of the seabed in the vicinity of Fish Rock off Smokey Cape, New South Wales. Source: Jordan,A., Davies,P., Ingleton,T., Mesley,E., Neilson,J. and **Pritchard,T.** (2010).

Table 7.6 NSW Offshore Islands (numeric code applies to Figure 7.8)

NSW OFFSHORE (>1km) ISLANDS*	Distance south of Qld border (km)	Distance from shore (km)	N-S Extent (km)	E-W Extent (km)	Max dimension (km)	Indicative depth** (meters)	Indicative Island Wake Parameter***
12. North West Rock	195	10.6	0.3	0.1	0.3	37	**8.63**
17. Little Island	519	3.1	0.2	0.2	0.2	37	**11.63**
19. Fish Rock	311	2.1	0.1	0.1	0.1	27	**12.54**
2. Montague Island	947	6.7	1.9	0.7	1.9	37	**1.40**
3. North Solitary Island	197	10.9	0.6	1.1	1.1	37	**2.35**
6. Boondelbah Island	520	2.1	0.6	0.5	0.6	18	**1.06**
7. South Solitary Island	228	7.6	0.6	0.4	0.6	37	**4.39**
8. Groper Islet	224	1.8	0.4	0.5	0.5	24	**2.26**
9. North West Solitary Island	209	5.2	0.5	0.2	0.5	27	**3.34**
10. North Rock Island	203	1.6	0.3	0.3	0.3	18	**2.09**
11. Split Solitary Island	233	2.4	0.2	0.3	0.3	18	**2.09**
13. Flinders Islands	739	1.7	0.3	0.2	0.3	18	**2.23**
14. Bird Island	591	1.4	0.3	0.3	0.3	18	**2.31**
15. Bass Islet	740	2.8	0.2	0.3	0.3	18	**2.48**
16. Martin Islet	743	1.3	0.1	0.2	0.2	18	**2.91**
18. Julian Rocks	50	2.4	0.2	0.2	0.2	18	**3.52**
1. Broughton Island	508	2.3	2.7	3.0	3.0	37	**0.90**
4. Cabbage Tree Island	518	1.4	1.0	0.5	1.0	18	**0.70**
5. Tollgate Islands (2)	894	2.2	0.7	0.7	0.7	18	**0.88**

** numbered and ordered within category by size rank (consistent with bubbble plot annotation)*

*** depths converted from fathoms using regional isobaths from Admiralty Charts (Australian Hydrogra[phic Office,1962)*

*** calculated using assumptions described in Section 7.3.1 and Figure 7.6

Bay morphologies ranged from sparse, sand dominated bays in northern NSW to abundant, highly variable, rocky bays in southern NSW, reflecting the supply of sediment and underlying geology, which has been described above and by Jordan et al. (2010). The majority of all types of *Bays* identified in this classification were found in the southern half of the State (Figure 7.10). The length to width ratios (L:W) of *Bays* typically remained constant irrespective of size, especially for *Open Rectangular* (OR) and *Open Sweep* (OS) types (Figure 7.11). The vast majority of NSW *Bays* identified in this classification were less than 900m in length (L) and less than 1700m in width (W).

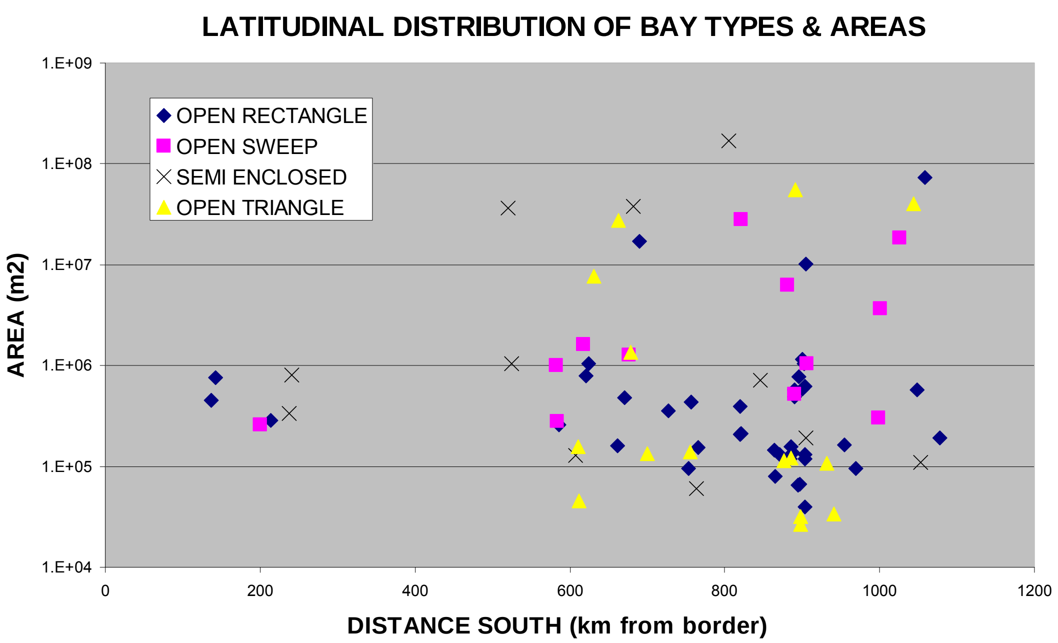
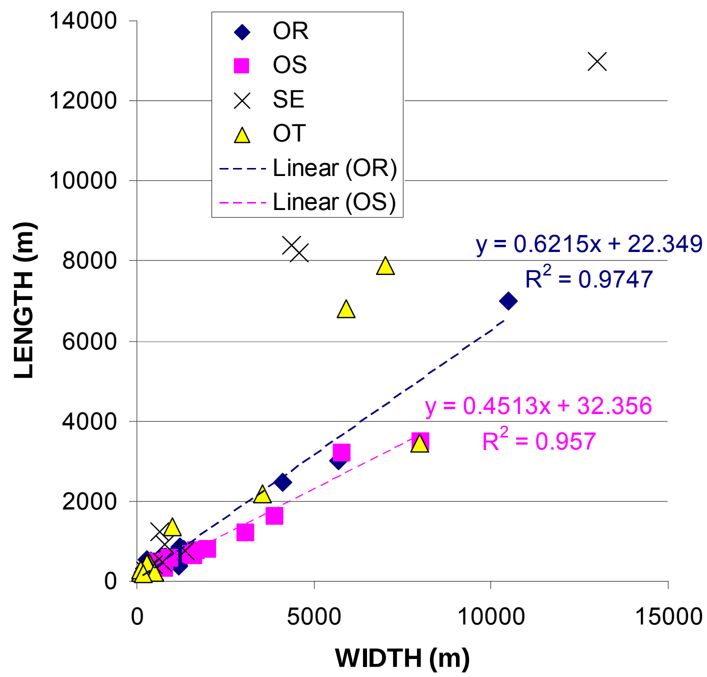


Figure 7.10 Latitudinal distribution of NSW bay types: *Open Rectangular* (OR); *Open Sweep* (OS); *Semi Enclosed* (SE); *Open Triangular* (OT).



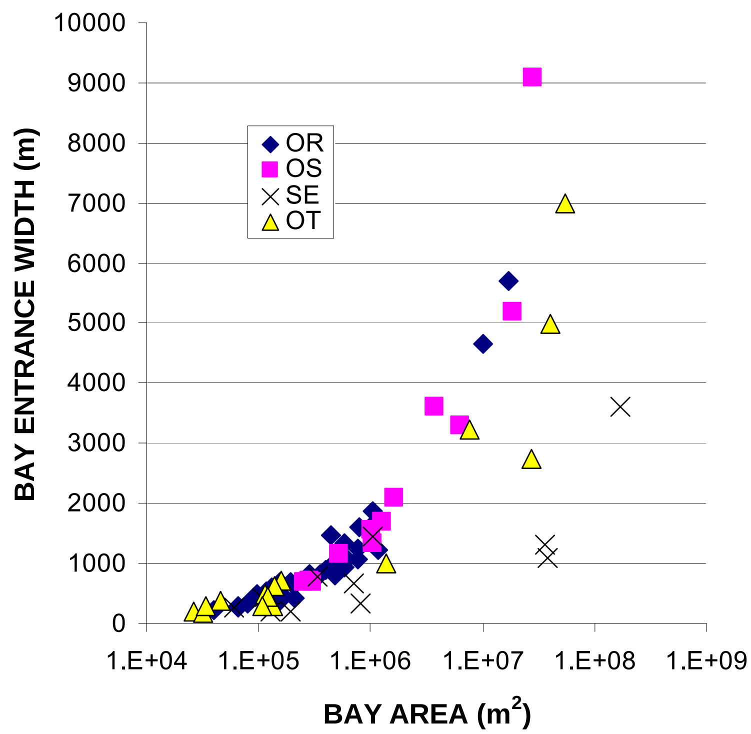


Figure 7.11 NSW bay type dimensions: *Open Rectangular* (OR); *Open Sweep* (OS); *Semi Enclosed* (SE); *Open Triangular* (OT).

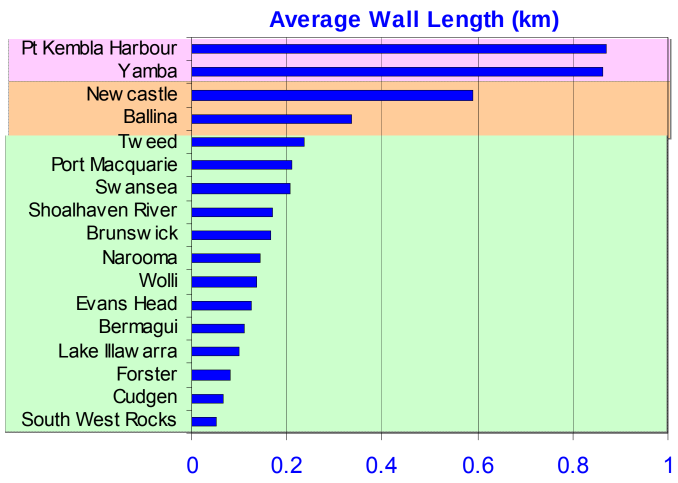
Training walls are included in this morphological classification because they protrude from the shoreline creating obstacles to regional flows, similar to headlands. However, freshwater emanating from trained river/estuary mouths also affects local circulation patterns due to momentum effects (exit velocity) and broader effects associated with plume dynamics.

Categorical rankings based on flow (High/Medium/Low) are provided for both average annual flow and the ratio of flow to the width of the entrance maintained by the training walls (Figure 7.12). The broader scale effects of large river plumes are discussed in more detail in Chapter 9. Colour coded flow-based groupings of NSW training walls are not sensitive to entrance width although rankings within groups may differ when width (which influences exit velocity) is considered (bottom Figure 7.12).

Seventeen *NSW Training Walls* have significant offshore expression, protruding up to nearly one kilometer from the shoreline and training the discharge of river and estuary water to the coastal boundary layer (Table 7.7 and Figure 7.12). Training walls at Yamba extend the entrance of the Clarence River more than 0.8 km offshore and maintain the greatest coastal discharge of freshwater of any river in NSW. No other training wall protrudes further eastward from shore, although Port Kembla Harbour seawall is greater in length. Other significant training walls are likely to have affect local dispersion and advection of pollutants including Ballina at the mouth of the Richmond River (Figure 7.13) , Newcastle Harbour at the mouth of the Hunter River, South West Rocks at the mouth of the Macleay River, and Port Macqaurie at the mouth of the Hastings River (Table 7.7).

The purpose of most of these training walls is to maintain a channel in to the river/estuary so it is not surprising that interception of northward bound sediment (mostly sand) results in ten $S_{step}E$ discontinuities in the shoreline (eastward shoreline displacement when traveling southward) compared to just two $S_{step}W$ training walls. However, the direction and magnitude of shoreline displacement across the training walls was not correlated with length/protrusion of training walls or average annual discharge from river/estuary entrances.

The training wall system at the entrance of the Clarence River at Yamba is an obvious candidate for more detailed evaluation of the influence that such structures may have on boundary layer dynamics.



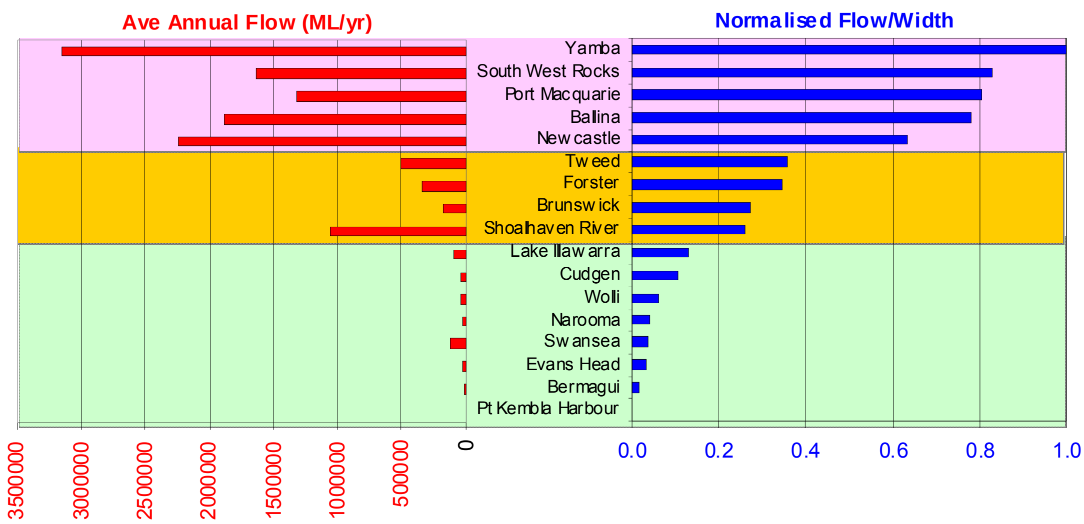


Figure 7.12 NSW training walls ranked by hydrodynamic factors relating to protruding wall length (top) and ratios of average flows to entrance widths (bottom right). Average annual flows (bottom left) are from de la Cruz, et al. (2009).

Figure 7.13 Trained entrance of the Richmond River at Ballina illustrating wave structures and turbulence along the seaward front of the river plume. OEH Aerial Photogram 13/5/83.

Table 7.7 Hydrodynamic categorisation of NSW training walls

TRAINING WALLS (human interventions)	Distance south of Qld border (km)	North Wall Extension (km)	South Wall Extension (km)	Average Wall Length (km)	Length Factor* (L/M/H)	Ave Annual Flow** (ML/yr)	Normalised Flow/Width***	Flow Factor (H/M/L)	Overall Factor (Flow/ Length)
Yamba	140.95	0.98	0.75	0.865	H	3153224	1.0	H	HH
Ballina	79.03	0.28	0.39	0.335	M	1891884	0.8	H	HM
Newcastle	532.69	0.72	0.46	0.59	M	2232712	0.6	H	HM
South West Rocks	305.24	0.04	0.06	0.05	L	1640980	0.8	H	HL
Port Macquarie	367.20	0.37	0.05	0.21	L	1306676	0.8	H	HL
Pt Kembla Harbour	740.78	0.7	1.04	0.87	H	2434	0.0	L	LH
Tweed	0.47	0.32	0.15	0.235	L	516372	0.4	M	ML
Brunswick	41.36	0.2	0.13	0.165	L	172230	0.3	M	ML
Forster	456.13	0.1	0.06	0.08	L	339332	0.3	M	ML
Shoalhaven River	790.58	0.34	0	0.17	L	1065761	0.3	M	ML
Cudgen	10.78	0.08	0.05	0.065	L	37571	0.1	L	LL
Evans Head	106.00	0.07	0.18	0.125	L	19232	0.0	L	LL
Wolli	195.03	0.14	0.13	0.135	L	31689	0.1	L	LL
Swansea	574.34	0.26	0.15	0.205	L	125922	0.0	L	LL
Lake Illawarra	749.89	0.12	0.08	0.1	L	92099	0.1	L	LL
Narooma	945.08	0.14	0.15	0.145	L	21321	0.0	L	LL
Bermagui	968.97	0.11	-	0.11	L	14874	0.0	L	LL

Notes: *Length factor categorisations are based on eastward extent of seawalls
***Annual flow estimates based on Roper, et al. (2011)*
**** (flow/width) expressed as proportion of maximum*

7.6 Conclusion

All geomorphic classification systems attempt to infer environmental attributes from limited but broadly available physical information to provide immediate preliminary advice and focus subsequent research. As such classifications can be employed to inform immediate, broad scale, management decisions and they provide a logical framework to structure and justify subsequent more detailed examination of research and management questions. This may rightly challenge the classification system itself. For example, debate continues to question the ecological relevance of well-established geomorphologic estuarine classifications (Zacharias and Roff, 2001; Salomon et al. 2001; Dye 2006; Harris and Heap, 2007). This morphological classification of bays and headlands is no different. It has been developed to focus investigations, for researchers to challenge its broad predictive skill and for managers to evaluate its relevance to environmental protection and conservation management. The scientific, ecological and management implications of this classification are explored further in the Chapter 9.

The classification of headlands presented in this chapter indicated a borderline propensity for flow separation and re-circulation in the lee of Corambirra Point at Coffs Harbour in northern NSW. This will be explored in the next chapter as a detailed case study.

7.7 References

Baldock, T.E., Barnes, M.P., Guard, P.A., Hie, T., Hanslow,D., Ranasinghe,D. and Neilson,O. (2007) Modelling tsunami inundation on coastlines with characteristic form. 16th Australasian Fluid Mechanics Conference, Gold Coast, Australia, 2-7 December, 2007. pp 939-942.

Berthot, A. and Pattiaratchi, C. (2006) Field measurements of the three-dimensional current structure in the vicinity of a headland-associated linear sandbank. Continental Shelf Research 26, 295–317.

Black K., Oldman J and Hume T (2005) Dynamics of a 3-dimensional, baroclinic, headland eddy. New Zealand Journal of Marine and Freshwater Research 39 (1), 91-120.

Boffetta,G, Celani,A, Dezzani, D and Seminara, A (2008) How winding is the coast of Britain? Conformal invariance of rocky Shorelines. Geophysical Research Letters, 35, L03615.

Branagan, D.F. and Packham, G.H. (2000) Field Geology of New South Wales. Department of Mineral Resources New South Wales, Sydney, Australia.

Denniss, T. and Middleton, J.H. (1994) Effects of viscosity and bottom friction on recirculating flows. Journal of Geophysical Research, 99 (C5), 10183-10192.

Duplantier, B. (2000), Conformally invariant fractals and potential theory, Phys. Rev. Lett., 84, 1363.

Dye, A. H. (2006) Is geomorphic zonation a useful predictor of patterns of benthic infauna in intermittant estuaries in New South Wales, Australia? Estuaries and Coasts 29:455-464.

Dyer, K.R. and Huntley, D.A. (1999) The origin classification and modelling of sand banks and ridges. Continental Shelf Research 19, pp. 1285-1330

Harris,P.T. and Heap,,A.D. (2007) Comment on "Is geomorphic zonation a useful predictor of patterns of benthic infauna in intermittent estuaries in New South Wales, Australia?" by A. H. Dye 2006. Technical Notes and Comments, Estuaries and Coasts 29:455-464.Estuaries and Coasts, 30, 3, pp. 562-566.

Harris P.T., Heap,A.D., Bryce, S.M., Porter-Smith, R., Ryan, D.A., Heggie, D.T. (2002) Classification of Australian clastic coastal depositional environments based upon a quantitative analysis of wave, tide and river power. Journal of Sedimentary Research;72(6):858–70.

Jordan,A., Davies,P., Ingleton,T., Mesley,E., Neilson,J. and **Pritchard,T**. (2010) Seabed Habitat Mapping of the Continental Shelf Waters of NSW, DECCW Technical Report www.ozcoasts.org.au

Kurtzi, J. C., Detenbeck, N. D., Engle,V. D., Ho, K., Smith, L. M., Jordan, S. J. and Campbell D. (2006) Classifying Coastal Waters: Current Necessity and Historical Perspective. Estuaries and Coasts, 29, 1, pp. 107–123

Large, D., Holden, C., Xie, J.,Tate, P. (1994) Bate Bay Pollution Study Volume 2 Physical Oceanography Summary Report. Australian Water Technologies Water Board, Sydney.

Littleboy,M., Sayers,J. and Dela-Cruz,J. (2009) Hydrological modelling of coastal catchments in New South Wales, 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009, http://mssanz.org.au/modsim09

Middleton, J.H.; Griffin, D.A. and Moore, A.M. (1993) Oceanic circulation and turbulence in the coastal zone. Continental Shelf Research, 13 (2-3): 143-168.

Oke, P. R., A. Schiller, D. A. Griffin, G. B. Brassington (2005). Ensemble data assimilation for an eddy-resolving ocean model. Quarterly Journal of the Royal Meteorological Society, 131, 3301-3311.

Pattiaratchi,C., James,A and Collins,M. (1986) Island wakes and headland eddies: a comparison between remotely sensed data and laboratory experiments. Journal of Geophysical Research, 92, C1, pp783-794.

Pritchard, T.R. (1997) Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, 24/1.

Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T.R., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Refereed Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N., (1996) Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

Roper T., Creese B., Scanes P., Stephens K., Williams R., Dela-Cruz J., Coade G. and Coates B. (2011) Assessing the condition of estuaries and coastal lake ecosystems in NSW. Office of Environment and Heritage, Sydney

Roughan, M., Macdonald,H.S., Baird,M.E., Glasby,T.M. (2011) Modelling seasonal and interannual variability in a Western Boundary Current and its impact on coastal connectivity. Deep-Sea Research II 58(5), 628–644.

Roy P.S., Williams R.J., Jones A.R., Yassini I., Gibbs P.J., Coates B., West R.J., Scanes P.R., Hudson J.P., Nichol S. (2001) Structure and function of south-east Australian estuaries. Estuarine Coastal and Shelf Science, 53:351–84.

Salomon A.K., Ruesink, J. L., Semmens, B.X. and Paine, R. T. (2001) Incorporating human and ecological communities in marine conservation: An alternative to Zacharias and Roff. Conservation Biology 15:1452-1455.

Short, A. (1993) Beaches of the New South Wales Coast: a guide to their nature, characteristics, surf and safety. Australian Beach Safety and Management Program. ISBN 0 646 15055 3.

Short,A.D. and Woodroffe,C.D (2009) The Coast of Australia, Cambridge University Press, pp288.

Suthers, I, Roughan,M, Morris,B, Armand,L, Baird,M, Boomer,A, Booth,D, Brassington,G, Byrne,M, Cato,D, Coleman,M, Couriel,E, Creese,R, Doblin,M Figueira,W, Gladstone,B, Harcourt,R, Hill,K, Holbrook,N, McCauley,R, Pritchard,T, Ralph,P, Richardson,A, Robertson,R, Rogers,T, Speer,M, Steinberg,P, Taylor,M, Wang,H, Williams,W, and others. (2010) NSW-IMOS Node Science and Implementation Plan (NSIP) July 2009-June 2013. http://imos.org.au/fileadmin/user_upload/shared/IMOS%20General/EIF/NSIP_2010/NSW_IMOS_NSIP-Aug10-v10.pdf

Wessel, P., and W. H. F. Smith (1996), A global, self-consistent, hierarchical, high-resolution shoreline database, J. Geophys. Res., 101, 8741–8743.

Wolanski (2007). Estuarine Ecohydrology, pp 17-39

Wolanski, E., Imberger, J. and Heron, M. L. (1984) Island wakes in shallow coastal waters. Journal of Geophysical Research 89(C6): 10,553–10, 569.

Zacharias, M.A. and Roff, J.C. (2001) Zacharias and Roff vs. Salomon et al.: Who adds more value to marine conservation efforts? Conservation Biology 15:1456-1458.

8. COFFS HARBOUR: A CASE STUDY OF INNER CBL DISPERSION

8.1 Introduction

There were scientific and management imperatives for the research reported in this chapter.

The scientific imperative was to provide a case study to explore the formation and characteristics of the coastal boundary layer in northern NSW coastal waters, an area where the East Australian Current generally flows along the continental shelf while near shore currents are heavily influenced by local winds and interactions with irregular coastal bathymetry including headlands. Shear zones and eddies can form in the wake of headlands such as Corambirra Point, immediately south of Coffs Harbour. Turbulent wake effects are fundamental to the formation of the coastal boundary layer at the land sea interface.

Modified flow patterns associated with headland wakes determine the potential for pollutant impacts because they affect pollutant dispersal, residence times, as well as having the potential to modify biological systems by affecting the distribution of and productivity of biological systems that are exposed to pollutants (e.g. transport and settlement of larvae/juveniles, aggregating prey and predators and primary productivity as described in Section 8.4). Very few previous studies have investigated wake effects in relation to dispersion of pollutants from point source discharges such as sewage outfalls.

The management imperative was to assess and develop options for an ocean discharge. After a long and contentious history a Coffs Harbour Sewage Strategy was proposed to accommodate rapid urban development in and around Coffs Harbour (CHEIS, 2000). The Strategy proposed to sewer new areas to the north of Coffs Harbour, maximize re-use and discharge excess effluent to the ocean from a new outfall that would replace three existing outfalls. The proposed outfall was to be located in about 20m of water off Boambee Beach immediately south of Coffs Harbour, with a discharge of over 20ML/day by 2021. This area is bounded to the north by the Solitary Islands Marine Park, which includes rich natural assets such as extensive corals as described in Chapter 2. Understanding the local circulation of ocean waters is critical to determine the fate and possible impacts of effluent discharged from the new outfall.

The body of this chapter (Section 8.3 and 8.4) has been published as international peer reviewed papers:

> **Pritchard, T.R.**, Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

> **Pritchard, T.R.**, Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

The first paper (Pritchard et al., 2001) analyses and explores mostly current meter and wind data in order to identify driving processes, assess the representativeness of the sampling period, simulate dispersion characteristics along a shore normal transect, and focus subsequent three dimensional model simulations. These analyses delivered timely advice to inform critical management decisions.

The second paper (Pritchard et al., 2007) describes time series analysis and three dimensional model simulations that define coastal boundary layer formation off Coffs Harbour. This paper focuses on transient re-circulation in the lee of Corambirra Point to improve understanding of dynamics and to map dispersion capacity across the study region.

Further background information on the study region is provided in Chapter 2 while sampling methodologies, data validation and quality assurance procedures are described in detail in Chapter 3.

8.2 Motivation and Relevance to Thesis Objectives

The purpose of this chapter is to investigate the principal forcing mechanisms, the importance of morphology in controlling the dispersion and retention times of pollutants and the potential for ecological impacts. As such this chapter relates directly to the following thesis objectives:

- ⇨ investigate Coastal Boundary Layer processes, their relationship to coastal morphology, and their role in controlling the dispersion, fate and potential impacts of pollutants discharged to the New South Wales coastal waters

- ⇨ investigate physical processes and dispersion characteristics for specific pollutant discharges to New South Wales coastal waters through case studies off Sydney (outer coastal boundary layer) and Coffs Harbour (inner coastal boundary layer)

To understand possible impacts and optimise the performance (location) of the new Coffs Harbour outfall it was necessary to quantify:

- ➢ location and persistence of any recirculation cells off Boambee Beach – this is a defining characteristic of the coastal boundary layer which can result in re-entrainment of effluent and limit flushing
- ➢ current shear along a shore normal transect aligned with the preferred orientation of the outfall – shear is a fundamental feature of the wake and a fundamental limiting factor that determines maximum potential initial effluent dilution (i.e. ambient water available for dilution equals incident current speed multiplied by the effective cross sectional area through the water column above the outfall)
- ➢ distributions of predominant along-shore and cross shore flows (Section 8.3) and particle retention times within the study area (Section 8.4) – this is necessary to understand the fate of effluent (especially with respect to the frequency of possible effluent exposure in Solitary Islands Marine Park) and may influence the distribution of biota.

8.3 'Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour'

Citation: **Pritchard, T.R**., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

SUMMARY: Efficient dispersion of pollutants discharged into coastal environments is predicated on a detailed understanding of the interactions of flow and local bathymetry. The purpose of our study was to investigate such interactions in order to assess the dispersion of effluent from the Coffs Harbour Sewerage Strategy. Times series and transect Acoustic Doppler Current Profiles (ADCP) were used together with local wind data, 3DD hydrodynamic modelling and CORMIX modelling to evaluate dispersion characteristics in coastal waters south of Corambirra Point just beyond the southern limit of the Solitary Islands Marine Park. Based on the good correlation between local winds and observed surface currents we found that our study period (September to November 2000) favoured southward flows compared to long-term wind data which indicated that wind driven along-shore flows were typically equally distributed northward and southward. Current meter records indicated wake effects and phase eddies (transient re-circulation) in the lee of Corambirra Point. The resulting shear zone was located inshore of the 30m isobath, where surface flows were 2-3 times less than those offshore. Retarded and variable flows within this sheltered zone in the lee of Corambirra Point limit the potential for dispersion and increase potential for re-entrainment of plume waters compared to offshore waters. ADCP transects suggested that the shear zone may be relatively discrete with little evidence of increasing along-shore current gradient offshore from the 30m isobath. Offshore flows included a lower proportion of northward currents compared to inshore locations. Observations together with plume modelling (CORMIX) indicate potential benefits in discharging beyond the shear zone. These factors together with cost considerations provide a basis to optimise discharge designs and subsequent monitoring strategies.

INTRODUCTION

Natural physical processes profoundly effect the dispersion, fate and consequent impacts of discharges of effluent to the dynamic coastal waters. If it becomes necessary to discharge effluent to coastal waters, environmental impacts can be minimised by optimising outfall location and configuration. In this way, sensitive areas can be avoided, initial mixing can be maximised and residency times within the coastal boundary layer can be minimised.

A clear understanding of flow structures over various spatial and temporal scales is also necessary to design adequate impact assessment monitoring programs.

Our study focused on the near shore environment off Boambee Beach immediately south of Coffs Harbour, New South Wales, Australia where a new ocean outfall will be constructed to replace three existing outfalls as part of a regional sewerage management strategy (CHEIS, 2000). This area is bounded to the north by the Solitary Islands Marine Park, which includes rich natural assets such as extensive corals.

Our study investigated flow structures off Boambee Beach, especially wake effects and re-circulation associated with the complex morphology around Corambirra Point. We also assessed the potential impact of these flows on the dispersion of effluent discharged at locations offshore from Boambee Beach.

BACKGROUND

Interactions between regional currents and local bathymetry are a major factor controlling flow structures and thus the dispersion and fate of both water borne and sediment bound pollutants.

Outer shelf current flows tend to be directed primarily alongshore and are usually consistent, both in speed and direction, for distances of hundreds of kilometers alongshore (Middleton, 1995). But bathymetry is more convoluted on the inner shelf where reefs, islands, headlands and embayments modify flows

(Deleersnijder, Norro & Wolanski 1992, Middleton, Griffin & Moore 1993). Near-shore bathymetry can predispose some areas to rotational flows and result in semi-closed recirculation and/or complex transient eddies.

Observations and numerical simulations have shed light on the processes that induce and modify flows around headlands, reefs and islands to form eddies (Black and Gray 1987, Black 1989, Signell and Geyer 1991, Middleton et al. 1993, Denniss et al. 1995). From these studies it is clear that a multiplicity of processes determine the characteristics, prevalence and persistence of eddies including near-shore bathymetry, bottom friction, unsteadiness of flow, tidal excursion and current direction, and horizontal eddy viscosity. It is therefore, not surprising that eddy characteristics are highly site specific. General hypothesises have, however, been developed to explain the effect of headlands on the development of eddies. 'Phase eddies' may develop in response to large scale pressure gradient reversals (Black and Gray 1987). That is, a phase eddy evolves when flow reversals occur earlier in the wake of the headland than in the free stream where currents are still continuing to decelerate. In this way the formation of phase eddies is governed by the inertia of the wake relative to the free stream flow. An alternative hypothesis is that eddies develop as a consequence of the separation of flow downstream of the tip of the headland which carries high vorticity fluid from the coastal boundary to the interior of the flow. In this way eddies form within the wake initiated by vorticity entrained into the flow downstream of the point of separation (Signell and Geyer 1991).

In the Coffs Harbour region, isobaths are aligned approximately parallel to the coastline with local irregularities associated with reefs, headlands and the Solitary Islands. Significant bathymetric features lie within the 35m isobath off Boambee Beach including Corambirra Point, Korffs Islet and a number of offshore reefs. Previous studies (PWD 1979 in CHEIS R28) off Coffs Harbour found large offshore areas of exposed rock with much of the inner shelf covered by a thin veneer of sands and gravels (~15 m thick at shore, 1-2 m at 30 m depth).

Density stratification is less than 0.5 kg m^{-3} between the surface and seabed during May to November with essentially unstratified conditions in the upper 20 m of the water column, based on observations during the late fifties by Commonwealth Scientific and Industrial Research Organisation at a site off Coffs Harbour in 50m of water. In summer, density stratification increases reaching a maximum density difference of ~1.5 kg m^{-3} between the surface and seabed in February and March (<1.0 kg m^{-3} in upper 20 m).

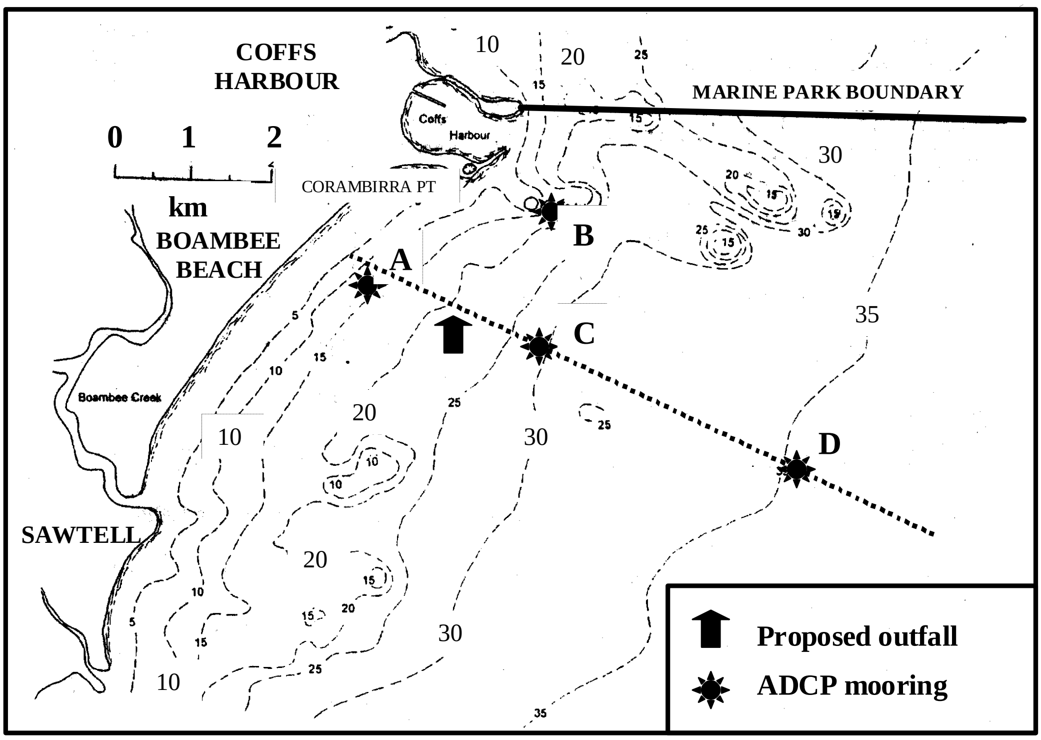


Figure 1: Study location showing ADCP deployments (A-D) and transects (dotted lines).

Major factors driving offshore dynamics include the East Australian Current and wind forcing. Tidal ranges are typically less than 1.5 m with minimal phase difference along the New South Wales coastline, so tidal currents are weak except near the mouths of estuaries and harbours.

METHODS

Observations

Four upward looking Acoustic Doppler Current Profilers (ADCPs) were deployed from 6/9/00 to 29/11/00. Two ADCPs were positioned along the alignment of the proposed outfall (Sites A and C). Other ADCPs were located within offshore flows (Site D) and as close as practicable to the eastern end of the bathymetric high that extends offshore to Korffs Islet (Site B) - Figure 1 and Table 1. Prior to deployment, ADCP compasses were calibrated, and units were set to 240 pings per ensemble every 30 minutes with ping rate at 2 Hz. Transducer heads were located 0.5m (Sites B,C,D) or 1.0m (Site A) above the sea floor and currents were recorded in 1 metre depth bins. Blanking depths of 1.75m (300KHz ADCPs) and 0.5m (1200KHz ADCPs) were set to avoid 'ringing' effects near the transducer heads.

Table 1: ADCP deployment specifications

SITE	Head Depth (m)	Blanking Depth (m)	Frequency (KHz)	No. Bins (after QA)
A	13	0.5	1200	11
B	21	0.5	1200	17
C	28	1.75	300	22
D	35	1.75	300	33

ADCPs at sites B, C and D operated continuously for the full deployments but reliable data ceased to be recorded at Site A towards the end of October when excessive marine growth developed around the transducer head.

Our interest focused on the upper water column where hard signal reflection at the sea-surface and other factors such as bubbles, waves, current shear and turbulence may reduce the profiling range. We adopted manufacturer criteria (beam correlation, error velocity, fish detection and percent good) for quality assurance and used the uppermost good bin for much of the analysis reported here.

In addition to moored ADCPs, we conducted across shelf transects along the proposed outfall alignment to investigate shear (evidence for re-circulation cells) and along two similar northern alignments (not provided here) to investigate potential for northward counter currents (Figure 1). A 300KHz ADCP was used for transects with depth bins set at 1m and 20 pings per ensemble recorded every ~3 seconds. Most transects were ~7km in length, ranging from water depths of 10m to 50m.

The Bureau of Meteorology provided average wind speed and direction for the last five years at 30 minute intervals from a weather station at Coffs Harbour airport, located immediately inshore from Boambee Beach.

Modelling

Two modelling approaches were pursued. Model 3DD (Black, 1995) was used to investigate effects of reversing pressure gradient fields on the development of eddies in the study area. And the model CORMIX which incorporates near field mixing processes, was used to investigate relative differences in effluent dispersion for various outfall locations along the outfall alignment.

Model 3DD is an explicit finite difference model, which has been applied to many studies of this type (e.g. Black and Gay 1987, Young et al. 1994, Jenkins et al. 1997). While the model is 3-dimensional, in this paper, the model was configured in two-dimensional depth averaged mode. The boundary conditions were set to oscillate to simulate the flow reversals. Reversals in the current can occur due to tides, winds, coastal trapped waves or regional scale circulation. As such, we have not attempted to calibrate the model but use the model instead to examine the spatial variations in flow structure around the complex morphology in a non-steady simulation. The need for this type of simulation became evident after analysis of the field measurements which showed that flow reversal and eddy formation were characteristic features of the local circulation. To accentuate the effect of flow reversal, a short period oscillation of 20,000 s (5.56 hrs) period was adopted. The northern boundary was a 0.7 $m.s^{-1}$ sinusoidally oscillating current, while the southern boundary was a 0.5 m sinusoidally oscillating sea level. The offshore (eastern) boundary was a zero through-flow boundary, which guided currents longshore. The model grid size was 150 m and seabed roughness length was 0.001 m. The horizontal eddy viscosity was 1 m^2s^{-1} in accordance with previous studies (e.g. Black, 1989). The wind was neglected in the simulation.

Bathymetry was based on Australian Hydrographic Chart AUS 812 (1:150,000) and studies reported in CHEIS R28 (2000), gridded by Kriging using Surfer software.

CORMIX is a robust composite flow and mixing zone prediction model developed by the School of Environmental Science and Engineering at Cornell University, New York (www.steens.ese.ogi.edu) and recommended by United States Environment Protection Agency for analysis of point source discharges to waters. The model provides a prediction for both near-field and far-field plume behaviour. A multi-port diffuser system has been proposed for Coffs Harbour (CHEIS, 2000). In the absence of an existing offshore outfall, the model was not calibrated, but a range of model scenarios were conducted to test sensitivity. The simulations used northward and southward flowing (along-shore axis 22.5°N) currents at 20th, 50th and 80th percentile ambient velocities although only 20th percentile simulations are reported here. Velocities were calculated from ADCP data at Sites A (14m depth) and C (28m depth), and at the proposed outfall site (20m depth - using data collected by Lawson and Treloar for CHEIS 2000). Discharge flow rates included Average Dry Weather Flow (ADWF of 20.7ML/day) and high flow Wet Weather (130ML/day) conditions.

RESULTS

Our analysis focused on near surface currents and northward transport because predominantly surface effluent plumes were expected and the Solitary Islands Marine Park lies approximately 4 kilometres north of the proposed outfall alignment.

Based on near surface currents observed offshore from Boambee Beach at four ADCP moorings (A-D), the predominant axis of flow was along shore, parallel to isobaths and coastline. Consequently, current components were defined as along-shore (022°) and cross-shore (112°).

Wind Driven Flows

Alongshore components of near surface currents and winds were well correlated ($r^2 \sim 0.65$) with the currents typically corresponding to about 1% of the wind speed at the inshore Boambee site (A) and 2-3% of the wind speed at the offshore Boambee site (C) - Figure 2.

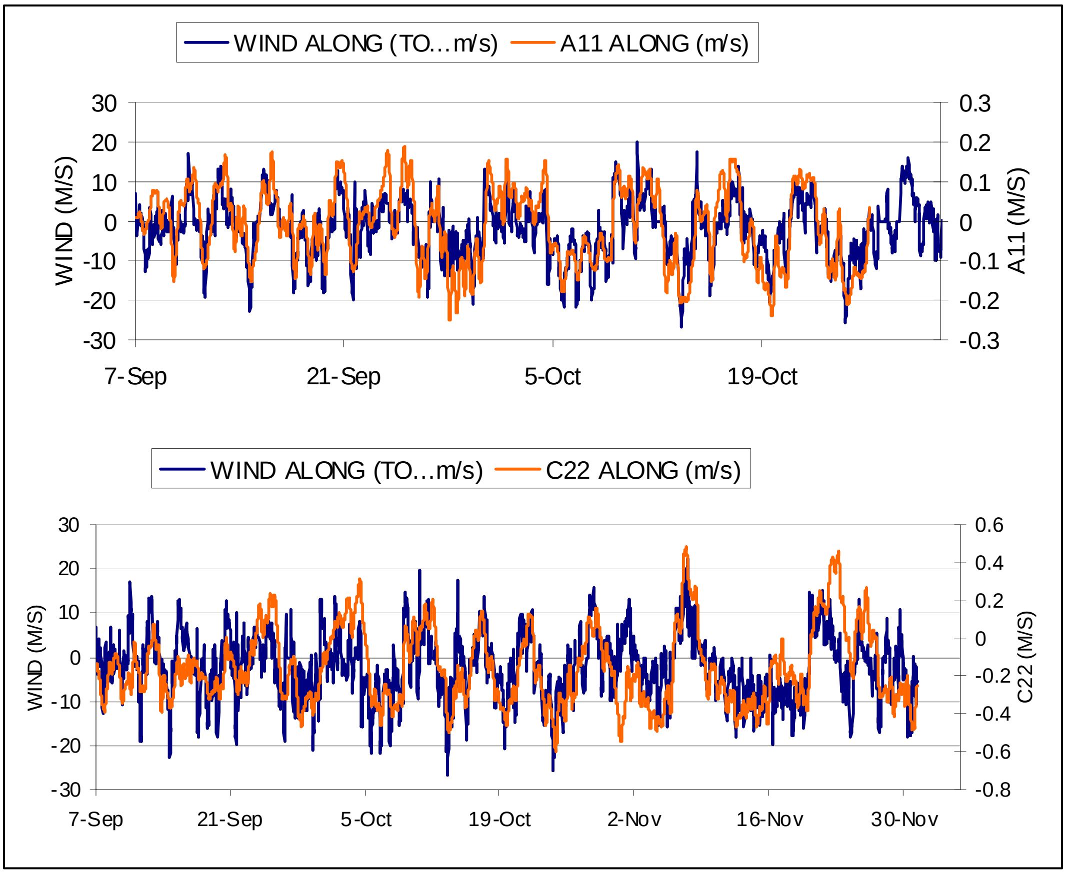


Figure 2: Alongshore winds and surface currents Site A (14m) and Site C (30m). Current scale is 1% of wind scale for Site A and 2% of wind scale for Site C.

Temporal Context

Given the strong correlation between alongshore winds and currents we compared the distribution of winds during our sampling period with long term distributions of winds and found that our sampling period may include a greater proportion of wind driven southward currents than would normally be expected - Figure 3. Indeed long-term wind data suggested a tendency for wind driven currents to be northward (53%) at least as often as southward currents in the study region.

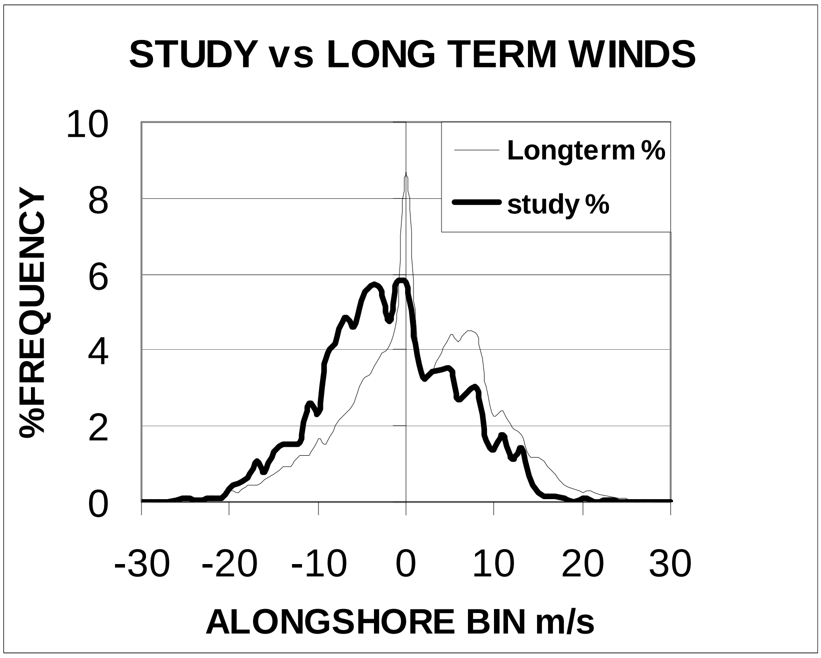


Figure 3: Alongshore local wind distributions for our study (Sept-Nov 2000) and long-term (1996-2000).

Spatial Flow Structure

Current magnitude controls the quantities of water available to dilute the effluent while current direction is a major factor controlling the fate of effluent.

A clear outcome from a cursory assessment of the current meter data was that current strengths at the inshore Boambee Site A were considerably less (2-3 times) than those at sites further offshore (Figure 4). The proportion of northward surface currents was greatest at the inshore Boambee Site A (A = 49%) with fewer northward and more southward currents observed at the offshore sites (B=30%; C=24% & D=20% northward). Winds were northward for ~35% of the time during these deployments (compared to average of 53%). There was little difference in the distributions of currents at the two offshore Boambee sites. And, not surprisingly, the proportion of eastward currents (not shown) was greatest inshore of the 30m isobath because land constrains surface flows at the western boundary. However, conclusions based on these comparisons must be tempered by the fact that a shorter data record existed for the inshore site (A).

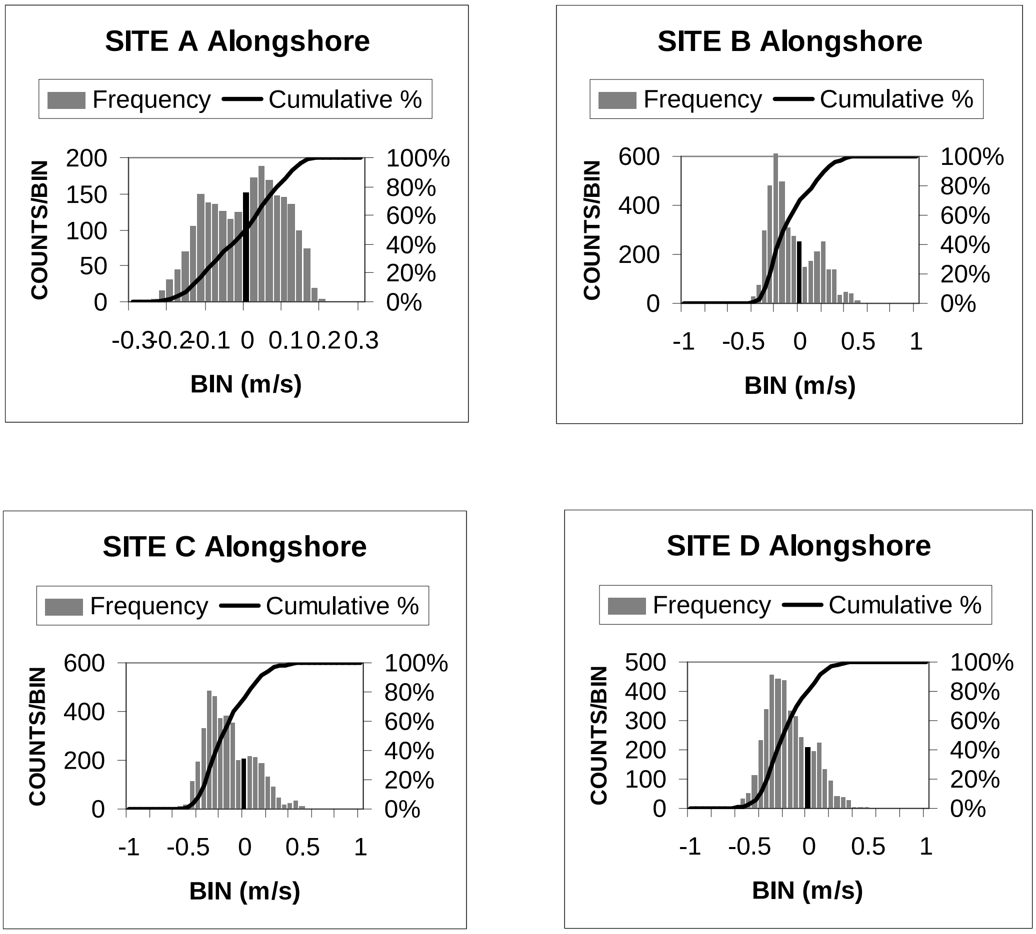


Figure 4: Distributions of surface along-shore currents at Sites A (Boambee 14m), B (Korffs Islet 23m), C (Boambee 30m) and D (Boambee 38m). Negative speeds indicate southward flows.

Along-shore surface currents have the potential to carry effluent toward or away from the Solitary Islands Marine Park some 4 km north of the proposed outfall site. So current meter records (Sites A and C) were examined for along-shore excursion 'events' - Figure 5.

At the inshore Boambee site (A) currents were weak and variable resulting in relatively small excursions (average ~500m) lasting on average less than a day (17hrs). In contrast, at the offshore Boambee site (C) currents were stronger with 'events' persisting for an average of 3.5 days, resulted in excursions of ~6km (average). Furthermore, along-shore currents reverse in direction more frequently at the inshore site thus increasing the likelihood of re-entrainment of diluted effluent into subsequent discharges. A greater proportion of southward flows/events was evident at the offshore Boambee site (C).

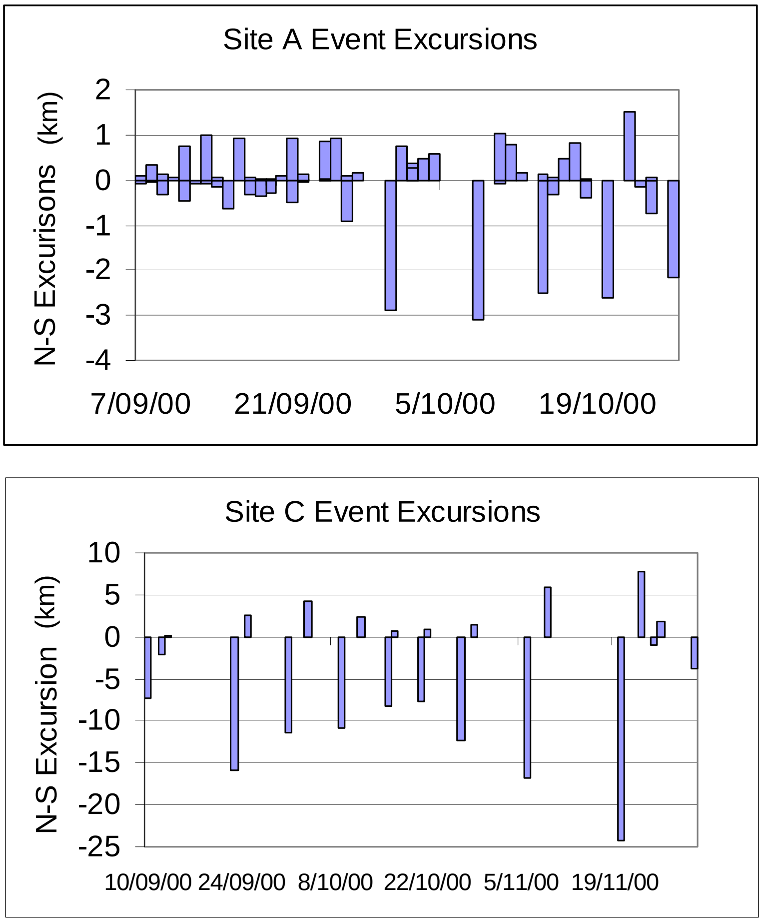


Figure 5: Along-shore excursion events calculated from records of surface currents observed at Site A (inshore Boambee) and Site C (offshore Boambee).

Excursions shown above were based on the simplifying assumption that currents observed at the current meter site were representative of currents throughout the range of the excursion. This assumption becomes tenuous close to shore where complex bathymetry and other processes such as wave-induced transport, produce complex current patterns such as re-circulation cells.

Rotational Flows

Much of the current structure described above can be explained in terms of wakes and rotational flows in the presence of Corambirra Point and associated bathymetric features.

Re-circulation is evident in current meter records as unidirectional shear between two sites on the same side of a rotational centre, or as opposing current shear between two sites which span the centre of a closed circulation cell.

Shear observed between the inshore (Site A) and offshore (Site C) sites along the outfall alignment is consistent with clockwise (positive) shear/rotation during most of the period - Figure 6. Significant variability was apparent with transient 'events' of opposing current shear mostly persisting for less than 2 days. Closed re-circulation cells (inferred by opposing current directions at sites A and C and indicated by blocked intervals in Figure 6) were typically associated with periods when the rate of change of shear was greatest. We have already noted that the magnitude of offshore currents were typically 2-3 times that of inshore currents so much of the variability seen in Figure 6 is due to variability of the stream flow (offshore). Thus, eddies appear to be developing after peak flow as the free stream is decelerating. This is a defining characteristic of phase eddies (Black and Gay, 1987).

There was little evidence for the development of stable (persistent) re-circulation cells during our study period (a full revolution would take ~1.5 days with a notional current speed of 0.1m/s and a cell diameter of 2km which is equivalent to the separation between Sites A & C).

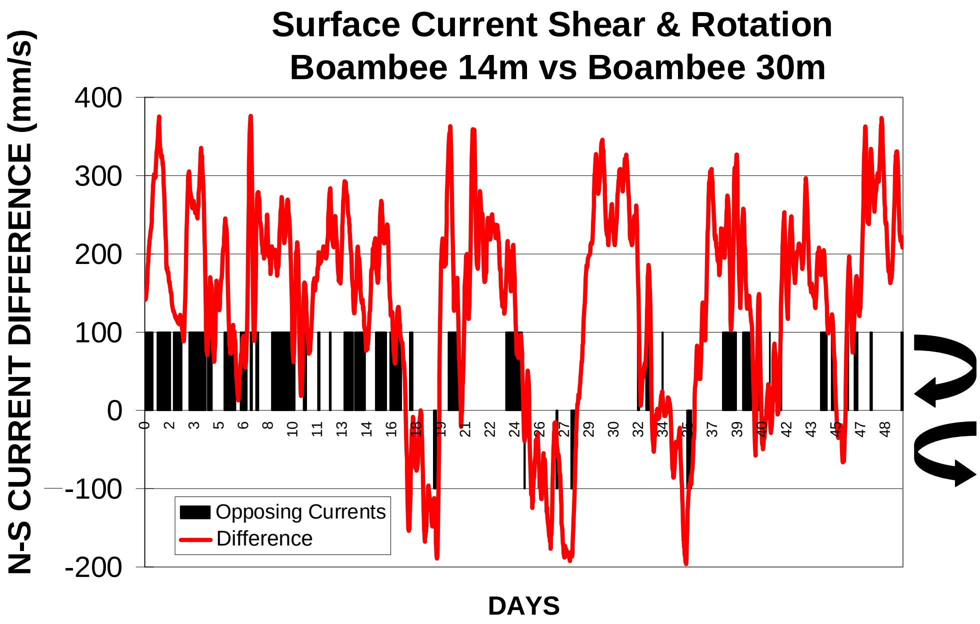


Figure 6: Surface north-south current difference between inshore Boambee site (A) and offshore Boambee site (C). Blocked intervals indicate periods opposing currents.

ADCP transects along the proposed outfall alignment from water depths of ~10m to ~50m defined general southward offshore flows (~0.4m/s) with currents generally decreasing shoreward (Figure 7). On these occasions, rotational flows were evident with weak northward flows (~0.1m/s) inshore of Site C and currents appeared relatively homogeneous offshore from Site C.

Numerical simulations (3DD) were used to investigate the formation of phase eddies off Coffs Harbour under the influence of idealised north-south reversing pressure gradients (Figure 8).

Simulations show convergence and acceleration of flow around the bathymetric feature associated with Corambirra Point and Korffs Islet and a wake develops in the lee of the tip of the headland as offshore southward stream flow is established (14.5hrs)

Currents in the wake begin to accelerate toward the headland and the eddy grows while the free flow reaches a peak and begins to decelerate (15.5hrs)

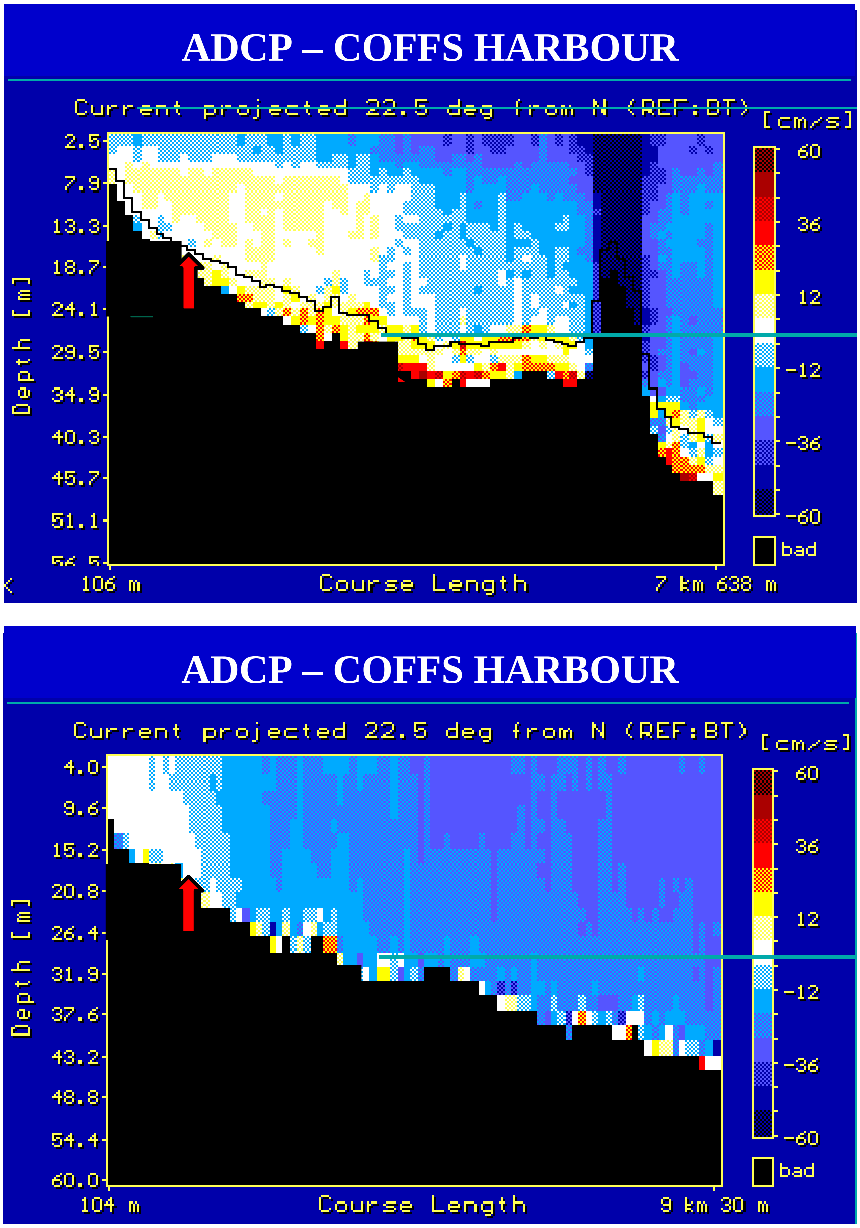


Figure 7: West-east cross section oriented along the proposed outfall alignment showing along-shore current strengths (2m depth bins; negative = southward). Arrow indicates proposed outfall location.

Flows along the tip of the Corambirra/Korffs headland remain strong while the free stream is essentially stationary and the core of the eddy migrates offshore (16.5 hrs)

A similar pattern evolves on the other side of the headland albeit somewhat more complex due to differing morphology (17.5hrs).

In this way near-shore currents respond more rapidly to reversing pressure gradients and lead the offshore stream flow, forming transient phase eddies in the lee of the headland. Simulations by others have shown that phase eddies may develop wherever there is bathymetric sheltering and transience of flow even in the absence of advection of momentum and horizontal shear (e.g. Hume et al. 1997).

Effluent Dispersion

Effluent dilution modelling was undertaken to identify the relative benefits of various discharge locations under wet and dry effluent flow scenarios with a specific emphasis on northward flowing scenarios which result in effluent travelling towards the Solitary Islands Marine Park (Figure 9).

CORMIX simulations indicated that the proposed outfall achieved effluent dilutions only slightly better than those at the inshore Boambee Site A (14m) but significantly worse than at the offshore Boambee Site C (30m) which was typically within the offshore stream flow.

DISCUSSION & CONCLUSIONS

Implications for Outfall Performance

Our study indicates that the presence of an eddy in the lee of the headland has a potentially profound effect on the fate of the plume. While the eddy is ephemeral, it nevertheless has a strong influence on net movement. Similarly, the sheltering caused by the headland creates a low current zone, which is not an optimal site for effluent discharge.

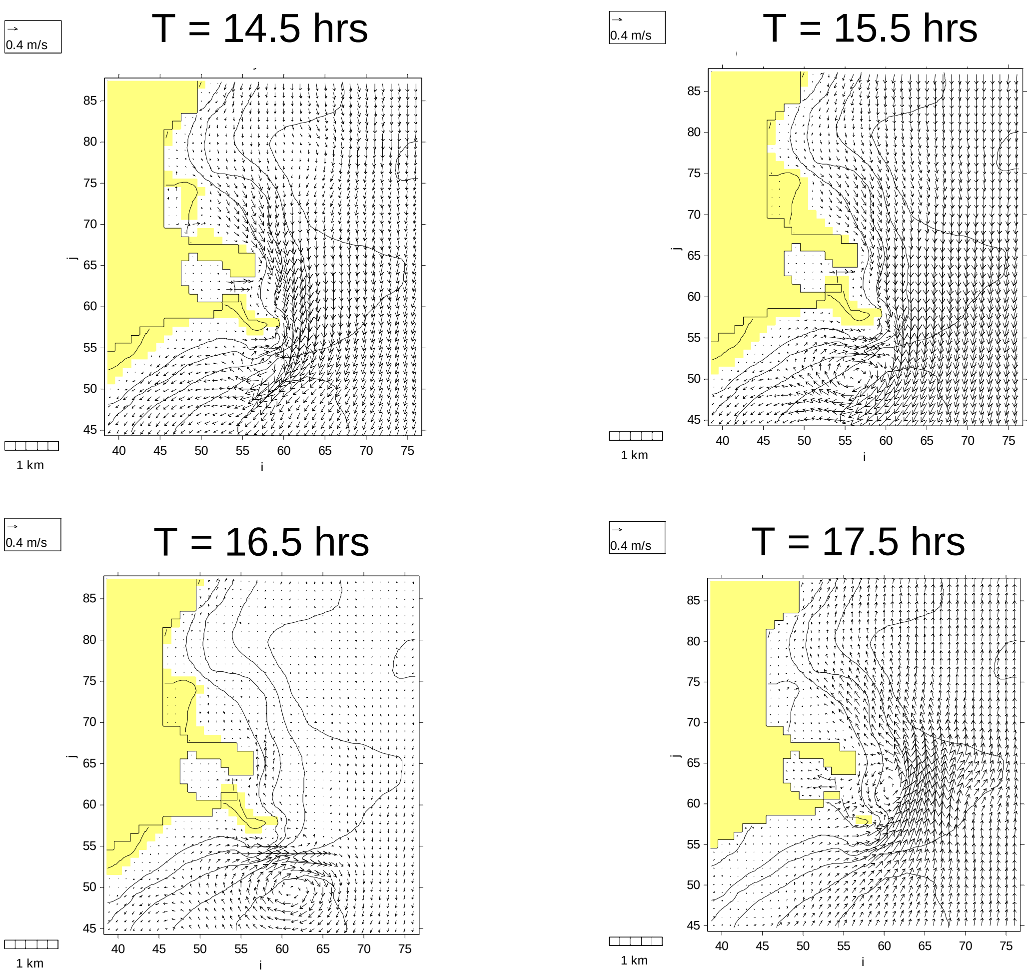


Figure 8: Simulated depth averaged flows due to pressure gradient reversals.

During our study, the low current zone was typically located inshore of the ~30m isobath, where flows were 2-3 times less than those offshore. These retarded inshore flows limit the potential for effluent dilution compared to conditions at and beyond the 30m isobath. ADCP transects suggest that the shear zone may be relatively sharp with little evidence of increasing current strengths offshore from the 30m isobath. Offshore flows included a lower proportion of northward currents compared to inshore locations.

The relative benefit of offshore outfalls was clearly demonstrated by CORMIX modelling (Figure 9). For a well designed outfall, dilution is fundamentally a function of the volume of ambient water available for dilution (i.e. water velocity and depth). The high dilutions achieved for discharges at Site C under dry weather effluent flow conditions are due to the significantly greater depths at Site

C (30m compared to 14m at Site A), significantly stronger currents (0.095m/s compared to 0.04m/s at Site A), and low effluent flow rates (20.7ML/day compared to 130ML/day for WWF).

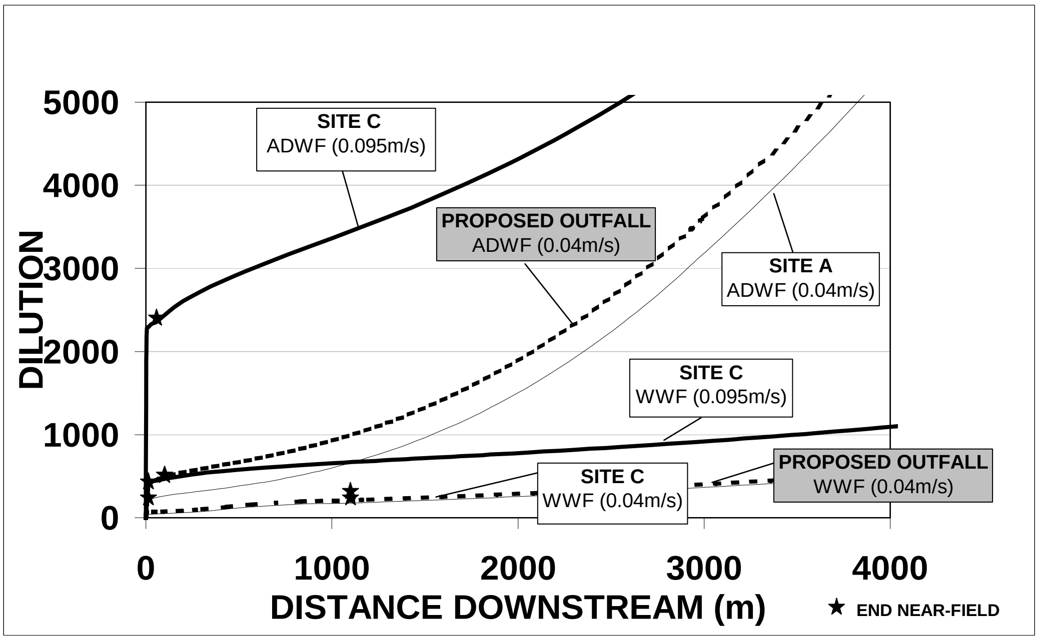


Figure 9: Indicative effluent dilutions for 20th percentile northward flow scenarios (CORMIX simulation) for average dry weather effluent flows (ADWF of 20.7ML/day) and wet weather effluent flows (WWF of 130ML/day) at Sites A and C, and at the proposed outfall location (between sites A & C).

Implications for Subsequent Monitoring

In principle, biological measures are the most relevant indicators of environmental impact. However, high natural variability, lack of appropriate replicate control locations and poorly understood relationships between components of the ecosystem limit the precision with which biological measures can distinguish natural from anthropogenic changes. Causal relationships are, therefore, often inferred and justified by correlation between biological differences/changes and anthropogenic disturbances such as the presence of sewage derived pollutants. An understanding of the dispersion and fate of the introduced pollutants is, therefore, critical to all impact assessment monitoring designs.

Conclusions from time-limited studies are often implicitly extrapolated to all times without proper evaluation of assumptions. In our study currents were principally wind driven, as is the case for many near-shore environments with minimal tidal forcing. The long-term wind record, therefore, provided a means to assess the degree to which our study represented average (long-term) conditions. Our study period was found to include a small bias favouring southward currents compared to long term wind data, which were evenly distributed northward and southward.

Opportunities

Further hydrodynamic simulations based on actual scenarios may clarify the spatial context and relative importance of wake effects and rotational flows which have the potential to reduce dispersion of effluent by retarding flows and re-entraining plume waters especially for discharges near the centre of eddies.

Likewise, time series analysis (power spectra) may provide a better understanding of the temporal scales of variability and the relative importance of associated driving mechanisms at various levels through the water column.

Worthy areas for research include the development of techniques to extract information currently obscured in the uppermost bins of ADCP records. This information is important because effluents discharged to near-shore environments typically form surface plumes.

Information such as that derived from our study provides the means to conduct a rigorous cost effectiveness assessment to optimise the location and design of outfalls. Furthermore, it serves to focus and interpret data from subsequent environmental monitoring programs.

ACKNOWLEDGEMENTS

This study was supported by the New South Wales Environment Protection Authority (EPA). The authors gratefully acknowledge mainly field assistance from Clive Holden, Paul Watts, EPA Water Science staff, the Solitary Islands Marine Park Authority and Coffs Harbour City Council.

REFERENCES

Black,K.P (1989) Numerical simulation of steady and unsteady meso-scale eddies, in Proceedings, 9th Australasian Conference on Coastal and Ocean Engineering, Adelaide, 204-208.

Black,K.P. (1995) The hydronamic model 3DD and support software. Occasional Report No.19, Department of Earth Sciences, Uni.Waikato. 53pp.

Black,K.P. & Gray,S.L. (1987) Eddy formation in unsteady flows. J.Geophys.Res., 92 (C9), 9514-9522)

CHEIS (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coff Harbour City Council, NSW, Australia.

CHEIS R28 (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Volume 10 - Specialist Reports Part 7, 1-47.

Deleersnijder,E., Norro, A. & Wolanski, E. (1992) A three dimensional model of the water circulation around an island in shallow water. Cont.Shelf Res., 12:891-906.

Denniss,T., Middleton,J.H. & Manasseh,R. (1995) Recirculation in the lee of complicated headlands: A case study of Bass Point. Journal of Geophysical Research 100: 16,087-16101.

Hume,T.M., Black,K.P., Oldman,J.W., and Vennell,R. (1997) Signatures of wave and current forcing on the seabed about a large coastal headland. In: Pacific Coasts and Ports '97, Proceedings of 13th Australasian Coastal & Ocean Engineering Conference, Christchurch, New Zealand, Vol.1: 319-324. Centre for Advanced Engineering, University of Canterbury.

Jenkins,G.P., Black,K.P., Wheatley,M.J., and Hatton,D.N. (1997) Temporal and spatial variability in recruitment of temperate seagrass-associated fish is largely determined by physical processes in the pre- and post-settlement. Marine Ecology Progress Series.

Middelton, J.H. (1995) The oceanography of Australian seas. In. Ed. Zann,L.P. & Kailola,P. The State of the Marine Environment Report for Australia. Technical Annex: 1 The Marine Environment, 1-10. GBRMPA.

Middleton,J.H., Griffin,D.G. & Moore,A. (1993) Oceanic circulation and turbulence in the coastal zone. Cont.Shelf Res., 13:143-168.

Signell,R.P. & Geyer,W.R. (1991) Transient eddy formation around headlands, Journal of Geophysical Research, 96, (C2), 2561-2575.

Young, I.R., Black,K.P. and Heron,M.L. (1994) Circulation in the Ribbon Reef Region of the Great Barrier Reef. Continental Shelf Research.

8.4 'Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia'

Citation: **Pritchard, T.R**., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

ABSTRACT

Time series analysis and model simulations defined dynamics of coastal boundary layer formation off Coffs Harbour based on four deployed acoustic Doppler current (ADCP) meters and wind data from Coffs Harbour airport. Variance preserving spectra revealed peak energies at 7.8, 3.9 and 2.5 days plus ~24 and ~12 hours consistent with dominant forcing by winds. At inshore sites the highest energy levels occurred at the surface and decrease uniformly with depth at all frequencies with local peaks centred at exactly 24 hours, corresponding to peak local wind energy. In contrast, offshore sites showed depth dependency in the peak spectral energy with evidence of regional influences and wave-guide effects due to density stratification. Hydrodynamic simulations using the 3-dimensional explicit finite difference model 3DD revealed local bathymetric controls on circulation. A coastal boundary layer, delineated by a shear zone ~2km offshore in the lee of Corambirra Point, south of Coffs Harbour, was associated with formation of transient eddies. Model simulations and independent ADCP data identified 3 dimensional flow structures typified by clockwise rotation of flows down through the water column at all sites except for the quiescent, shallow water site in the headland wake south of Corambirra Point. The area south of Corambirra Point was predisposed to clockwise eddy rotation while offshore flows were generally shore-parallel. Pollutant dispersal was shown to be significantly less within this coastal boundary layer thus highlighting the need to consider effects of coastal boundary layers when locating discharges such as ocean outfalls.

ADDITIONAL INDEX WORDS: *Headland wake, pollutant trapping, ocean outfall, coastal boundary layer*

INTRODUCTION

The coastal settlement of Coffs Harbour is located at 30.16ºS 153.05ºE, about 550km north of Sydney, with a population of ~65,000 and an economy dominated by tourism. It's rapidly growing population demands sewerage services without compromising the adjacent high value marine environment. Until recently, the discharge of treated effluent from an existing shoreline outfall at Coffs Harbour resulted in significant impacts observed along the length of Corambirra Point (SMITH, 1996; SMITH and SIMPSON, 1993). In the late 1990's a $170 million Coffs Harbour Sewerage Strategy was developed to serve the community to the year 2021 including the construction of a new offshore outfall off Boambee Beach immediately south of the Solitary Islands Marine Park. This paper examines the physical characteristics of Coffs Harbour coastal waters to illustrate the importance of the coastal boundary layer and its role in determining the dispersal of pollutants for management decision making.

The continental shelf off Coffs Harbour is narrow (<30km) with isobaths aligned approximately parallel to the coast across the mid and outer shelf but interrupted near shore by reefs, islands and headlands such as Corambirra Point (Figure 1). The inner shelf is covered by a thin veneer of sands and gravels: ~15 m thick at shore decreasing to 1-2 m at 30 m depth (CHEIS, 2000), indicative of a high energy environment (ROY and THOM, 1981). The sea floor offshore from Boambee Beach includes outcrops of rock near Corambirra Point and Korffs Islet in the north and Whitmore Shoal and Sawtell Shoal in the south. The regional coastline is aligned obliquely to the south-east, inner-shelf, modal wave direction and hence sediment is transported obliquely on the shoreface with a net northward movement (GOODWIN et al., 2006). However, further offshore shelf waters experience strong and persistent southward East Australian Current (EAC) flows which carry warm, oligotrophic waters and associated tropical species. Indeed, the Solitary Islands just north of Coffs Harbour mark the southernmost extent of some of the ninety species of corals found there (HARRIOTT et al., 1994).

Coastal waters are driven by processes that operate over a wide range of spatial and temporal scales from high frequency internal tides and waves (e.g. GRIFFIN and MIDDLETON, 1992) to weatherband, northward propagating coastal trapped waves (e.g. CHURCH et al., 1986) and wind driven upwelling/downwelling, to seasonal variation of the EAC on the shelf off Coffs Harbour. While the EAC often dominates offshore regional flows (e.g. MIDDLETON, 1995; ROUGHAN and MIDDELTON, 2004), winds typically drive shallow water flows on the continental shelf (e.g. **PRITCHARD** et al., 2001) and to a lesser extent waves drive flows near the shoreline (e.g. GOODWIN et al., 2006). Tides are semidiurnal with a microtidal range (mean spring range ~1.2 m) and little phase difference along the coast so barotropic tidal currents are weak except near the entrances of estuaries and harbours (HARRIS et al. 1991). In many cases counter currents flow northward while offshore deep ocean currents flow southward (e.g. FREELAND et al. 1986). Furthermore, constraints imposed by the coastline and inner shelf morphology modify the effects of near shore flows to define a complex coastal boundary layer where dispersion is spatially highly variable.

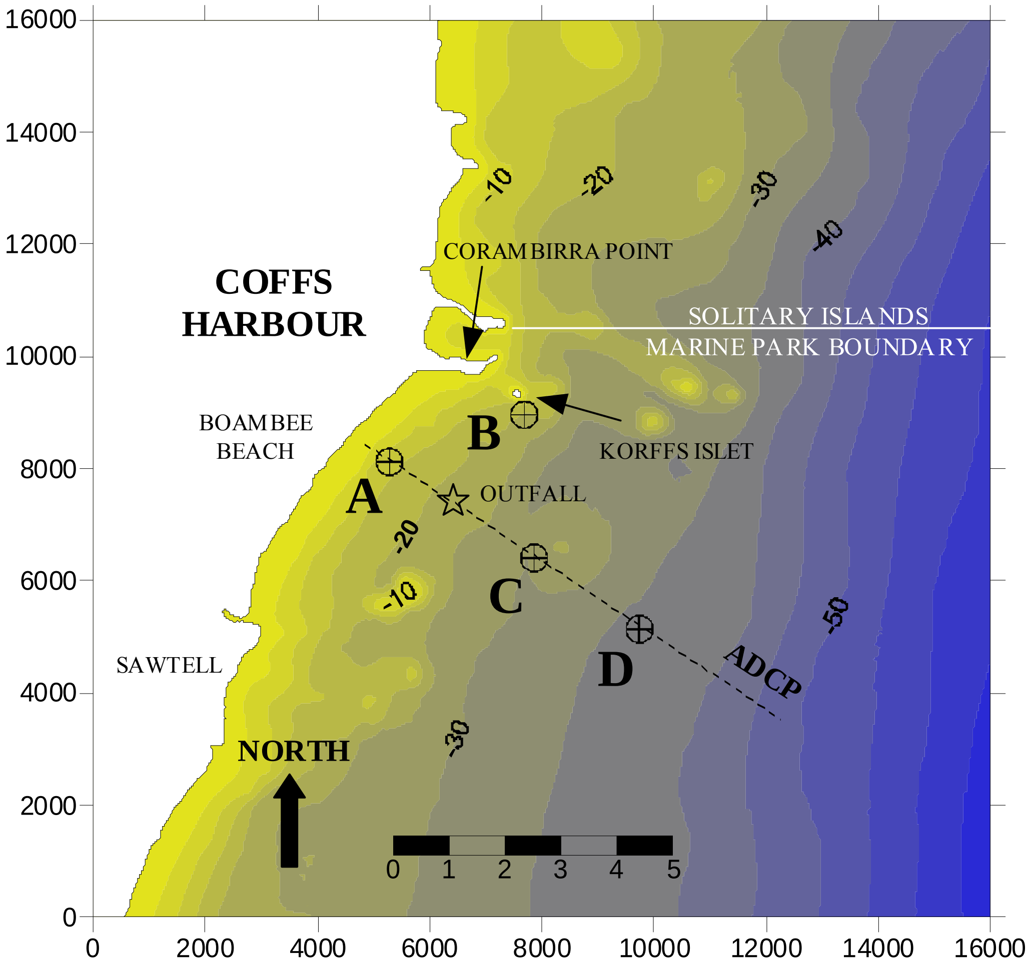


Figure 1. Study location showing local bathymetry, ADCP deployments (A-D) and transects (dotted lines).

Initial analysis of current meter records deployed for a three month period in late 2000 revealed evidence of wake effects and transient re-circulation in the lee of Corambirra Point with a shear zone located inshore of the 30m isobath off Boambee Beach (**PRITCHARD** et al., 2001). Constrained and variable flows within this sheltered zone in the lee of Corambirra Point limit the potential for dispersion and increase potential for re-entrainment of plume waters compared to offshore waters. Observations together with plume modelling (CORMIX) indicated potential benefits in discharging beyond the shear zone (**PRITCHARD** et al., 2001). The objective of research presented here is to improve understanding of dynamics and map dispersion capacity within the coastal boundary layer near Coffs Harbour.

Headland wake effects

The term headland wake is used to describe the area of quiet water adjacent to the free stream current. At the tip of the headland a separation point can develop where inertia carries the free stream current past slower currents in the lee of the headland creating a pronounced shear zone.

Eddies associated with headland wakes can induce cross-shelf advection and mixing (e.g. BLACK et al., 2005), enhance vertical mixing (e.g. FARMER et al., 2002), bring nutrients to the surface at the centre of eddies (e.g. ROUGHAN et al., 2005) and act to trap effluent along irregular coastlines (e.g. CHEN et al., 2005). These attributes of headland wakes have great potential to modify biological systems by affecting biological exposure to pollutants, primary production (e.g. ROUGHAN et al., 2005), transport and settlement of larvae and juveniles (e.g. RANKIN et al., 1994) and by aggregating prey and predators (e.g. JOHNSTON et al., 2005).

Most intensive headland wake investigations have tended to focus on individual, prominent headlands such as Bass Point in eastern Australia (DENNISS et al, 1995; AITKIN et al, 2002) and Cape Rodney in New Zealand (BLACK et al., 2005). Early investigations of flow separation and the formation of eddies in the lee of these features involved two dimensional simulations often with simplified geometries (WOLANSKI, et al., 1984; BLACK and GAY, 1987; SIGNELL and GEYER 1991). More recently, three dimensional flow simulations have been attempted (e.g. WOLANSKI, et al., 1996; FURUKAWA AND WOLANSKI, 1998) but few have been adequately verified with corresponding three dimensional flow observations. Some notable exceptions include wave, current and temperature measurements which revealed the detailed internal dynamics of a baroclinic eddy off Cape Rodney, New Zealand (BLACK et al., 2005) and Eulerian and Lagrangian current measurements which revealed tidally driven three dimensional headland wake effects off Cape Levillain in northwest Australia (BERTHOT and PATTIARATCHI, 2006).

The majority of these studies were seeking an understanding of larval settlement potential or sediment dynamics. Very few studies have investigated wake effects in relation to dispersion of pollutants from point source discharges such as sewage outfalls.

METHODS

Currents

Four upward looking Acoustic Doppler Current Profilers (ADCPs) were deployed for three months (6th September, 2000 to 29th November, 2000) to investigate possible headland wake effects. Two ADCPs were positioned along the alignment of the proposed outfall (Sites A and C). Other ADCPs were located within offshore flows (Site D) and as close as practicable to the eastern end of the bathymetric high that extends offshore to Korffs Islet (Site B) - Figure 1 and Table 1. Prior to deployment, ADCP compasses were calibrated, and units were set to 240 pings per ensemble every 30 minutes with ping rate at 2 Hz. Transducer heads were located 0.5m (Sites B, C, D) or 1.0m (Site A) above the sea floor and currents were recorded in 1 metre depth bins. Blanking depths of 1.75m (300KHz ADCPs) and 0.5m (1200KHz ADCPs) were set to avoid 'ringing' effects near the transducer heads.

ADCPs at sites B, C and D operated continuously for the full deployments but reliable data ceased to be recorded at Site A towards the end of October when excessive marine growth developed around the transducer head.

Table 1: ADCP deployment specifications

SITE	Head Depth (m)	Blanking Depth (m)	Frequency (KHz)	No. Bins after QA
A	13	0.5	1200	11
B	21	0.5	1200	17
C	28	1.75	300	22
D	35	1.75	300	33

Across shelf transects using 300KHz ADCPs were conducted at 4 knots along the alignment of Sites A, C and D from water depths of about 10m to 50m with depth bins set at 1m and 20 pings per ensemble recorded every ~3 seconds (~6m along track).

Acceptance criteria for ADCP data were based on time series plots of beam correlation (auto correlation between pings), percent-good (a range of RDI acceptance criteria) and vertical error velocity (difference between simultaneous vertical velocity estimates from adjacent beams).

Progressive vector displacements were calculated from ADCP data sets to characterise overall flow patterns and to suggest relative advection of pollutants and plankton. Variance preserving spectra were produced to assess dominant energy frequencies and related to various forcing using MATLAB routines for each depth layer (bin) using a lag window of 256 hours; equal areas under the curve represents equal energy.

Bathymetry, Winds and Water Temperatures

Bathymetry based on Australian Hydrographic Chart AUS 812 (1:150,000) and studies reported in CHEIS (2000) was gridded for modelling by Kriging using Surfer software.

The Australian Bureau of Meteorology provided wind speed and direction data at 30 minutes from Coffs Harbour airport located behind Boambee Beach for the study period. For modelling, the bathymetry was rotated 18 degrees anticlockwise from true north in order to align the modelling grid with the preferred orientation of surface currents observed at Site C which was in approximate alignment with isobaths.

StowAway temperature loggers (range –5ºC to 37ºC; accuracy 0.1ºC) were deployed at each of the four ADCP sites at 10m intervals through the water column to measure thermal stratification and its sensitivity to forcing. Each logger was calibrated prior to deployment and on recovery according to the manufacturer's instructions.

Modelling

Model 3DD (BLACK, 1995) was used to simulate three dimensional flows over the study region because ADCP data from our study revealed vertical shear and rotation (described below) and recent headland and island wake investigations have demonstrated the importance of three dimensional flow structures (e.g. BERTHOT and PATTIARATCHI, 2006; BLACK et al., 2005). The critical value above which a stable wake is formed can be considerably overestimated by depth-averaged modelling in the case of shallow wakes (STANSBY, 2006). The three-dimensional baroclinic form of model 3DD is based on well established momentum and mass conservation equations. An explicit finite difference (Eulerian) solution is used to solve the momentum and continuity equations for velocity and sea level, through a series of vertical layers that are hydrodynamically linked by the vertical eddy viscosity. The model provides for spatial variation in roughness length and horizontal eddy viscosity. Non-linear terms and Coriolis force can be included or neglected, whereas the land/sea boundaries can be set to free slip or no-slip. The model 3DD has been successfully applied and verified in a diverse range of situations (BLACK 1987, BLACK et al. 1989, 1993; MIDDLETON and BLACK 1994; YOUNG et al. 1994) and has been previously applied to investigate the parameters responsible for eddy formation behind islands and reefs (BLACK and GAY 1987; BLACK 1989; HUME et al. 2000; BLACK et al., 2005).

For the Coffs Harbour application horizontal grid cell size was set at 100m with six vertical layers increasing in thickness from surface to bottom (1, 3, 6 , 10, 10, 100m) reflecting the variability of vertical shear observed in the water column. A body force was applied based on ADCP observations at Site C to simulate large-scale pressure gradients. The body force is a surrogate for a calculated sea gradient, obtained by inverting the vertically-averaged momentum equation and solving using measurements of currents, sea levels and winds. The body force is,

$$Fy = g\frac{\partial \varsigma}{\partial y} = \left[-\frac{\partial V}{\partial t} + \frac{Wy}{\rho h} - \frac{gV(U^2 + V^2)^{1/2}}{C^2 h} - fU \right]$$

where ς is sea level, U and V are velocities in x and y directions, Wx and Wy are the wind stress components, C is Chezy's C, f the Coriolis parameter and h the depth.

Representation of bottom friction in the model requires parameterisation of the bed roughness length. In the area offshore from Boambee Beach the seabed is predominantly fine to medium sand with outcrops of rock scattered to the north (Corambirra Point, Korffs Islet and adjacent reefs) and to the south on shoals off Sawtell (CHEIS, 2000). In order to reproduce frictional characteristics over this seabed we used a roughness length parameter of 0.001m similar to that used by BLACK et al. (1989). We used a free-slip boundary at the land-sea interface so no lateral friction exists to generate vorticity in the simulation. This gives more realistic results in the context of a 100m numerical modelling grid where velocities would be unrealistically damped up to at least two cells from land; this means that vorticity and eddies are generated by other mechanisms.

The input that is typically least well known is the horizontal eddy viscosity, as it represents processes that are not resolved by the model physics (SIGNELL and GEYER, 1991). The horizontal eddy viscosity was set at 5 $m^2 s^{-1}$ which takes into account the 100m grid size that does not allow accurate representation of small scale natural viscous processes. Eddy viscosity can range to extremes of 15 $m^2 s^{-1}$ as observed off Bass Point (a headland some 500kms south of Coffs Harbour) by MIDDLETON et al. (1993) but observed horizontal eddy viscosity is typically orders of magnitude less than this.

Pollutant dispersion potential was mapped using a three dimensional numerical dispersal model called POL3DD (BLACK, 1995) which solves the transport/dispersion equations using Lagrangian particle tracking techniques.

POL3DD outputs gridded arrays of concentration, particle numbers, integrated particle visits, and various particle characteristics. Neutrally buoyant, conservative particle simulations were adopted in order to examine potential pollutant pathways, destinations and residence times and thus construct maps to indicate generalised dispersion potential. Particles were tracked until they all left the model region or until the simulation was terminated and the numbers of particle visits to model cells were logged.

RESULTS

Hydrographic setting and drivers

During the ADCP deployment period (6th September, 2000 to 29th November, 2000) East Australian Current stream flow occurred on or near the continental shelf with elevated water temperatures reflecting proximity of EAC influences (Figure 2).

During early November the EAC impinged on the inner shelf with strong southward advection of warm (24ºC) waters. Despite this regional southward dynamic, a local northward flow was driven by a strong southerly (northward) bluster demonstrating the dominance of local winds. Indeed **PRITCHARD** et al. (2001) found alongshore components of near surface currents and winds were well correlated ($r^2 \sim 0.65$) with the currents typically corresponding to about 1% of the wind speed at the Site A and 2-3% of the wind speed at Site C.

Temperature stratification at offshore Site D varied through the period from essentially homogenous barotropic conditions during early spring (September) to baroclinic with temperature differences of up to 4ºC through the water column by late spring (November). When present, the thermocline was typically found at about 20m depth. This is consistent with observations during the late fifties by Commonwealth Scientific and Industrial Research Organisation at a site off Coffs Harbour in 50m of water (**PRITCHARD** et al., 2001). Local wind events such as the southerly bluster in early November rapidly de-stratified the water column (indicated by the double arrow in Figure 2). At all other shallower sites (Sites A, B & C) the water column was well mixed with vertical temperature differences rarely exceeding 0.5ºC.

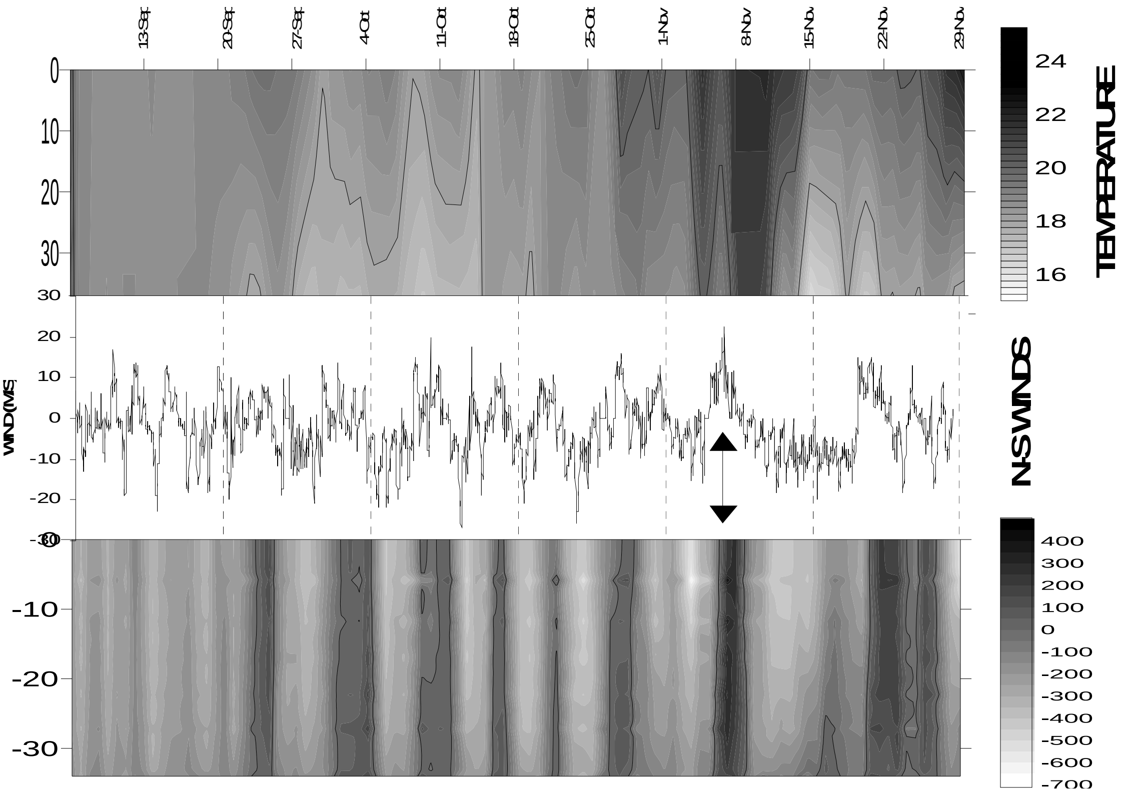


Figure 2. Water temperature profile (ºC), north-south current profile (m/s) time series at Site D and local north-south wind (m/s) time series recorded at the airport just west of Boambee beach. Negative southward currents and winds.

Time series analysis of ADCP data revealed patterns of spectral energy through the water column (Figure 3). In general, variance preserving spectra for the four ADCP sites show prominent peaks at ~12 and ~24 hours, highlighting the relative contribution of the semi-diurnal tides, inertial motions and local land-sea breezes. Strong peaks are also evident at 2.5, 3.9 and 7.8 days, associated with the regional weather band. Complex spectral features are also present in the vertical energy structure, particularly within the diurnal band at Site D as shown in Figure 4, and to a lesser extent at Sites B and C. At Site D energy levels fall steadily from the surface to a depth of 15m (bin 19), and throughout the lower 11m (25-36m). In between, the diurnal energy shows local maxima, most likely coincident with the pycnocline layer, which acts a waveguide, trapping energy entering from above and below. Temperature data in Figure 2 are consistent with a pycnocline typically at this depth interval. There are distinct albeit small, shifts in peak energy between the three layers shown in Figure 4 with peaks equivalent to periods of 23.8 hrs (upper), 24.2 hrs (mid) and 24hrs (bottom). These peaks are all close to the inertial period at this latitude (23.7hrs) so it is difficult to infer remote or local forcing.

Observed wake effects – shear and rotational flows

Although the spectra at all sites exhibit peaks at similar frequency bands, Site A exhibits energy levels across the spectrum that are significantly lower than all other sites indicating shallow water frictional effects and wake effects which are expected to result in quiescent zones in the lee of the headland. Furthermore, the weatherband signal at Site A is diminished relative to diurnal and semi-diurnal bands when compared to spectra from other sites which is consistent with observations of headland wakes elsewhere (e.g. DENNISS et al., 1995).

In contrast to Site A, energy levels at Site B are generally high relative to the two offshore sites C and D due to its close proximity to the tip of the bathymetric extension of Corambirra Point where convergence is likely to result in local current accelerations. However, the high energy levels at Site B are mostly confined to the upper water column with near bottom energy levels well below those evident in the offshore spectra at Sites C and D.

Progressive vector plots for the entire deployment (Figure 5) revealed patterns of long term rotation across sites and through the water column. Near surface circulation (indicated by bold dark displacement traces) is characterised by surface divergence between mainstream and the coast in the lee of Coffs Harbour especially at Site B, and net offshore displacement at Site A.

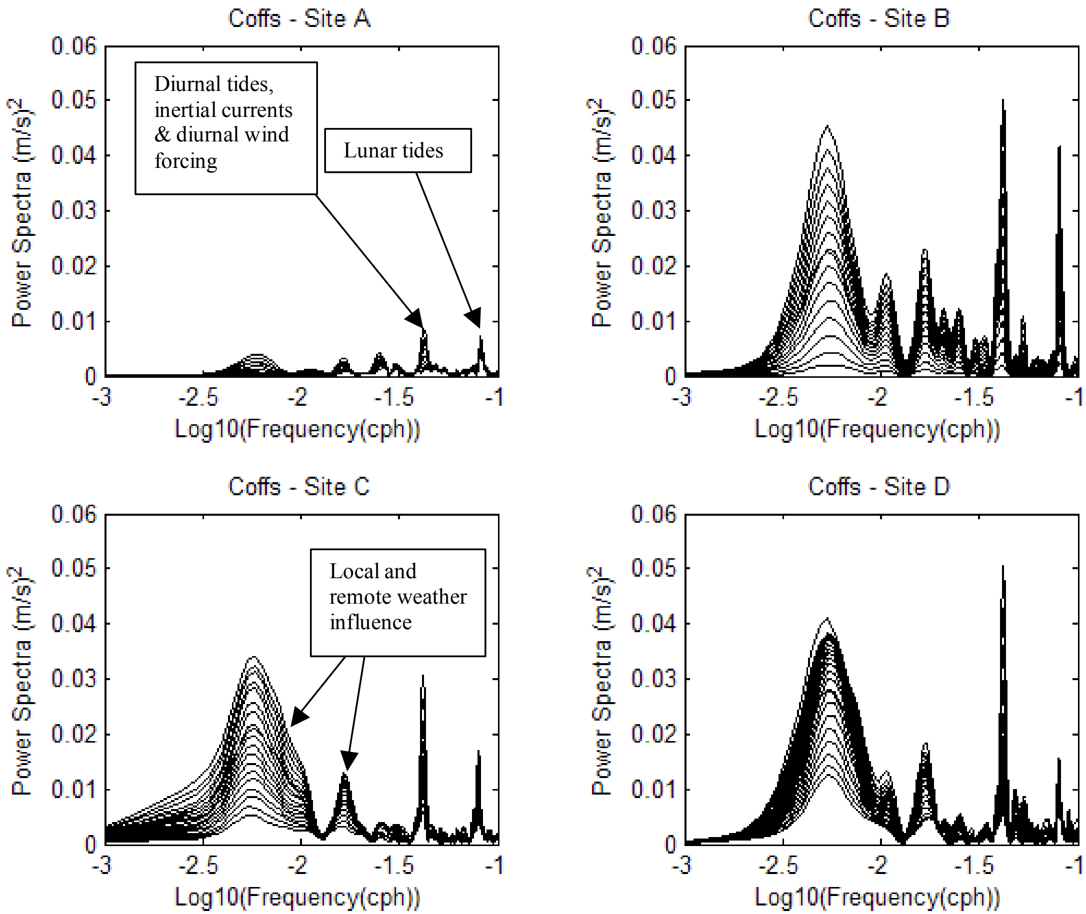


Figure 3. Variance preserving spectra illustrating energy distribution throughout the water column at Sites A, B, C and D. Spectra shown for 1m depth bins at Sites A (11 bins across 13m depth), B (17 bins; depth = 21m), C (22 bins; depth = 28m) and D (33 bins; depth = 35m depth).

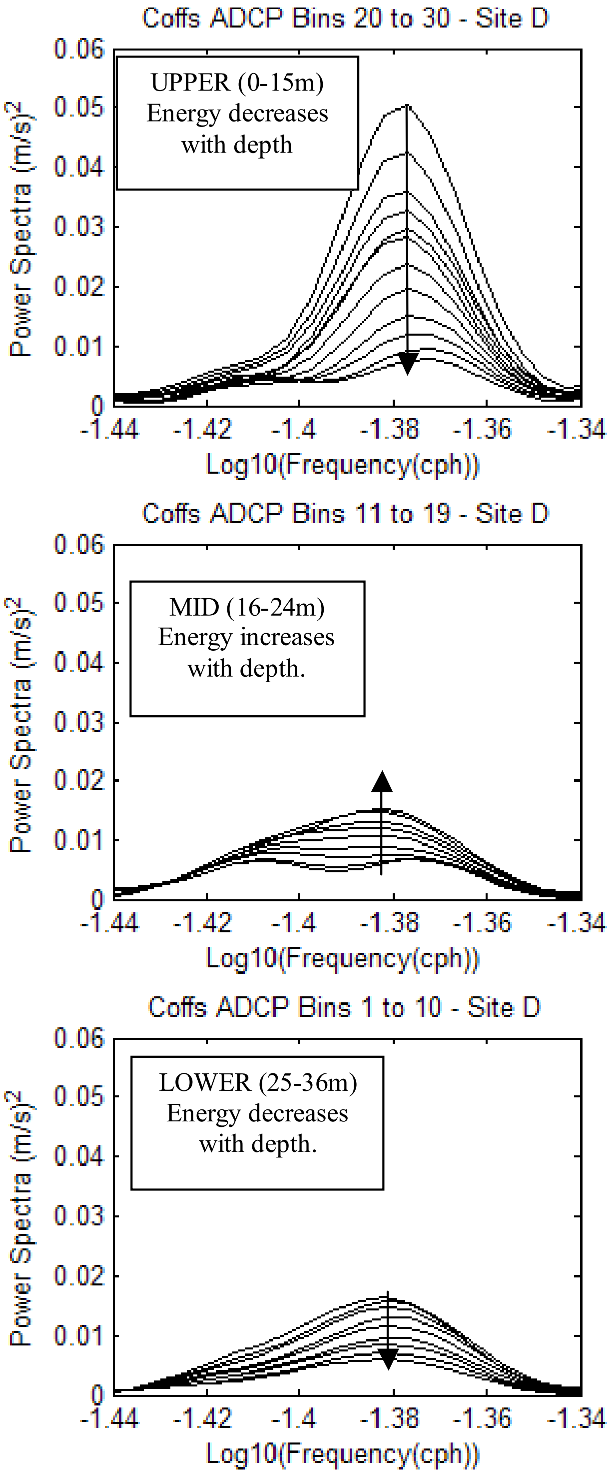


Figure 4. Variance preserving spectra illustrating shifts in diurnal energy distributions through the water column at Site D.

Despite this net offshore displacement at Site A, the vector displacement path comprises a series of reversing path segments reflecting intervals of southward flows similar in direction to that seen at Sites C (and Site D) interspersed by periods of northward flows which were steered offshore. These northward flows are consistent with recirculation in the lee of Corambirra Point centred about a point southeast of Site A. Similar reversing flow patterns were observed in upper waters at Site B although southward segments dominated the displacement path suggesting near proximity to flow separation off Corambirra Point.

Net bottom water displacements (indicated by bold white traces in Figure 5) also indicate a predisposition for cyclonic eddy recirculation in the lee of Corambirra Point (Sites A, B and C) and shore parallel flow along isobaths at Site D. Net bottom water vector displacements are almost diametrically opposed at Sites A and C while flow patterns at Site D are similar to those at Site C. Increased bottom stress and accelerations associated with the bathymetric extension of Corambirra Point contribute to the clockwise rotation of currents downwards through the water column exhibited at Sites C and D.

Site A clearly falls within a headland wake with a shear zone located between Sites A and C. Figure 6 shows the north-south velocity differences across the 3025m that separates Sites A and C. Near surface and near bottom velocity differences are highly correlated although opposing flows (solid blocks) occurred more frequently in near bottom waters. The variability in north-south flow differences presented in Figure 6 reflects the flow variability at Site C and indicates a propensity for clockwise rotation inshore of Site C. A number of cross-shelf ADCP transects were undertaken to assess the gradients and eddy formation suggested from the moored data. Results (not shown) indicated discrete shear zones that were investigated further through model simulations.

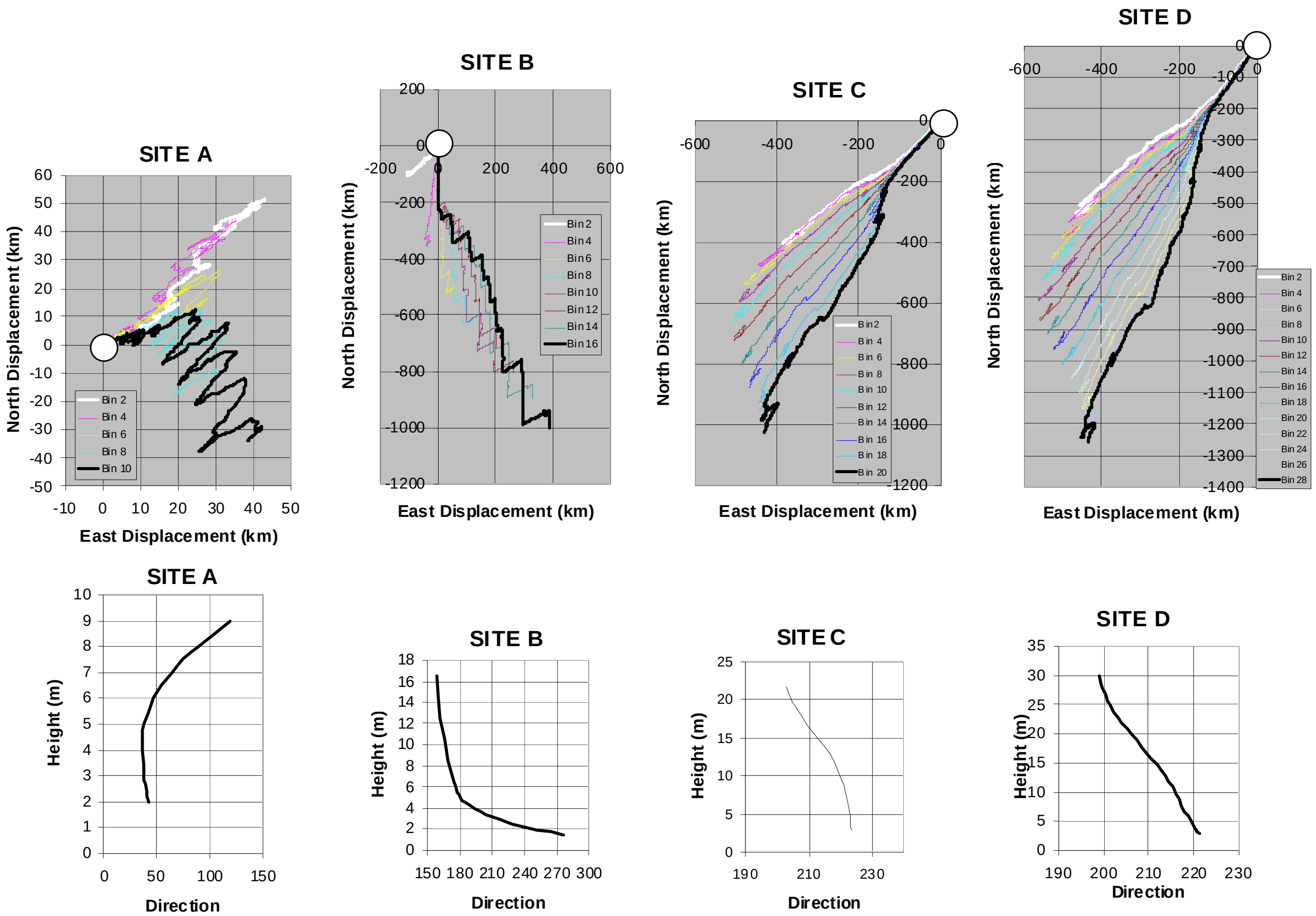


Figure 5. Three dimensional flow field illustrated by progressive vector plots for alternate one metre depth bins at Sites A, B, C and D with upperm bins indicated by bold black traces and lowermost bins indicated by bold white traces (top); and, direction of total displacements (anticlockwise w.r.t. tr north) corresponding to end points of the progressive vector plots for each ADCP depth bin (bottom). Note duration of record at Site A is approximat one month shorter than at other sites.

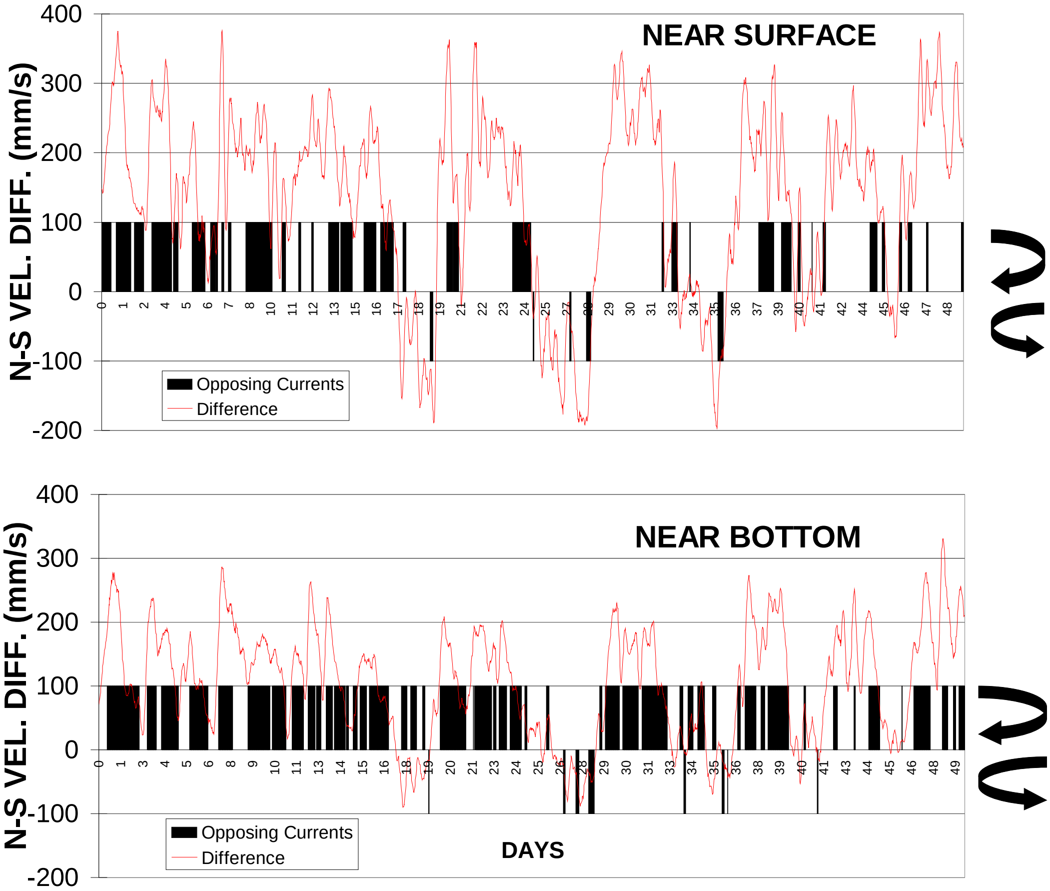


Figure 6. Difference in north-south current components observed at Sites A and C which lie along the alignment of the outfall straddling the shear zone caused by the wake of Corambirra Point. Plots based on uppermost (top trace) and lowermost (middle trace) ADCP depth bins with rotation (dark blocks) indicated by arrows. Positive current differences correspond to clockwise rotation.

Model Simulations

Model simulations were undertaken to investigate the spatial extent of wake effects, to better define the shear zone indicated by ADCP observations at Sites A and C, and to investigate potential pollutant trapping due to wake effects. Three dimensional simulations were employed because ADCP observations indicated three dimensional flow features.

Model simulations reproduced salient features of independent ADCP data collected in the model domain (Figure 7). For example, the amplitude and phase of simulated and observed alongshore current reversals were well matched with observations although at depth, simulated along shore current amplitudes were overestimated by about 0.05m/s. This difference may be due in part to the reduced vertical resolution of simulations compared to ADCP observations (i.e. 10-20m simulation vs 15-16m ADCP bin). Across shore current components throughout the water column at Site C were significantly weaker than along shore components in both simulated and observed data sets but similar across shore flow patterns were discernable in both simulated and observed cross shore flows; the model generally underestimated the amplitudes of observed cross shore variability.

Simulated vector averaged flow fields (Figure 8) were generally consistent with ADCP observations (Figures 5 and 6) with convergence of flows approaching the tip of Corambirra Point and divergent flows in the lee of the point. The shear zone located between sites A and C was clearly evident in model simulations as a 2km wide zone centered 2km offshore (Figure 8). Horizontal shear is represented in Figure 8 by the gradient of along-shelf and cross-shelf velocity components of the velocity gradients along the transect T1-T2 which is aligned with the Coffs Harbour outfall.

Numerical particles were released into the simulated flow field at various discrete locations along transect T1-T2 to investigate potential exposure and fate scenarios. Rather than presenting this compendium of individual scenario outputs we illustrate generalised particle visitations for particles released from along the entire transect; that is, transect T1-T2 was treated as a line source and subsequent particles visitations were mapped across all cells in the modeling domain (Figure 9).

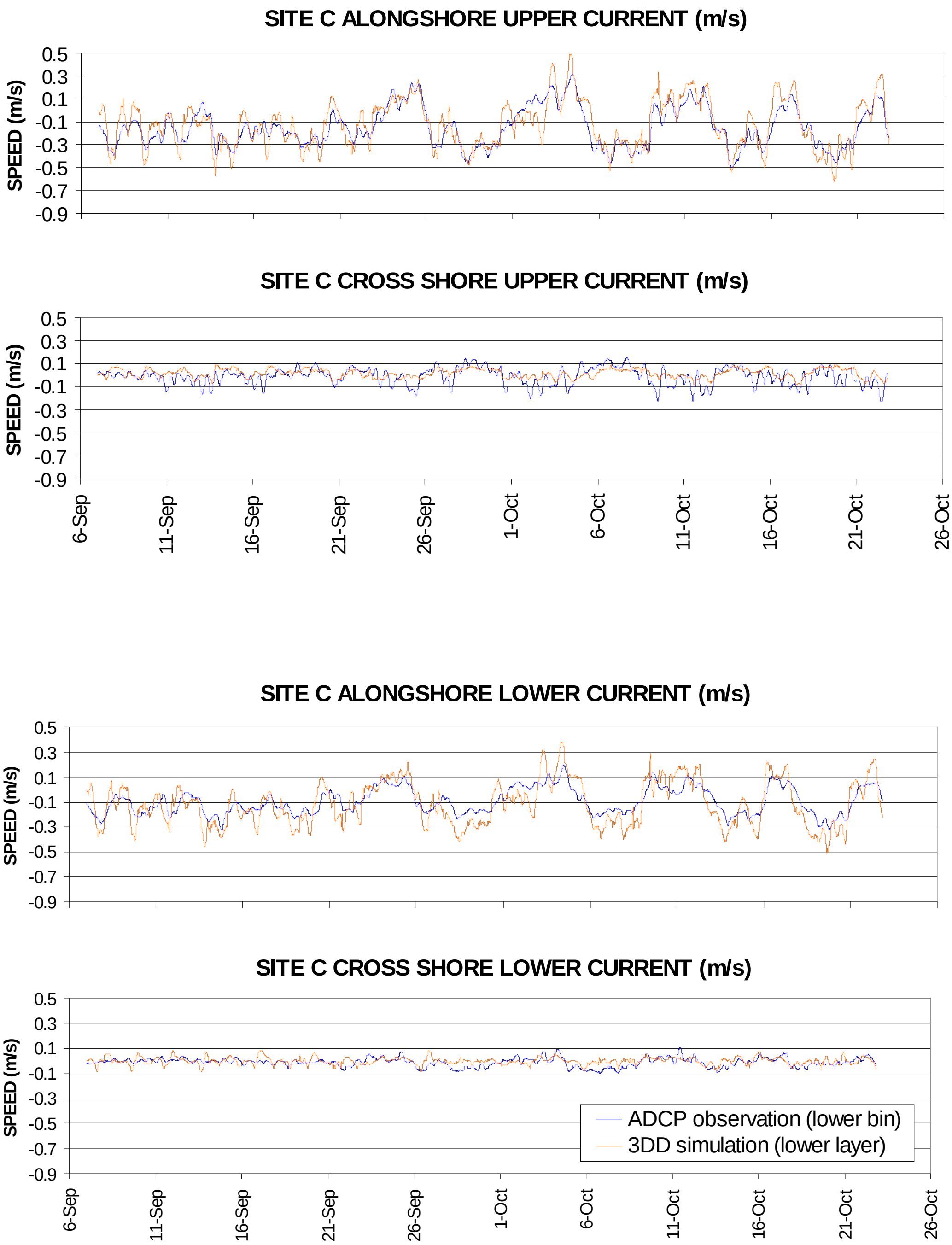
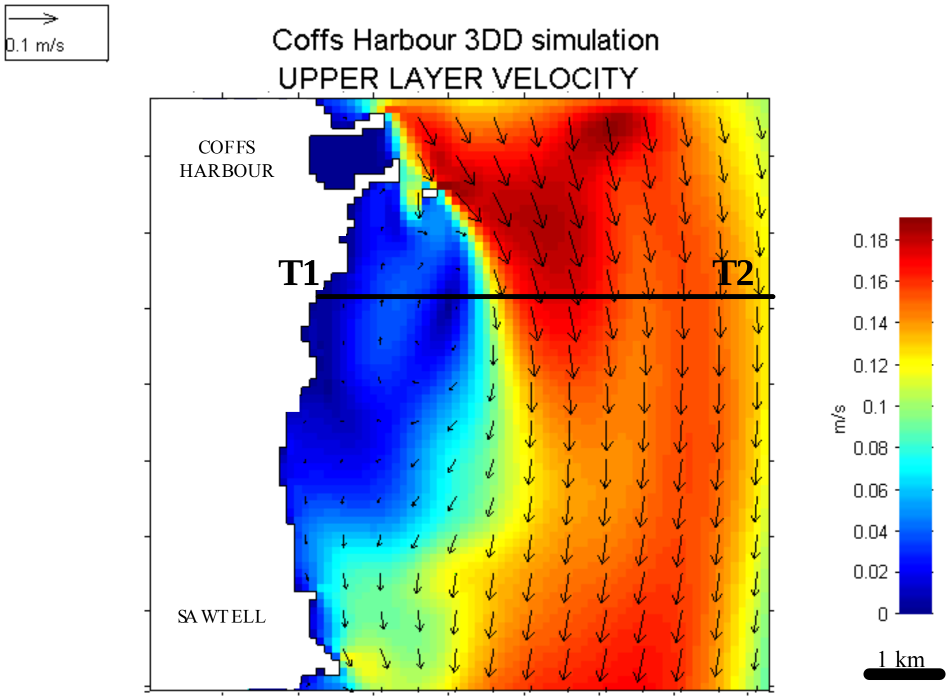
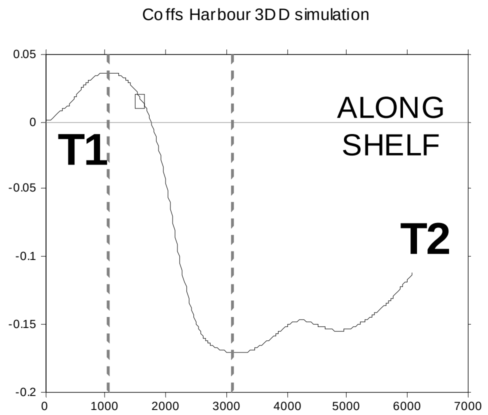


Figure 7. 3DD model simulations compared to independent ADCP observations for along shelf and cross shelf components of upper and lower currents at Site C.





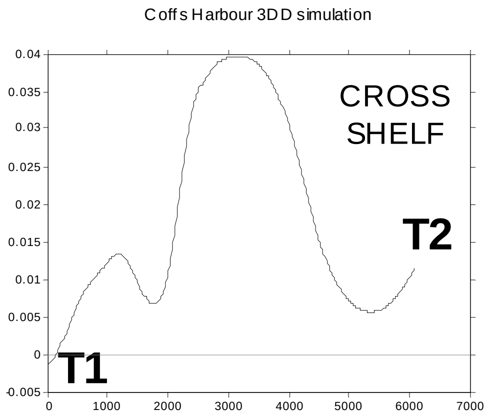


Figure 8. Vector averaged upper layer velocities based on 3DD model simulations (top) together with alongshore and cross shore vector averaged velocities across transect T1-T2 (bottom).

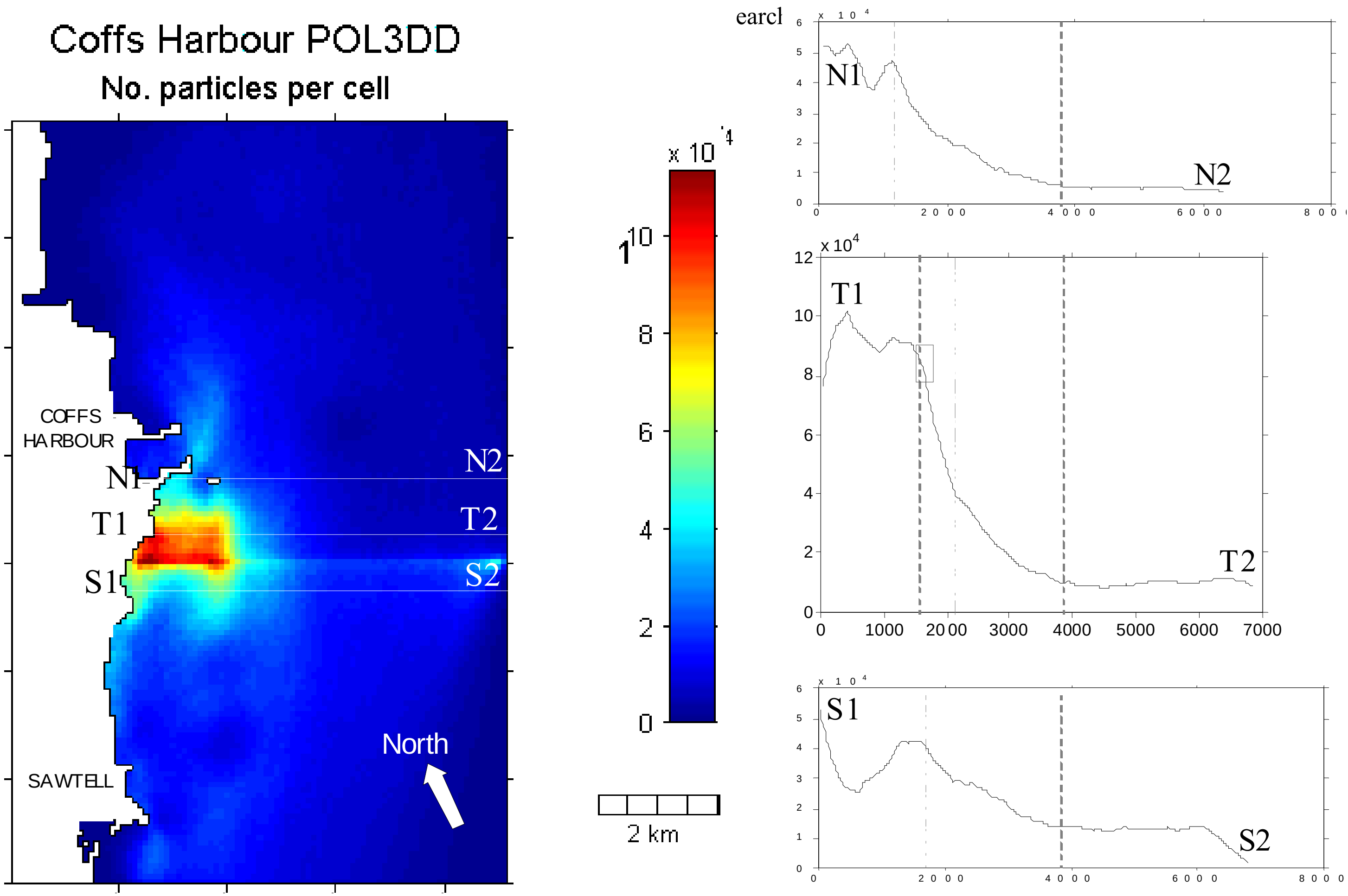


Figure 9. Total number of particle visits mapped across the modelling domain (left) and along transects N1-N2, T1-T2 and S1-S2 based on POL3DD particle tracking using conservative, neutrally buoyant particles released at every time step from a line source just south of transect T1-T2. Advection driven by the three dimensional flow field generated by model 3DD and results plotted as depth integrated total particle visits.

DISCUSSION

Headland wakes

In simple terms topographic features like headlands lead to local flow separation, formation of an intense transverse shear layer and return velocities in the lee of the feature. Ultimately re-circulation cells decay due to turbulent bottom friction or are displaced by stream flow reversals. However, the formation of headland wakes is often variable and case specific. For example, some prominent headlands rarely develop recirculation cells: Bass Point, south of Sydney (NSW, Australia) protrudes almost 4km onto the continental shelf where strong longshore currents (0.2–0.5 m s^{-1}) often exist yet large-scale recirculation is rarely observed in the lee of the headland (MIDDLETON et al., 1993).

Spectral observations off Coffs Harbour were consistent with those off Bass Point (DENNISS et al., 1995) where weatherband spectral energy dominated in the stream flow while diurnal energy dominated in the lee of the headland. However, the tendency for re-circulation south of Corambirra Point (Figure 7) differs from the broad turbulent wake observed off Bass Point. DENNISS et al. (1995) attributed this broad wake to high levels of turbulence near the tip of the Bass Point (eddy viscosity of 15 m^2 s^{-1}) which appeared to prevent the formation of a single narrow shear layer (caused by separation at the point). Instead a much wider turbulent shear layer developed off Bass Point which was not conducive to large-scale recirculation. AIKEN et al. (2002) attributed this turbulence to three sources of stochastic forcing: variability in the wind stress; variability in the flow incident on the headland; and, variability generated in the flow by complex reef topography at the headland's tip and upstream.

The offshore environment at Coffs Harbour shares some similarities, with turbulent flows associated with the complex bathymetry of Corambirra Point including Korffs Islet (Figure 1), and the Solitary Islands group to the north may increase turbulence in incident flows. These external sources of vorticity may have contributed to the turbulent wake especially in the shear zone but inertial forces appear to contribute to the formation of re-circulation cells. That is, frequent short duration (<36 hrs) opposing flows (re-circulation) appear to be associated with accelerations of flow (especially during regional flow reversals) rather than periods of sustained high shear/difference (Figures 5 and 6). This led **PRITCHARD** et al. (2001) to suggest that re-circulation may result from flow reversals when reversal occurs earlier in the wake of the headland than in the free stream where currents continue to decelerate. In this way the formation of phase eddies is governed by the inertia of the wake relative to the free stream flow.

Three dimensional flow structures were also observed with somewhat different near surface and near bed flow patterns (Figure 5 & 6) which is consistent with observations of re-circulation wake effects at Cape Rodney in northeast New Zealand where the structure of the eddy was often partitioned vertically (BLACK et al., 2005). In both cases wake effects were strongly influenced by wind.

Dispersion and advection of pollutants

Few studies have investigated pollutant trapping although experimental dye studies by CHEN et al. (2005) found significant trapping for discharge points in the recirculation zone behind a model headland due to the slower velocities.

Dilution and dispersion can be limited by re-entrainment of pollutants trapped in re-circulation cells. The propensity for re-circulation south of Corambirra Point is clearly evident in ADCP data (Figures 5 & 6) and model simulations (Figure 8). However, in this case re-circulation cells are not considered to be the most important wake effect limiting near field dilution of treated effluent discharged off Coffs Harbour because re-circulation cells occur sporadically with opposing currents at Site A and Site C persisting for periods mostly less than 10 hours and always less than 36 hours. Model simulations suggest typical re-circulation cell diameters of 2-3km in the lee of Corambirra Point (Figure 8) so for an average water depth of ~20m the volume of the re-circulation cell is four orders of magnitude greater than daily effluent discharged from the outfall.

Instead the most profound effect of the wake created by Corambirra Point is the reduced ambient current speeds. For a well designed outfall, initial mixing is fundamentally a function of the volume of ambient water available for dilution (i.e. water velocity and depth). Consequently, dilution potential varies dramatically across shear zones such as along transect T1-T2 in Figure 8, where the upper limit of initial dilution increases by a factor of up to 18 over a cross-shore distance of just 1.4km (from 1.6km to 3km along T1-T2), mostly due to increasing velocity rather than increasing depth. Given a relatively constant sea floor slope the rate at which potential dilution increases in an offshore direction is almost directly proportional to this velocity gradient. Therefore, the greatest gain per unit extension of the discharge point coincides with the greatest shear given by the greatest slope in Figure 8 at the centre of the shear zone located 2km offshore.

Slower current velocities in the lee of Corambirra Point also serve to reduce clearance times of pollutants in the coastal boundary layer shoreward of the shear zone defined in Figure 8. Wake effects due to Corambirra Point were characterised and mapped in terms of pollutant clearance by releasing numerical particles into the simulated flow field at random from along the entire length of a shore normal transect along the alignment of the Coffs Harbour outfall (adjacent to T1-T2 in Figure 9). The numbers of particle visits to each cell in the model domain were recorded for the entire simulation period and mapped in Figure 9 for upper layer cells. Numerical particles were assigned conservative and neutrally buoyant properties so it is not surprising that during the model simulation particles visited most of the model domain. Notably high numbers of particle visits were recorded within the island wake reflecting the combined effects of quiescence waters and re-circulation. Transects through this wake region (N1-N2, T1-T2 and S1-S2) indicated low relative levels of clearance (high number of visitations) within 1.5km of the coast, with wake effects detectable out to 4km offshore. Particle clearance increases (visits decreases) most rapidly between 1.5km and 2km offshore along the outfall alignment (T1-T2), generally consistent with the shear zone depicted in Figure 8.

These results are generally consistent with experimental studies by CHEN et al. (2005) which found that flushing times for dye discharged into the re-circulation zone were very much greater than for the main current.

Results clearly indicate that the greatest scope to increase offshore outfall performance (dilution and dispersion) results from offshore extension of the outfall within the interval from 1.5km to 2.5km along transect T1-T2. In this case, the Coffs Harbour line diffuser outfall was located 1.5km offshore (indicated by the open rectangle on T1-T2 in Figure 9), based on a range of factors including existing commitments to high levels of treatment prior to discharge and economic considerations.

Coastal Boundary Layer Effects

Headland wake effects are just one expression of the coastal boundary layer which is the transition zone between the shoreline and the open ocean. Turbulence, shear zones and frontal features develop near the coast due to a range of interactions with inner shelf bathymetry, irregular coastlines and estuarine outflows. Headland wakes generally operate over length scales of hundreds to thousands of metres but major changes in coastline/shelf orientation can result in coastal boundary layer effects that are orders magnitude greater than this, such the large cold core eddy (~60km diameter) observed by LEE et al. (2001) in the lee of Port Stephens some 250km south of Coffs Harbour.

Anthropogenic pollutant loadings typically enter the ocean via the coastal boundary layer and these coastal waters are highly valued by the rapidly increasing coastal populations. Clearly, the hydrodynamic characteristics of the coastal boundary layer are critical in determining the fates and impacts of pollutants. This paper has illustrated a common characteristic of coastal boundary layers; that is, long residence times relative to offshore regional flows due to flow retardation, re-circulation and zones of convergence as a function of the local coastal topography and variable coastal bathymetry.

However, the implications of boundary layer formation extend far beyond the dispersion of sewerage effluent. Regions of enhanced relative vorticity, like headland wakes, may aggregate prey and represent important foraging habitat for predators like cetaceans (JOHNSTON et al (2005). Wake induced upwelling and plankton retention can result in high productivity (e.g. ROUGHAN et al. 2005). Even in the absence of a well-defined eddy biological distributions can be affected by headland wakes; for example, RANKIN et al. (1994) found that juvenile Gem clams were deposited just inside the wake perimeter, where shear velocities decreased to levels below critical erosion velocities of the clams. Re-circulation can also shape the benthic environment of infauna and epibiota by driving sand circulation such as that observed between sandbanks and headlands by BERTHOT and PATTIARATCHI (2006).

CONCLUSION

Three dimensional characteristics of the coastal boundary layer off Coffs Harbour, especially flow retardation and re-circulation, have been revealed by direct observations and model simulation. Significant gains in initial dilution and dispersion of pollutants can be made across shear zones associated with headland wakes. A comprehensive assessment of sewerage management options should therefore consider the benefits of increased dilution against the incremental costs of extending the outfall across significant shear zones.

ACKNOWLEDGEMENTS

This study was supported by the New South Wales Department of Environment and Conservation (including the NSW Environment Protection Authority) especially Dr Klaus Koop. The authors gratefully acknowledge mainly field assistance from Paul Watts, EPA Water Science staff especially Tim Ingleton and staff from the Solitary Islands Marine Park Authority.

REFERENCES

AIKEN C.M.; MOORE A.M. and MIDDLETON J.H (2002) The non normality of coastal ocean flows around obstacles, and their response to stochastic forcing. Journal of Physical Oceanography 32 (10): 2955-2974.

BERTHOT, A. and PATTIARATCHI, C. (2006) Field measurements of the three-dimensional current structure in the vicinity of a headland-associated linear sandbank. Continental Shelf Research 26, 295–317.

BLACK, K.P. (1995) The hydronamic model 3DD and support software. Occasional Report No.19, Department of Earth Sciences, Uni.Waikato. 53pp.

BLACK, K. P. (1989) Numerical simulation of steady and unsteady meso-scale eddies. Proceedings of the 9th Australasian Conference on Coastal and Ocean Engineering, Adelaide. pp. 204–208.

BLACK K.; OLDMAN J and HUME T (2005) Dynamics of a 3-dimensional, baroclinic, headland eddy. New Zealand Journal of Marine and Freshwater Research 39 (1), 91-120.

BLACK, K. P.; HATTON, D. and ROSENBERG, M. (1993) Locally and externally-driven dynamics of a large semi-enclosed bay in southern Australia. Journal of Coastal Research 9(2): 509–538.

BLACK, K. P.; HEALY, T.R. and HUNTER, M. (1989) Sediment dynamics in the lower section of a mixed sand and shell-lagged tidal estuary. Journal of Coastal Research 5(3), 503–521.

BLACK, K. P. and GAY, S. L. (1987) Eddy formation in unsteady flows. Journal of Geophysical Research, 92: 9514–9522.

CHEIS (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coffs Harbour City Council, NSW, Australia.

CHEN D.Y.; TANG F.E. and CHEN, C.Q. (2005) Pollutant trapping at a coastal headland. Journal of Waterway Port Coastal and Ocean Engineering-ASCE 131 (3): 98-114

CHURCH, J. A.; FREELAND, H. J. and SMITH, R. L. (1986) Coastal trapped waves on the east Australian continental shelf. Part I: propagation of modes. Journal of Physical Oceanography 6, 1929-1943.

DENNISS, T.; MIDDLETON, J.H. and MANASSEH, R. (1995), Recirculation in the lee of complicated headlands: A case study of Bass Point, J. Geophys. Res., 100(C8), 16,087–16,102.

FARMER, D.; PAWLOWICZ, R. and JIANG, R. (2002) Tilting separation flows: a mechanism for intense vertical mixing in the coastal ocean. Dynamics of Atmospheres and Oceans, 36, 43–58

FREELAND H.J.; BOLAND F.M.; CHURCH J.A.; CLARKE A.J.; FORBES A.M.G.; HUYER A.; SMITH R.L.; THOMPSON R. and WHITE N.J. (1986) The Australian Coastal Experiment – a search for coastal trapped waves. Journal of Physical Oceanography 16 (7): 1230-1249.

FURUKAWA, K. and WOLANSKI, E. (1998) Shallow water frictional effects in island wakes. Estuarine, Coastal and Shelf Science 31: 231–253.

GOODWIN, I.D.; STABLES, M.A. AND OLLEY, J.M. (2006) Wave climate, sand budget and shoreline alignment evolution of the Iluka–Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. Marine Geology 226 (2006) 127– 144.

GRIFFIN, D.A. and MIDDLETON, J.H. (1992) Upwelling and internal tides over the inner New South Wales continental shelf. Journal of Geophysical Research 97(C9), 14389-14405.

HARRIOTT, V. J.; SMITH, S.D.A. and HARRISON, P. (1994) Patterns of coral community structure of subtropical reefs in the Solitary Islands Marine Reserve, Eastern Australia. Marine Ecology Progress Series 109, 67-76.

HUME, T.M.; OLDMAN, J.W. AND BLACK, K.P. (2000) Sediment facies and pathways of sand transport about a large deep water headland, Cape Rodney, New Zealand. New Zealand Journal of Marine and Freshwater Research 34: 695–717.

HARRIS, P.T.; BAKER, E.K. and COLE, A.R. (1991) Physical Sedimentology of the Australian Continental Shelf. Ocean Sciences Institute Report No. 51, University of Sydney, Sydney.

JOHNSTON, D.W.; WESTGATE, A.J. and READ. A.J. (2005) Effects of fine-scale oceanographic features on the distribution and movements of harbour porpoises Phocoena in the Bay of Fundy. Marine Ecology-Progress Series 295: 279-293

LEE, R.S.; AJANI, P.A.; WALLACE, S.; **PRITCHARD**, T.R. and BLACK, K.P. (2001). Anomalous Upwelling along Australia's East Coast. Journal of Coastal Research, 34, 87-95.

MIDDLETON, J.H. (1995) The oceanography of Australian seas. In Leon P. Zann, State of the Marine Environment Report for Australia: The Marine Environment - Technical Annex: 1.

MIDDLETON, J.F. and BLACK, K.P. (1994) The low frequency circulation in and around Bass Strait: a numerical study. Continental Shelf Research 14 (13/14): 1495–1521.

MIDDLETON, J.H.; GRIFFIN, D.A. and MOORE, A.M. (1993) Oceanic circulation and turbulence in the coastal zone. Continental Shelf Research, 13 (2-3): 143-168.

PRITCHARD, T.R., LEE, R.S., INGLETON, T.C. and BLACK, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour, Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institution of Engineers, Australia.

RANKIN, K.L.; MILLINEAUX, L.S. and GEYER, W.R. (1994) Transport of Juvenile Gem Clams (Gemma) in a Headland Wake. Estuaries, 17, (3), 655-667.

ROUGHAN, M.; MACE, A.J.; LARGIER, J.L.; MORGAN, S.G.; FISHER, J.L. and CARTER, M.L. (2005) Subsurface recirculation and larval retention in the lee of a small headland: A variation on the upwelling shadow theme. Journal of Geophysical Research, 110.

ROUGHAN, M. and MIDDLETON, J.H., (2004). On the East Australia Current: variability, encroachment, and upwelling. J. Geophys. Res. 109, C07003.

ROY, P.S. and THOM, B.G. (1981) Late Quaternary marine deposition in New South Wales and southern Queensland: an evolutionary model. Journal of the Geological Society of Australia, 28, 471-489.

SIGNELL, R. P. and GEYER, W. R. (1991) Transient eddy formation around headlands. Journal of Geophysical Research 96(C2): 2561–2575.

SMITH, S.D.A. (1996) The Effects of Domestic Sewage Effluent on Marine Communities at Coffs Harbour, New South Wales, Australia. Marine Pollution Bulletin, Vol. 33 (7-12), pp. 309-316.

SMITH, S.D.A. and SIMPSON, R.D. (1993) The effects of pollution on the holdfast macrofauna of the kelp Ecklonia radiata: discrimination at different taxonomic levels. Marine Ecology Progress Series 96, 199-208.

STANSBY, P.K. (2006) Limitations of Depth-Averaged Modelling for Shallow Wakes J. Hydr. Engrg., 132 (7), 737-740.

WOLANSKI, E.; ASAEDA, T.; TANAKA, A. and DELEERSNIJDER, E. (1996) 3-Dimensional island wakes in the field, laboratory experiments and numerical models. Continental Shelf Research 16(11): 1437–1452.

WOLANSKI, E.; IMBERGER, J. and HERON, M. L. (1984) Island wakes in shallow coastal waters. Journal of Geophysical Research 89(C6): 10,553–10, 569.

YOUNG, I.R.; BLACK, K.P. and HERON, M.L. (1994) Circulation in the Ribbon Reef Region of the Great Barrier Reef. Continental Shelf Research.

8.5 Summary and Outcomes

8.5.1 Scientific Findings: coastal boundary layer formation

Direct observations and model simulation revealed the attributes of the headland wake and the importance of morphology in controlling the dispersion and fate of pollutants discharged in to the coastal boundary layer off Coffs Harbour.

Key findings include:

- Coastal boundary layer effects include flow retardation and re-circulation.
- Current meter data revealed surface divergence between mainstream and the coast in the lee of Coffs Harbour. Net bottom water displacements also indicate a predisposition for cyclonic eddy recirculation in the lee of Corambirra Point (Sites A, B and C) and shore parallel flow along isobaths at offshore Site D.
- Simulations confirm a propensity for short duration (<36hrs) re-circulation cells south of Corambirra Point with typical re-circulation cell diameters of 2-3km.
- Clearance increases (simulated particle visits decreases) most rapidly in the interval 1.5km to 2km offshore from Boambee Beach (along the outfall alignment).
- Recirculation may result from flow reversals when reversal occurs earlier in the wake of the headland than in the free stream where currents continue to decelerate; that is, the formation of phase eddies is governed by the inertia of the wake relative to the free stream flow.
- But the most profound wake effect is a persistent shear zone located 2km offshore from Boambee Beach created by Corambirra Point.
- Inshore currents (Site A) exhibits energy levels across the spectrum that are significantly lower than all other sites indicating quiescent wake effects; observed current strengths at Site A were 2-3 times less than those at sites further offshore.
- Observed along-shore flow ‘events' lasted on average less than a day (17hrs) inshore at Site A while comparable ‘events’ persisted for an average of 3.5 days offshore at Site (C).

- Observed alongshore components of near surface currents and winds were well correlated (r^2 ~ 0.65) with the currents typically corresponding to about 1% of the wind speed at the inshore Site A and 2-3% of the wind speed at the offshore Site C.
- Variance preserving spectra for the four ADCP sites show prominent peaks at ~12 and ~24 hours, highlighting the relative contribution of the semi-diurnal tides, inertial motions and local land-sea breezes. Strong peaks evident at 2.5, 3.9 and 7.8 days are associated with the regional weather band.
- The vertical distribution of diurnal energy suggests that in the pycnocline layer may act as a waveguide, trapping energy entering from above and below.
- The study period may include a greater proportion of wind driven southward currents than would be expected based on long term wind data. Long-term wind data suggested a tendency for wind driven currents to be northward (53%) at least as often as southward currents in the study region; winds were northward ~35% of the study duration.

8.5.2 Management Findings: outfall optimisation options

There is significant scope to increase offshore outfall performance (dilution and dispersion) by extending the outfall across the interval from 1.5km to 2.5km offshore. Note that the initial preferred outfall location was 1.5km from shore (CHEIS, 2000).

Key findings include:

- The greatest gain per unit extension of the proposed discharge point coincides with the centre of the shear zone located ~2km offshore along the prescribed alignment of the outfall.
- The upper limit of initial dilution increases by up to 18 x over a cross-shore distance of just 1.4km (from 1.6km to 3km along outfall alignment).
- Along-shore currents reverse in direction more frequently at the inshore Site A compared to the offshore Site C, thus increasing the likelihood of re-entrainment of diluted effluent into plumes.

- However, recirculation cells are not considered to be the most important wake effect limiting dilution of effluent discharged off Coffs Harbour because re-circulation cells occur sporadically and the re-circulation cell volume (2-3km dia x 20m) is typically four orders of magnitude greater than daily effluent discharged from the outfall.
- A comprehensive assessment of sewerage management options should therefore follow consideration of the benefits of increased dilution against the incremental costs of extending the outfall across significant shear zones.

An indicative benefit-cost curve for outfalls located across the shear zones is shown in Figure 8A. The Indicative Benefit-Cost is expressed as a ratio of current strength to relative cost: averaged alongshore current speed is proportional to volume of water potentially available to mix with and disperse effluent; and, ‘relative cost’ is the outfall construction cost interpolated from engineering cost estimates provided by CHCC (pers comm., 2001) for outfalls extending to 1500m, 2500m and 3500m.

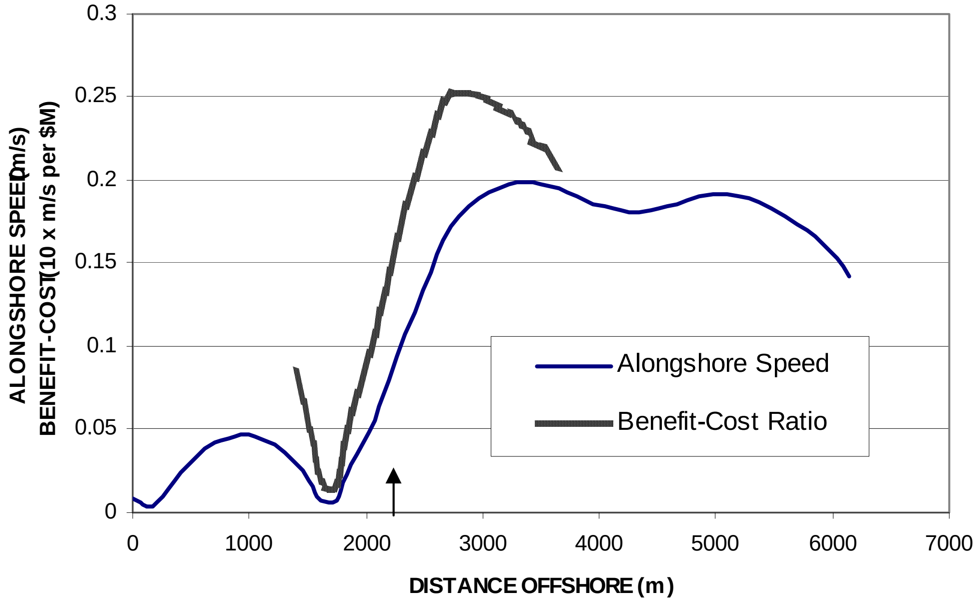


Figure 8A: Indicative Benefit-Cost based expressed as a ratio of current strength to relative cost. Incident averaged current speed is plotted and the arrow indicates the Outfall location.

Outfall construction cost estimates increased almost linearly with distance offshore. Detailed cost breakdowns were not provided although the almost constant cost per unit outfall length for all distances offshore suggests that initiation costs (mobilization including costs for construction of a temporary jetty) were insignificant compared to the incremental cost of extending the outfall. Other construction scenarios/locations may result in non-linear cost curves, especially if alternatives are considered earlier in the planning process. If the cost curve were flatter across the shear zone (i.e. if initiation costs were large compared to the incremental cost for extending the outfall) there would be an even greater incentive to extend the outfall beyond the shear zone.

In this case the management option to increase the length of the outfall was not selected possibly due to the inflexibility of funding and relatively high levels of treatment prior to release: a new outfall was commissioned about 1.5 km from shore in early 2005.

8.6 References

CHEIS (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coff Harbour City Council, NSW, Australia.

Pritchard, T.R., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

9 COASTAL BOUNDARY LAYER DYNAMICS AND POTENTIAL IMPACTS

9.1 Introduction

The purpose of this chapter is to explore and evaluate the Coastal Boundary Layer (CBL) classification first proposed in Chapter 4 (Figure 9.1) by considering evidence mostly in the form of case studies. It attempts to examine and illustrate how coastal and shelf morphologies interact with regional and local currents to shape Coastal Boundary Layer (CBL) processes, which in turn drive pollutant dispersion and determine potential environmental impacts.

In doing so this chapter brings together the findings from previous chapters, with particular emphasis on near-shore NSW waters which receive the bulk of NSW pollutants, and where CBL processes are mostly shaped by coastal irregularities. The morphological classification of headlands, bays and islands proposed in Chapter 7 provides an opportunity to develop a predictive risk-based framework for assessing potential pollutant impacts in various morphological settings.

This chapter also seeks to establish the link between coastal boundary layer processes and the distributions of the biological species and communities that are impacted by pollutants which are released in to the CBL. Finally, management implications are discussed and developed, illustrating the ways in which a process based understanding of the coastal boundary layer can deliver better and/or more efficient environmental outcomes.

9.1.2 Morphological Settings and Regional Circulation

In NSW pollutants typically originate from coastal catchments and are discharged to the coastal boundary layer via regulated outfalls and un-regulated flows, mostly through estuaries, as discussed Chapter 2. The dispersive characteristics vary across the Coastal Boundary Layer (CBL) due to the configuration of the continental shelf, including nearshore morphologies and irregularities in the coastline which until now have not previously been considered in a systematic manner.

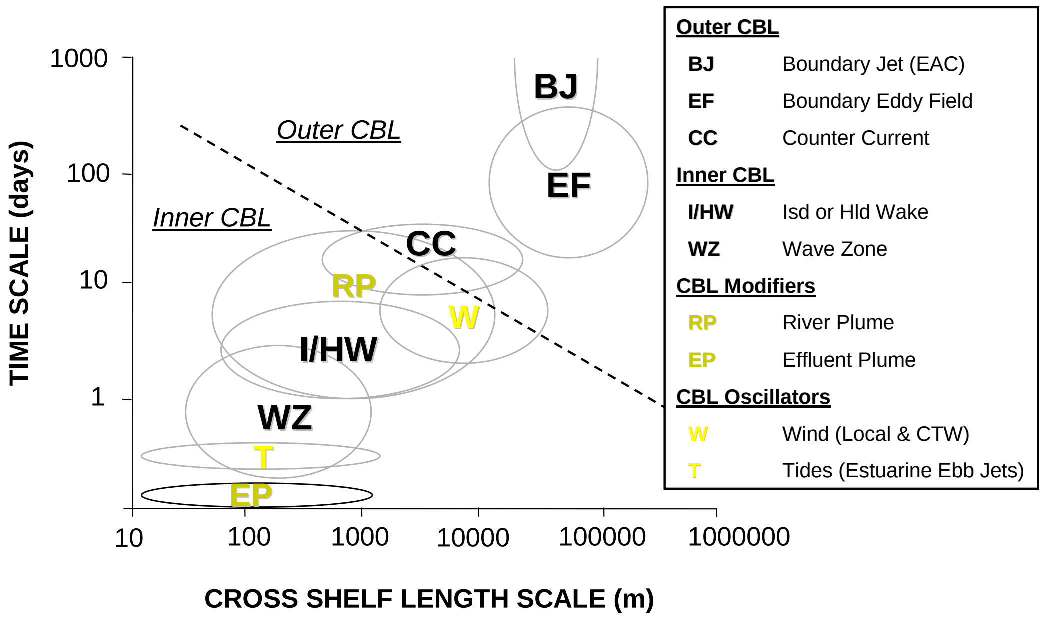


Figure 9.1 Schematic representations of the temporal and spatial scales of coastal boundary layer effects in NSW offshore waters. *CBL Modifiers* introduce density gradients (and are major pollutant vectors) while *CBL Oscillators* introduce vorticity. Ellipses represent indicative ranges of cross-shelf extents and dominant temporal expression (energy) based on data presented in this thesis, including referenced material and remote sensed imagery discussed in **Pritchard** & Koop (2005). This figure was first presented and discussed in Chapter 4.

The NSW coastal and shelf morphology is the product of past and present forces acting on its geology, including repeated fluctuations of sea level, as discussed in Chapter 7. Here coastal and shelf morphology are discussed in relation to *Outer* and *Inner Coastal Boundary Layer* processes, as described in Chapter 4.

Outer CBL processes are profoundly affected by the morphology and orientation of the continental shelf. Cross-shelf widths and slopes vary with latitude as shown in Figure 9.2, which is derived from the mapping exercise reported in Chapter 7.

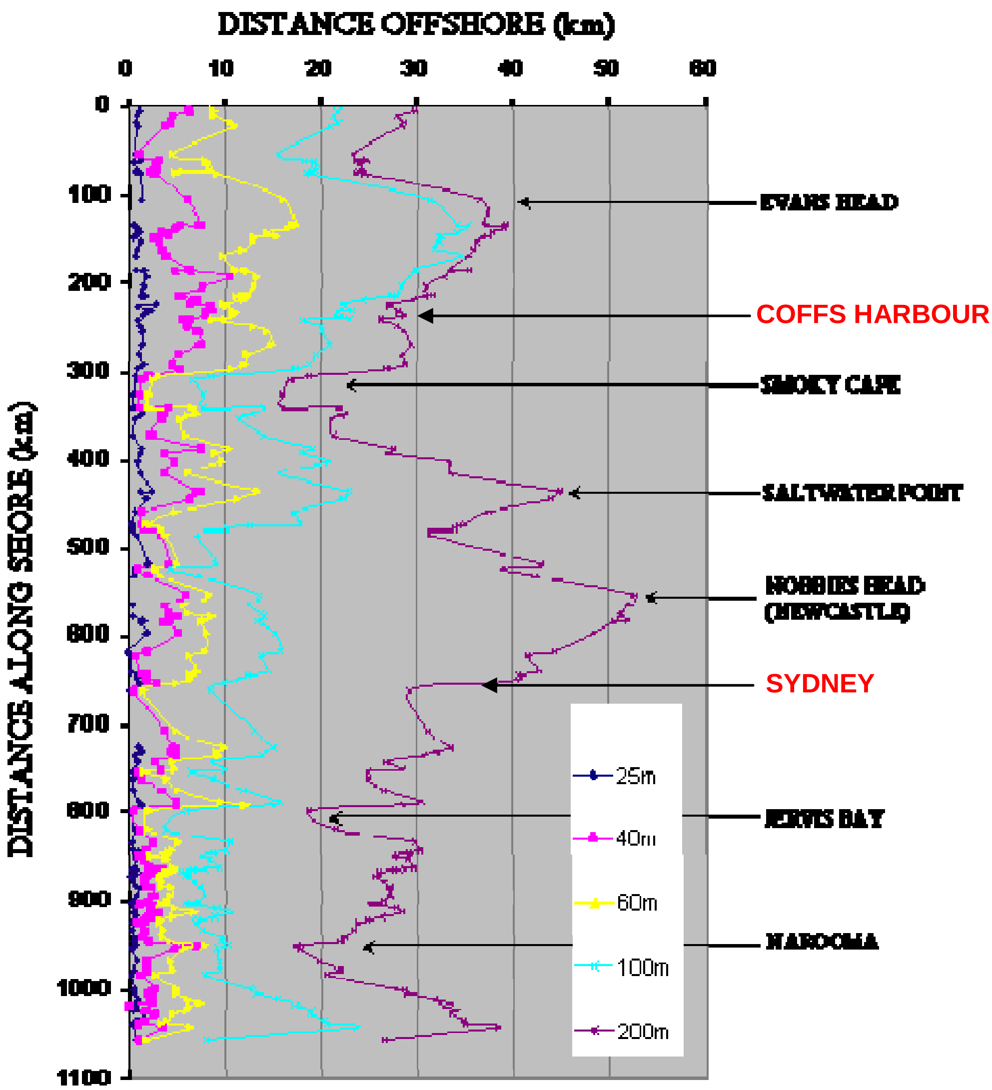


Figure 9.2 Continental shelf profile (cross shelf distance to isobaths) at each NSW headland location illustrating variability of shelf width and inner shelf profile with distance south from the NSW-Queensland border (28°10'S) to the NSW-Victorian border (37°30'S).

The structural complexity and orientation of the continental shelf exerts a profound influence on ***Outer Coastal Boundary Layer*** dynamics, especially through its interactions with the East Australian Current. The cross shelf profile of the continental shelf varies as illustrated by Figure 9.3. The local importance of narrowing of the continental shelf off Laurieton, just south of Smokey Cape, was first recognised by Rochford (1975) when he attempted to explain observations of upwelling in this region. Oke and Middleton (2000, 2001) later revealed how alongshore topographic variations near Laurieton caused local acceleration of the EAC over the narrowing continental shelf, with consequent bottom boundary layer dynamics uplifting nutrient rich slope water onto the shelf. Over a zone from

31ºS to 33 ºS, immediately south of Smokey Cape where the shelf is at its narrowest (~15 km), most of the current separates from the coast forming the Tasman Front, which trends eastward (Ridgway and Dunn, 2003).

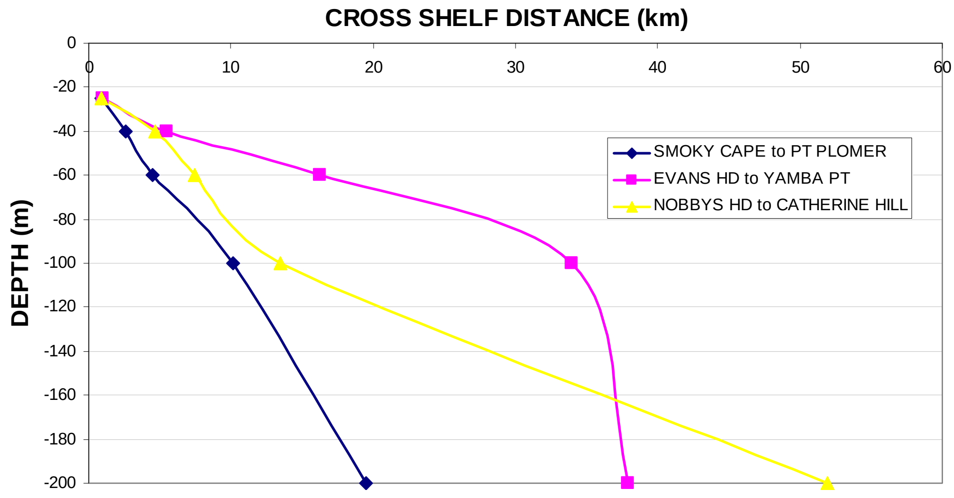


Figure 9.3 Range of cross-shelf profiles illustrating the steep sloping, narrow shelf off Smoky Cape in blue (similar to Jervis Bay and Narooma); the shallow sloping inner and mid shelf regions off Evans Head in magenta; and the broad, low gradient extension of the outer shelf off Newcastle in yellow.

Further north, topographic irregularities associated with mainland Australia's most eastern protrusion, Cape Byron, were also found to promote upwelling immediately south, off Evans Head, through the mechanism proposed by Oke and Middleton (2001). Much further south, prominent topographic features such as the rotation of the coastline near Port Stephens and the protrusion of Jervis Bay onto the continental shelf have also been associated with high frequencies of upwelling (Lee et al., 2007); that is, higher frequencies of anomalously cool, bottom water derived from the continental slope were observed immediately south (downstream of average EAC flow) of these changes of up to 50º in the orientation of shelf and shoreline. The narrow, steeply sloping, cross-shelf profile off Jervis Bay is similar to that of Smokey Cape (shown in Figure 9.3). The dynamics and biological significance of complex interactions of EAC eddies with the continental shelf are currently the target of challenging research led by the Sydney Institute of Marine Sciences using facilities provided by the Integrated Marine Observing System (IMOS), including autonomous gliders, remote sensed ocean colour and various onboard observations from Australia's marine research vessel, the Southern Surveyor (Suthers et al., 2010).

Together, these topographic induced upwellings explain much of the observed spatial variability of primary productivity in NSW coastal waters as seen in ocean colour satellite data (Figure 5.3 in Chapter 5, and Figure 9.4). Similar topographically induced CBL effects also provide insights into ecosystems dynamics operating in other areas affected by western boundary currents such as the Gulf Stream, the Kuroshio Current, the Brazil Current and the Agulhas Current, where alongshore topographic irregularities exist.

The entire NSW continental shelf is relatively narrow so steeply shelving inner shelf profiles, such as off Sydney (660 km south of the NSW-Queensland border in Figure 9.2), provide good opportunities for rapid mixing of pollutants relatively near to shore (**Pritchard** et al., 2001).

At both small and large spatial scales the roughness and configuration of the shoreline/shelf appear to result in similar flow patterns, as illustrated in Figure 9.4.

The 'roughness' of the coastline and the extreme complexity of near shore morphology exerts a profound influence on often highly variable ***Inner Coastal Boundary Layer*** dynamics. Natural headlands, bays, islands and shoals together with man-made rock walls, trained estuary mouths and harbors contribute to coastal 'roughness'.

Various environmental assessments have been conducted in relation to pollutants discharged to the *Inner CBL*, as required by NSW legislation (e.g. POEO, 1997). The morphological classification of NSW headlands, bays and islands proposed in Chapter 7 and the summary of previous studies provided in the NSW Ocean Outfall Inventory (Appendix 4 - attached DVD) describe the morphological setting for each of the licensed sewage discharges to NSW coastal waters. By applying this classification, simple morphological characteristics have been quantified along the entire NSW coastline. This can be used for environmental risk assessments of both controlled pollutant releases to the CBL via ocean outfalls and sporadic releases to the CBL via estuaries from diffuse pollutant sources in coastal catchments.

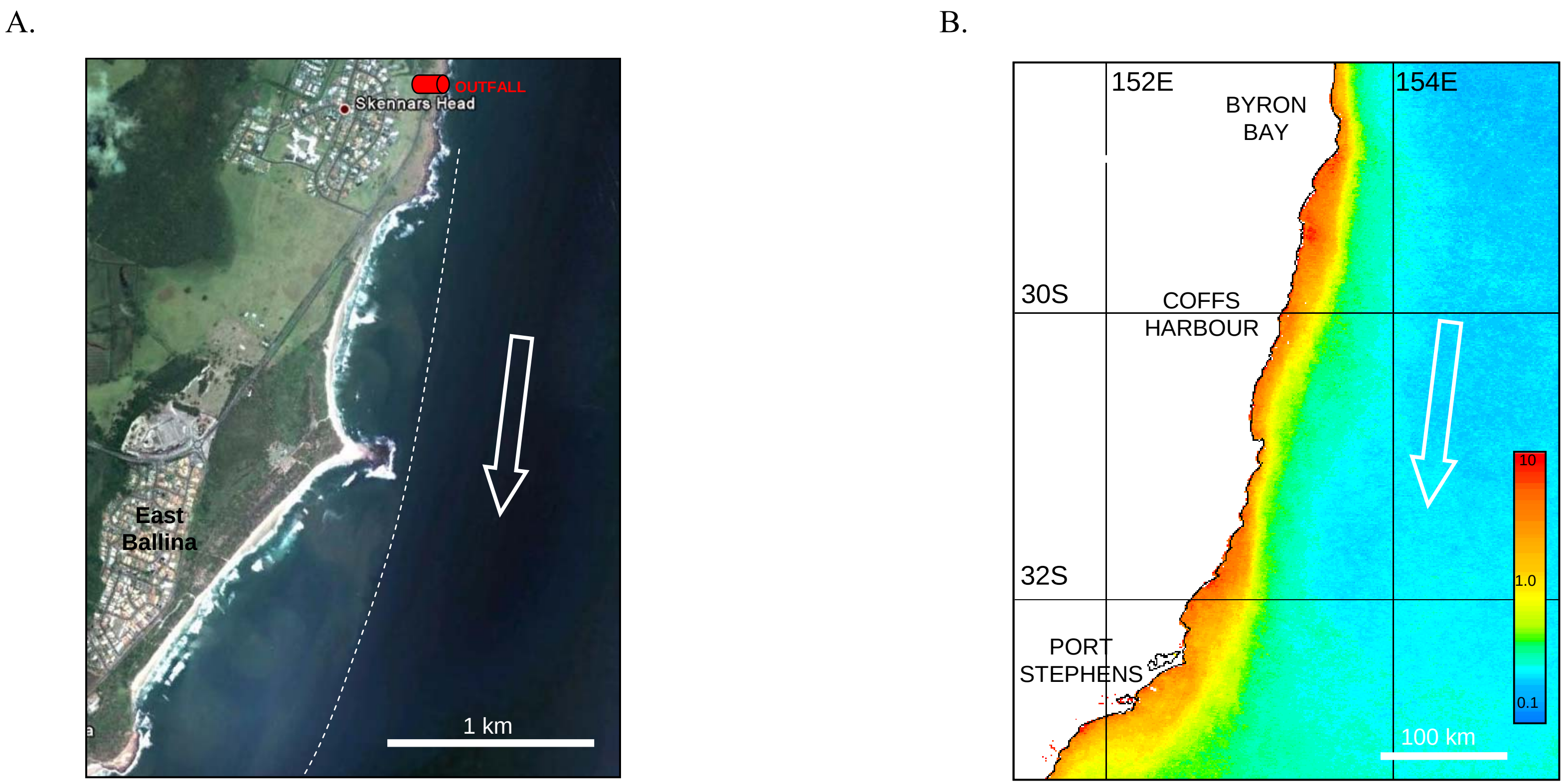


Figure 9.4. A: *Inner CBL* features which appear to be bounded by headlands under the influence of a shore parallel free flow (sediment from the Richmond River acts as a tracer). Wake effects appear at approximately the same spatial scale as the headland length with expansion associated with clockwise southward rotation of coastline orientation. Cresswell et al.(1983) noted the presence of weak clockwise cells in embayments of northern New South Wales. [GoogleEarth: Data SIO, NOAA, Us Nay, NGA, GEBCO. Image 20011GeoEye, SPOT IMAGE]. B: *Outer CBL* features illustrated by SeaWiFS ocean colour derived estimates of ninetieth percentile relative cholorophyll_a (µg/L) for summer seasons from 1998-2003.

This thesis presented two major case studies of pollutant discharges to the *Inner CBL* off Coffs Harbour (Chapter 8), and to the *Outer CBL* off Sydney (Chapter 6), as shown schematically in relation to *Coastal Boundary Layer* features in Figure 9.5. The CBL classification motivates consideration of *Headland Wakes* and *Wave Zone* effects for Coffs Harbour and consideration of regional oceanographic drivers for Sydney. Another significant difference between the settings of the two case studies is that Sydney lies south of the EAC separation point, in the *EAC Eddy Field*.

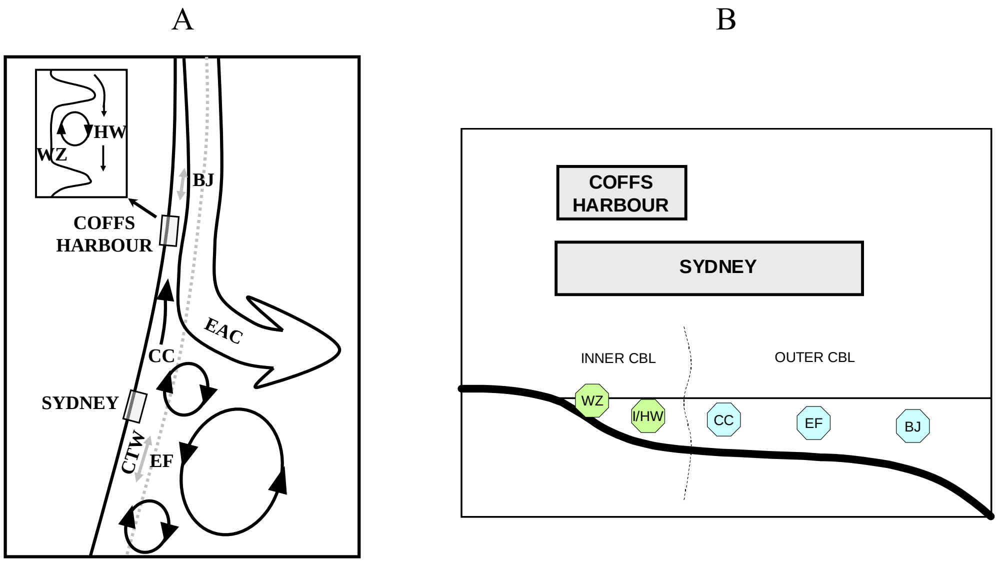


Figure 9.5 Schematic locations of two major case studies – Sydney (Chapter 5) and Coffs Harbour (Chapter 6) - in relation to configuration of major coastal boundary layer types of New South Wales proposed in Chapter 4. [WZ=Wave Zone; HW=Headland Wake; CC=Counter Current; EF=Effluent Field; BJ=Boundary Jet; EAC=East Australian Current; CTW=Coastal Trapped Waves]

The broad morphological settings of the two case studies are illustrated in Figure 9.6. Although the continental shelf width (to 200m isobath) is comparable at both case study sites and consistent with average shelf widths along this part of the coast (Figure 9.2), the inner- and mid- shelf slopes are very different corresponding to extremes illustrated in Figure 9.3. The inner shelf off Sydney is about twice as steep as that off Coffs Habour: the 110m isobath is 11-12 km from shore off Sydney while the more gently sloping shelf off Coffs Harbour reaches the 110m isobath some 25 km from shore.

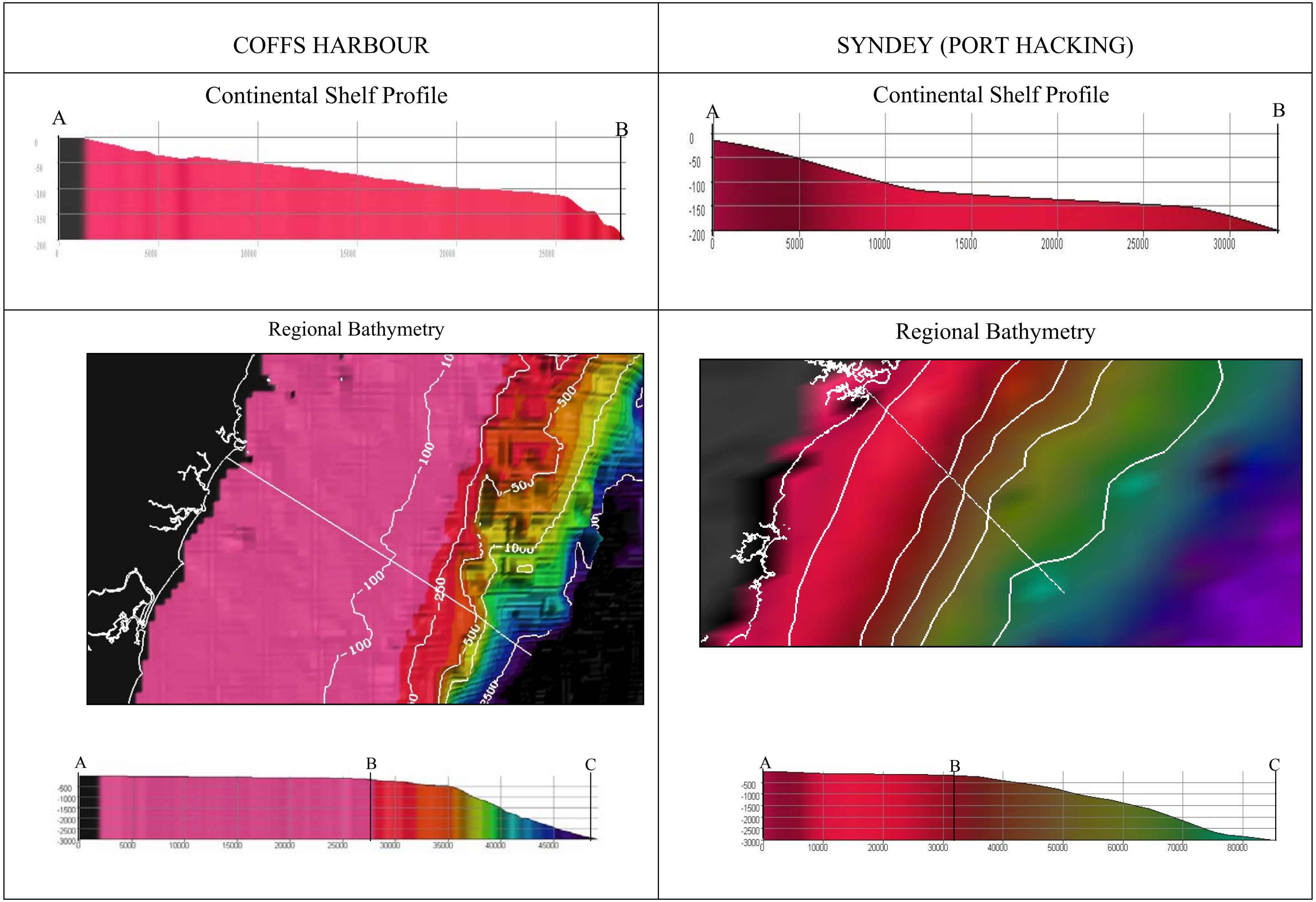


Figure 9.6 Coffs Harbour and Sydney continental shelf and slope morphologies (depths in metres). Source data: Jordan et al., 2010

9.2 Outer CBL

9.2.1 Outer CBL Dispersal Processes

The *Outer CBL* establishes the outer boundary conditions for the *Inner CBL* and affects pollutants discharged directly in to the *Outer CBL*. Here we consider the way that coastal morphologies and various *Outer CBL* processes shape flows.

Two new data streams from offshore Sydney have been established by the Integrated Marine Observing System (IMOS) since the analysis of long-term current and temperature data collected at the Sydney Ocean Reference Station (ORS), presented in Chapter 6 and **Pritchard** et al. (2005). Together with the ORS, they deliver observations of currents and temperatures along a cross shelf IMOS transect which now constitutes a National Reference Station (Figure 9.7).

Currents generally increase with distance from shore (Figure 9.8A) and with distance from the sea floor (Figure 9.8B) due to the effects of coastal roughness and frictional drag on the sea floor, respectively. However, the increase of current speed with distance from shore is restricted in extent (mostly to nearshore *Inner CBL*) and non-linear, especially where *Inner CBL* features like wakes result in discrete, small-scale, spatial heterogeneity. The non-linear increase in flow with distance from a lateral boundary has been generalised and expressed by relationships such as the Law of the Wall (Karman, 1931) which describes the average (alongshore) velocity of a turbulent flow as a function of the logarithm of the distance from the wall. This relationship applies to parts of the flow that are close to the wall and is valid for flows at high Reynolds numbers (ie when inertia dominates over friction). This Law of the Wall has been useful for some coastal investigations* although application of the Law to characterise the roughness of the coastlines is likely to be confounded by frictional effects associated with shallow seafloors sloping upwards towards coast. Furthermore, in NSW there is a scarcity of appropriate validation data.

** Lefebvre et al. (2010) applied the Law of the Wall to characterise variable roughness length scales of the seabed ('wall') in relation to log-linear gradients of the velocity above the seabed in a tidal inlet.*

A. Coffs Harbour **B**. Sydney IMOS

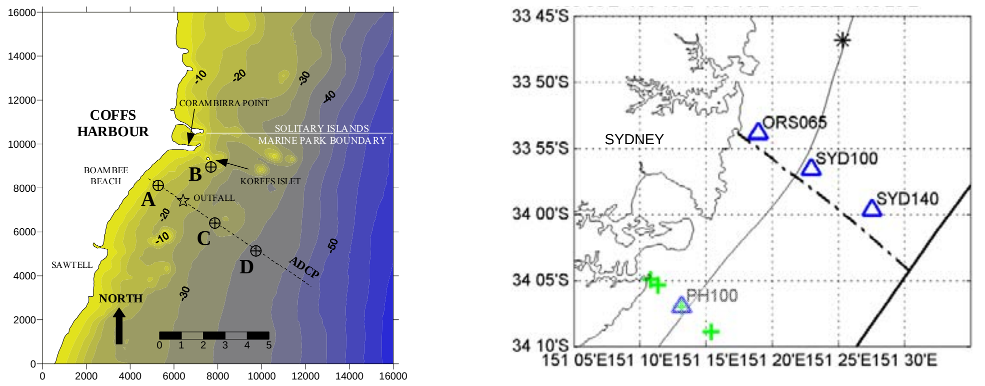


Figure 9.7 Location of current meter deployments at **A**: Coffs Harbour (from Chapter 8), and, **B**: Sydney IMOS moorings at ORS065, SYD100 and SYD140. Note that IMOS monitoring stations off Port Hacking (PH100) do not include current meter deployments.

A. Coffs Harbour **B**. Sydney IMOS

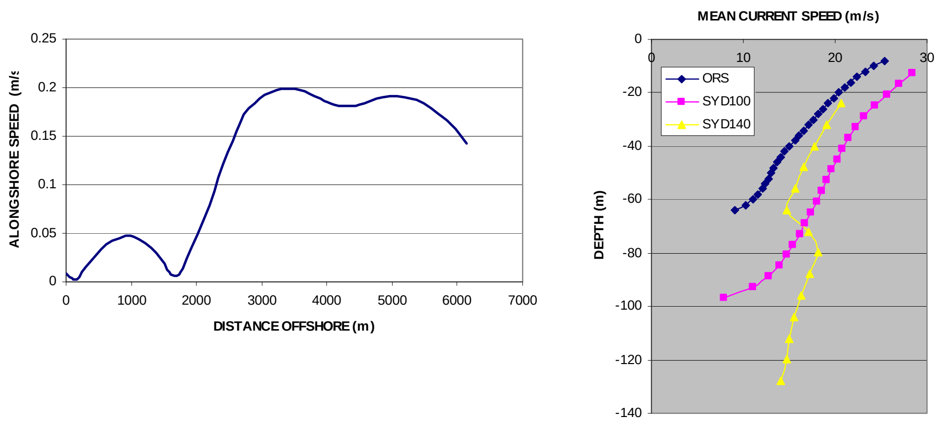


Figure 9.8 Current strengths at increasing distances from shore at **A**: Coffs Harbour (simulated currents across the alignment of A-C-D shown in Figure 9.7A from Chapter 8), and, **B**: vertical profiles at the three deployed current meter stations located along the IMOS transect shown in Figure 9.7B. (ORS: 28 September 2010 to 9 May 2011. SYD100 & SYD140: 14 October 2010 to 14 April 2011. Data from IMOS). Interestingly, current strengths increase with depth over the depth interval from 65m to 80m at SYD100 in Figure 9.8.

Current speeds appear to increase with distance offshore in the *Outer CBL* between the ORS site (2.1km offshore) and the SYD100 site (9.9 km offshore), although upper current speeds at the SYD140 site appear to lie between these extremes, as shown in Figure 9.8B. In contrast, spectral analysis shows a clear offshore increase across all three sites in peak energy in the diurnal frequency band (~1.4 log cycles per hour), and to a lesser extent in weather-band energy (centered on ~2 log cycles per hour), during the period of this IMOS deployment (Figure 9.9). The semi-diurnal band carries greater peak energy at the ORS compared to other sites.

Outer CBL effects observed off Sydney were described in Chapter 6 and **Pritchard** et al. (2005) and will not be repeated at length here; they include EAC *Eddy Field* influences and upwelling dynamics, as well as the effects of *CBL Oscillators* such as local wind, coastal trapped waves and tides, and *CBL Modifiers* like *River Plumes* and *Effluent Plumes*.

The latitudinal difference between case study locations places them under different influences of the East Australian Current (EAC): Coffs Harbour experiences variable southward EAC flows depending on the degree of westward encroachment of the EAC *Boundary Jet* onto the shelf; while, Sydney is affected by southward and northward flows associated with the encroachment of warm and cold cores EAC *Eddies*, such as those shown in Figure 9.10. These *Eddy Field* effects are partially responsible for the increase in weatherband spectral energy with increasing distance from shore off Sydney, as shown in Figure 9.9. In January 2011 a warm core eddy (W1) carrying East Australian Current water was embedded within the main EAC flow with a huge cold-core eddy (C) sitting immediately south, adjacent to an already detached warm core eddy (W2) (Figure 9.10). The encroachment of this second eddy (W2) dominated mid-shelf (southward) currents observed off Sydney in mid January 2011. While warm and cold core eddies such as these are common features of the *Eddy Field*, the sea surface elevation gradients associated with these eddies are extreme: up to ~1m over a distance of ~100km!

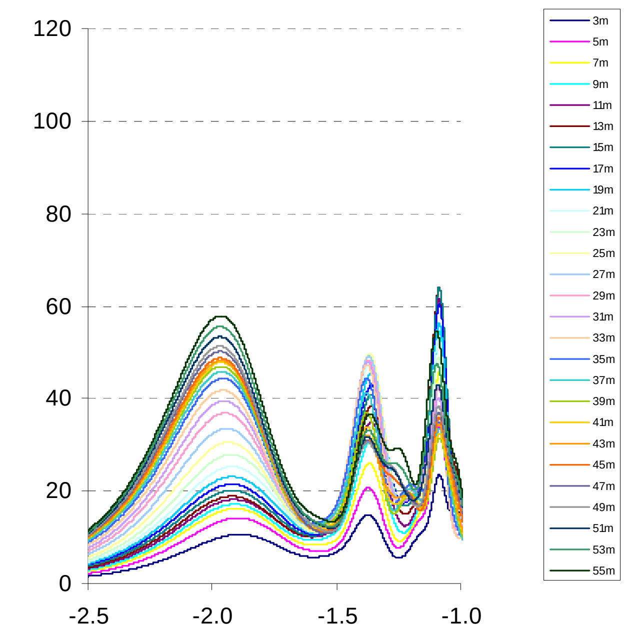


Figure 9.9a Variance preserving power spectra for currents at **ORS**: 28 September 2010 to 9 May 2011. Data from IMOS.

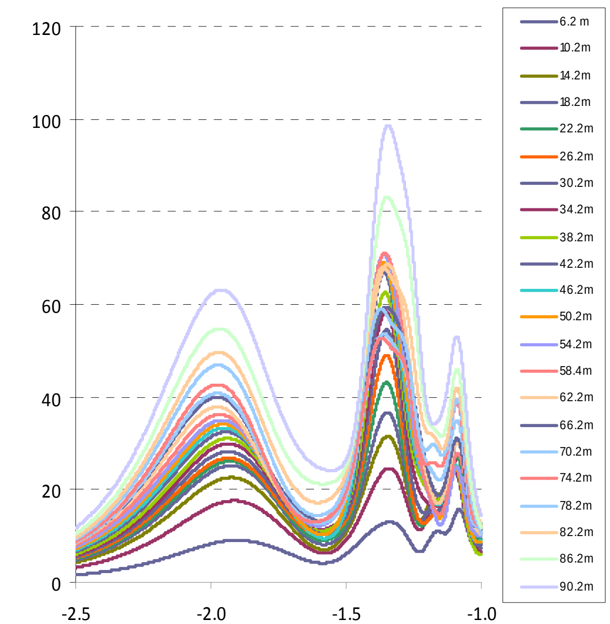


Figure 9.9b Variance preserving power spectra for currents at **SYD100**: 14 October 2010 to 14 April 2011. Data from IMOS.

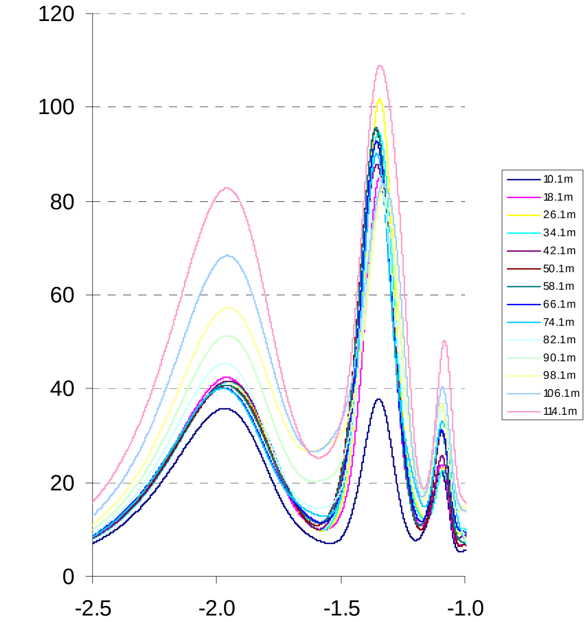


Figure 9.9c Variance preserving power spectra for currents at **SYD140**: 14 October 2010 to 14 April 2011. Data from IMOS.

[Hamming window applied with a 128 hour lag. Plot shows $(cm/s)^2$ vs log cycles per hour]

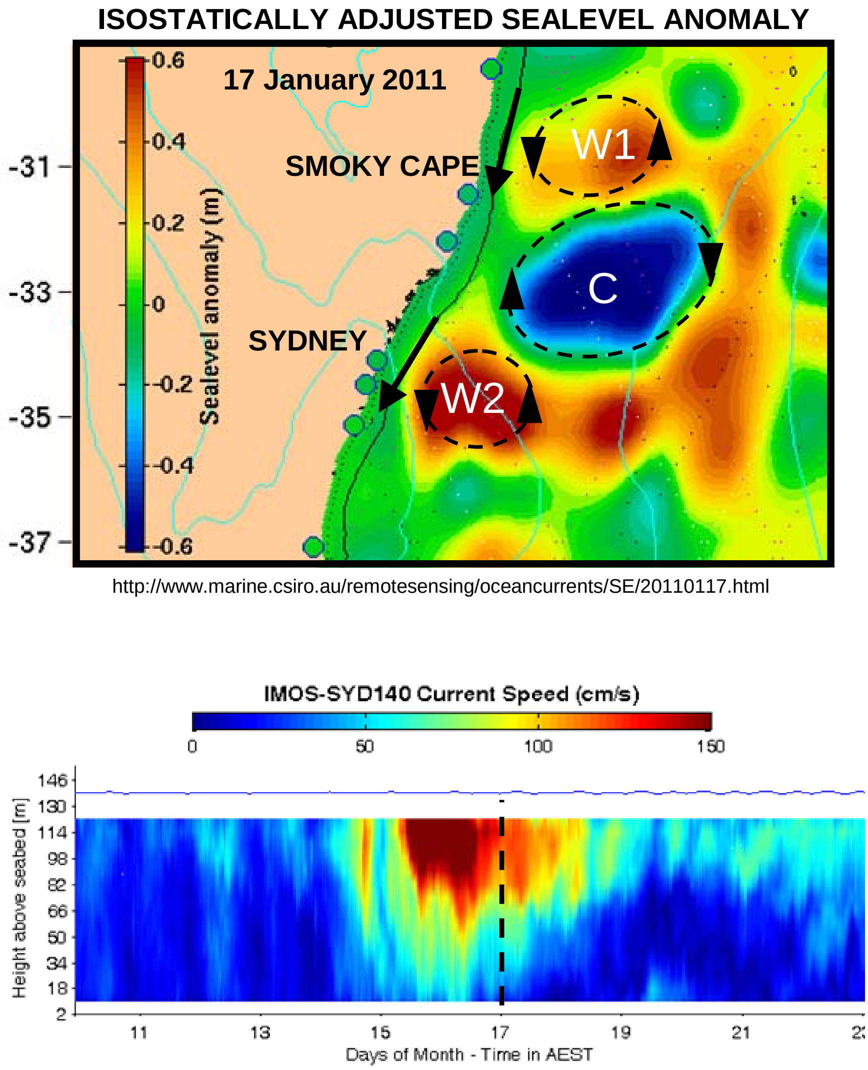


Figure 9.10 Energetic cold core and warm core eddies off the NSW coast during January 2011. Isostatically adjusted sea level anomalies courtesy of BLUElink Ocean forecasting Australia. Current speed data courtesy of IMOS (SYD140 location depicted in Figure 9.7B).

CBL Oscillators effects such as local *Wind* effects can de-stratify the water column over time frames of hours allowing effluent plumes to reach the surface and promoting vertical mixing of nutrient rich bottom waters.

Other *CBL Oscillators* effects such as *Tides* were implicated in the generation of internal waves at the shelf break with possible impacts on the initial mixing of effluent plumes, and on the vertical mixing of far-field effluent plumes in the shallow waters of the *Inner CBL* where internal waves may break (**Pritchard** et al., 2005). Similar internal wave breaking phenomena have been observed in California with water quality implications (Omand, et al., 2011). Other *Tidal* phenomena such as the effects of ebbs jets from Broken Bay, Sydney Harbour and Botany Bay were investigated during the Sydney Deepwater Outfalls Environmental Monitoring Program (EMP) because the presence of an ebb jet in the vicinity of Sydney's deepwater outfalls has the potential to influence the dispersion of effluent through local changes in currents and density stratification as well as concentrating the effect of floatable material along a surface front or the perturbation of the ambient along shelf current (Wilson et al., 1995). Ebb jet observations by a team including the author, defined a ~10m thick surface layer of relatively fresh and turbid water flowing up to 4 km offshore (4 km off Botany Bay; 2-3 km off Sydney Harbour; and, 4 km off Broken Bay), sometimes associated with small re-circulation eddies.

River Plumes discharging nutrient-rich catchment run-off to coastal waters have the potential to elevate nutrient concentrations (especially nitrate and ammonia) in surface waters as indicated by nutrient concentration data which was presented and discussed in Chapter 6 and in **Pritchard** et al. (2001, 2003). Likewise, *Effluent Plumes* of treated sewage were shown to have the potential to significantly elevate nutrient concentrations (especially ammonia) in coastal waters, while bottom waters may be enriched by slope water intrusions (especially nitrate and phosphate).

9.2.2 Ecological Consequences of Outer CBL Processes

In this section *Outer Coastal Boundary Layer* phenomena are discussed mostly in relation to distributions of biological communities and life histories of species, which may be impacted by pollutants. Environmental impacts of direct discharges to the *Outer CBL* are considered through Case Studies (Section 9.5) noting that few pollutants from both point sources (ocean outfalls and stormwater drains) and diffuse sources (coastal catchments) are discharged directly to the *Outer CBL*. In NSW only five ocean outfalls are located offshore and effectively removed from the influences of the *Inner CBL*: Malabar, North Head, and Bondi outfalls are located off Sydney, while smaller outfalls are located off Newcastle at Burwood and Belmont (see *Outfall Inventory* attached to Chapter 2). Other, more recently constructed offshore outfalls off Coffs Harbour and off Wollongong are potentially affected by coastline effects (points and harbours). However, dispersion of pollutants from these five outfalls is dominated by *Outer CBL* effects as well as *CBL Modifiers* and *CBL Oscillators*. Some of these discharges are discussed in relation to CBL effects as case studies in Section 9.5.

Suthers et al. (2011) contend that the greatest expression of the influence of the East Australian Current (EAC) *Boundary Jet* and its *Eddy Field* may be demonstrated by its relationship with the top end of the food web and from there to the fisheries that exist within and outside the EAC. The southward penetration of warm EAC waters provides the necessary thermal refuge for subtropical species such as yellowfin tuna, *Thunnus albacares* (Ward et al., 1996 cited in Suthers et al., 2011). Even when suitable habitat is abundant elsewhere flow fields have the potential to constrain a species' geographic range, as indicated by coupled population dispersal modeling undertaken by Gaylord and Gaines (2000).

Fish habitats on the continental shelf are influenced by EAC eddy encroachment as well as by sporadic discharges of freshwater in *River Plumes* (Kingsford and Suthers 1996). At lower trophic levels Moore et al. (2007) suggests that cold-core eddies represent an important offshore dispersal mechanism for phytoplankton has been confirmed by recent biomarker pigments studies (Hassler et al., 2011).

Overseas studies have shown that variability of coastal topography is ecologically important at large and small scales. For example, Botsford et al. (2001) found that 100-km spatial variability in the coastal topography of California influenced recruitment of crabs and sea urchins, while Roughan et al. (2005) reported retention of plankton associated with a small headland at the northern extremity of Bodega Bay in California, which represented a shoreward displacement of just 2-3 km. Other studies demonstrating the ecological importance of CBL processes are discussed later in Section 9.3.3.

Counter Currents have received little attention in eastern Australia although they are clearly important in relation to the dispersion of biological particles (such as larvae, propagules, pest species, etc.), sediments and pollutants many of which originate at the shoreline from coastal catchments and estuaries.

Coastal Boundary Layer (CBL) processes occurring on different spatial scales can explain the distributions of specific species or communities. For example, Coleman and Kelaher (2009) speculated that patterns of genetic differentiation seen for habitat-forming macroalgae (*Phyllospora comosa*) in NSW coastal waters were due to the combination of mesoscale EAC eddies and small scale coastal ‘barriers’. That is, EAC eddies may be responsible for substantial genetic connectivity among fragmented populations of *Phyllospora* spanning hundreds of kilometres (nonlinear dispersal in ‘leaps’) while coastal features such as sandy embayments may act as barriers to dispersal resulting in separation of genetically different populations at scales of tens of kilometres. Others confirm that sandy beaches can restrict macroalgae gene flow (Faugeron et al., 2001, Billot et al., 2003). These examples, illustrate the interplay between Inner and Outer CBL processes.

Clearly the physical processes operating in the *Outer CBL* establish the physical boundary conditions for *Inner CBL* phenomena as well as profoundly affecting biological distributions which may be impacted by pollutants discharged to the *Inner CBL*.

9.3 Inner CBL

9.3.1 Inner CBL Pollutant Dispersal Processes: Wake Effects

Although Creswell et al. (1983) noted the presence of weak clockwise cells in the embayments of northern NSW (e.g. between Smoky Cape and Korogoro Pt, Hat Head and Crescent Head; Crescent Head and Pt Plomer) there has been no systematic evaluation of the potential for wake effects in NSW coastal waters.

Turbulent flows, including eddies, are shed in the wakes of headlands, islands, shoals, man-made structures such as training walls, and in sudden expansions such as changes in the orientation of the coastline. The relative importance of inertial forces (advection of momentum) and frictional forces governs the nature of flow patterns in wakes of such obstacles (Tomczak, M., 1988; Wolanski, et al., 1984; Black and Gay, 1987; Signell and Geyer, 1991). If the frictional force dominates the particles will be dragged along the obstacle but if the inertial force dominates, the flow accelerates perpendicular to its intended path and separates from the obstacle resulting in a range of turbulent flow patterns, as illustrated in idealised form in Figure 9.10. The ratio of inertial and frictional forces and associated flow patterns have been expressed by various indices such as the Reynolds Number, the Wake Parameter which incorporates shallow water frictional effects (Wolanski et al, 1984), and the Keuleugan-Carpenter number which also incorporates headland width (Signell and Geyer, 1991). Other indices express the ratio between inertial forces and rotational effects of the Earth's rotation (Rossby number), the ratio between frictional and Coriolis terms (Ekman number), frictional damping effects (Frictional length scale) (Pattiaratchi et al., 1986; Signell and Geyer, 1991). The length and width of obstacles (headlands and islands) in the path of ambient flows together with water depth are common parameters in most of these indices.

A simple index - the Wake Parameter - was selected to illustrate idealised turbulence patterns and the relative importance of obstacle (headland or island) dimensions and water depths.

$$\text{Wake Parameter,} \quad P = \frac{U H^2}{K_z L}$$

where,

U	=	shear velocity
H	=	water depth
K_z	=	vertical eddy diffusion coefficient
L	=	length of obstacle

The Wake Parameter is the correct formulation for the Reynolds Number when the effects of lateral and bottom boundary frictional layer are taken in to account (Barton, 2009). It has been shown to work well in the description of re-circulation in two dimensional steady flows (Wolanski et al., 1984; Pattiaratchi et al., 1986; Dennis and Middleton, 1994). A stable wake is expected when $P \sim 1$, while bottom friction effects dominate when $P \ll 1$ and bottom frictional effects are negligible when $P \gg 1$.

The Wake Parameter was calculated for a range of headland/island lengths and water depths as shown in Figure 9.11 by assuming a steady current of 0.2 m/s and a ubiquitous constant vertical eddy diffusion coefficient (Kz) of 0.1 m^2/s. An ambient current of 0.2 m/s is consistent with average current speeds observed at the Ocean Reference Station off Sydney (see Chapter 6) and within the range of currents observed off Coffs Harbour (see Chapter 8). The vertical eddy diffusion coefficient (Kz) of 0.1 m^2/s represents the turbulent transport of momentum in the vertical direction which is of great importance in shallow waters where frictional forces associated with the surface and bottom boundary layers can dominate the water column. The Wake Parameter is directly proportional to ambient current velocity and inversely proportional to vertical eddy diffusion coefficient so the pattern in Figure 9.11 can be readily scaled according to variations in these parameters.

The vertical eddy diffusion coefficient (K_Z) is poorly defined across NSW coastal waters with limited relevant observations, and known spatial and temporal variability. Sensitivity analysis shows the relationship between vertical eddy diffusion coefficient (K_Z) and flow separation (Wake Parameter = 1) for various headland lengths and water depths (Figure 9.12).

By applying the theoretical Wake Parameter across a range of waters depth and headland depths (Figure 9.11) it is clear that in general shallow water depths inhibit large scale turbulent circulations. That is, wakes with large scale wave disturbances (Figure 9.10 b) and vortex streets (Figure 9.10 c) are not expected to be common in shallow coastal waters.

When applied to the Coffs Harbour case study in Chapter 8 (Corambirra Point L=860m, D=20m) the Wake Parameter equates to almost 1 (P= 0.93 based on assumptions outlined in Figure 9.11) and indicates a marginal propensity for eddy formation, which is consistent with observations (Chapter 8).

However, the specific Wake Parameter (or Reynolds number) values corresponding to the transition through the various turbulent flow states outlined in Figure 9.10 vary with upstream flow velocities and vertical eddy diffusion coefficients (Kz). For example, heterogeneous Kz fields may exist due to patchy reefs which affects bottom stress, and temporal variations in wind regimes which affects surface wind stress.

Indices such as the Wake Parameter were developed for simple morphologies and steady flows so real world factors associated with complex morphologies and unsteady flows must be expected to reduce the applicability of these indices. For instance, inertial forces would be expected to dominate over frictional forces around the sharp tip of a headland, promoting flow separation and re-circulation, consistent with mechanisms outlined by Signell and Geyer (1991). In contrast the greater surface area and the geometry of a round tipped headland would be expected to reduce the influence of inertial forces relative to frictional forces resulting in weaker wake effects. Likewise, submerged offshore extensions of headlands (reefs) may steer flows to promote or inhibit re-circulation depending on their configuration. In a similar way the temporal variability of flows, including current reversals, can profoundly affect re-circulation through processes such as phase eddies, as discussed in Chapter 8 and **Pritchard** et al. (2007).

Some studies have suggested that the transition to unsteadiness in coastal waters occurs through non-modal growth excited by the stochastic variability in the incident flow (e.g. Aiken et al., 2003); that is, it may be determined by the non-normality of the system. For example, some prominent headlands rarely develop recirculation cells: Bass Point, south of Sydney protrudes almost 4km onto the continental shelf where strong longshore currents (0.2–0.5 m s^{-1}) often exist yet large-scale recirculation is rarely observed in the lee of the headland (Middleton et al, 1993). Instead a broad turbulent wake was observed by Denniss et al. (1995) which Aiken et al. (2002) attributed to three sources of stochastic forcing: variability in the wind stress; variability in the flow incident on the headland; and, variability generated in the flow by complex reef topography at the headland's tip and upstream. Laboratory flume experiments confirmed that topography upstream of a headland can lead to a wider shear layer, a headland wake that extends further downstream, and enhanced horizontal diffusion out of the wake relative to the case with unperturbed oncoming flow (O’Byrne, et al., 2007). This wider shear layer means that the nonlinear terms are less effective at rolling up the flow to form a large-scale recirculation (Middleton et al., 1993).

In summary, the Wake Parameter and other dimensionless flow indices provide a highly generalised relative measure of the propensity for various turbulent flow regimes: they signal key morphological parameters that are critical to a hydrodynamically relevant morphological classification.

It is then possible for morphological classifications to spawn testable hypothesis because morphological parameters can be related through flow indices to broad classes of turbulent states. The appropriate applications of the morphological classification and flow indices are for screening level assessments which serve to develop hypotheses, and in turn focus and structure more detailed investigations.

The challenge for an index is to identify relevant morphological parameters to facilitate recognition of both likely (generalised) flow characteristics and possible exceptions, due to other factors such as wind regimes and proximity to islands in the flow path.

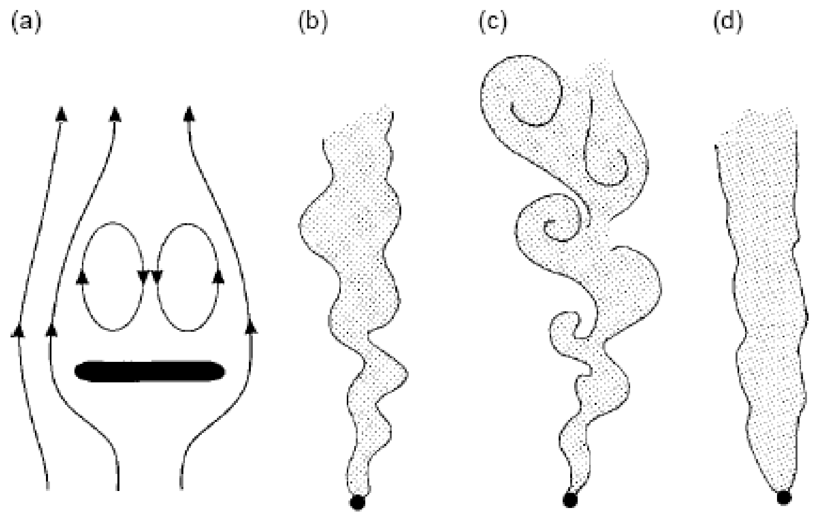


Figure 9.10 Shallow water island wakes corresponding to increasing dominance of inertial forces (increasing Reynolds Numbers and/or Wake Parameter): (a) vortex pair forms with central return flow; (b) turbulent wake exhibits wave disturbances; (c) meanders develop instabilities and roll to form a von Karmon vortex street; (d) fully turbulent (three dimensional) wake. Modified from Wolanski (2007) and Tomczac (1998).

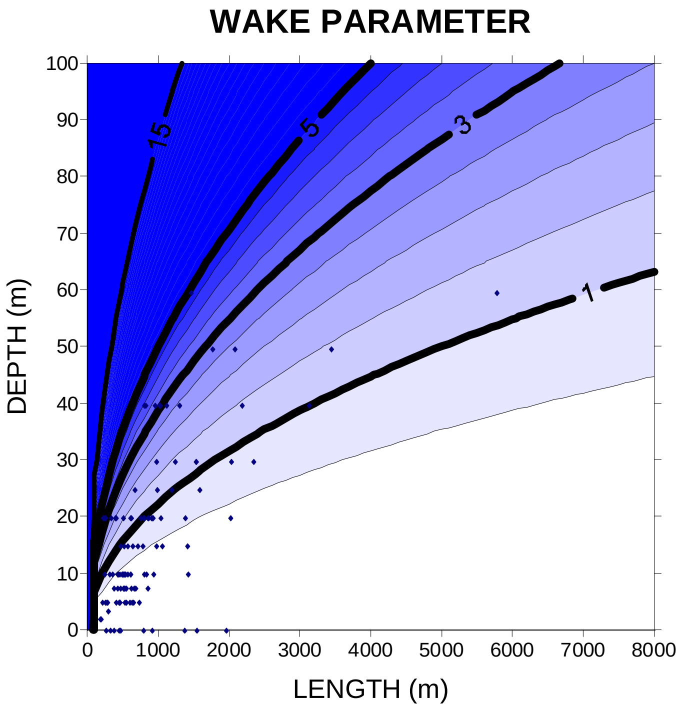
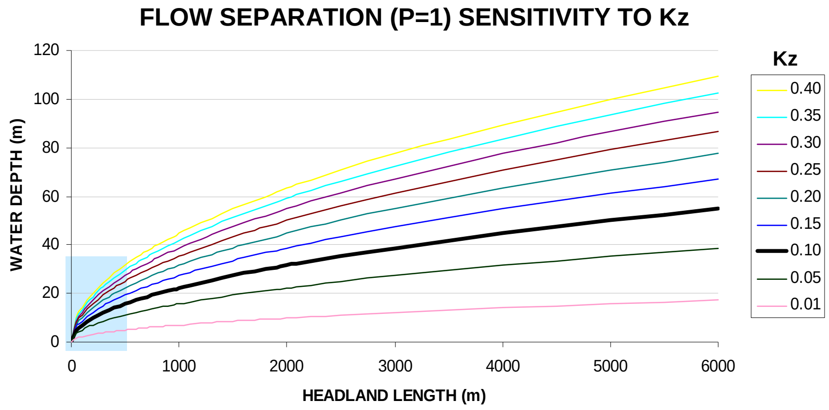


Figure 9.11 Wake Parameter (P) = UH^2/K_zL for depths (H) to 100m and obstacle lengths (L) to 8 km, where current (U) = 0.2m/s, and vertical eddy. diffusion coefficient (K_z) = 0.1 m^2/s. Indicative turbulent flow regimes have been suggested by Wolanski (2007):
P < 1, the flow does not separate and there is no eddy.
P ≈ 1, an eddy or an eddy pair exists – similar to (a) in Figure 9.10
P = 1–3, meanders develop – similar to (b) in Figure 9.10
P = 3–15, meanders develop instabilities & roll – similar to (c) in Figure 9.10
P > 20, the wake is fully turbulent downstream – similar to (d) in Figure 9.10
NSW *Triangular Headlands* are also plotted based on data in Chapter 7.

Here unknown variables needed to calculate the Wake Parameter are held constant at 'typical' values (current velocity = 0.2 m/s; and, vertical eddy diffusion coefficient = 0.1 m^2/s as discussed in Chapter 7) in order to indicate the relative propensities for flow separation and re-circulation based on the ratio of headland length to depth (Figure 9.11). A curve corresponding to P=1 on Figure 9.11 shows the theoretical threshold for flow separation and re-circulation. As outlined in Chapter 7, headlands protruding across steeply shelving inner shelf bathymetries are predisposed to wakes effects because the propensity for wakes as indicated by the Wake Parameter, is proportional to the square of the water depth and inversely proportional to the length of the headland.



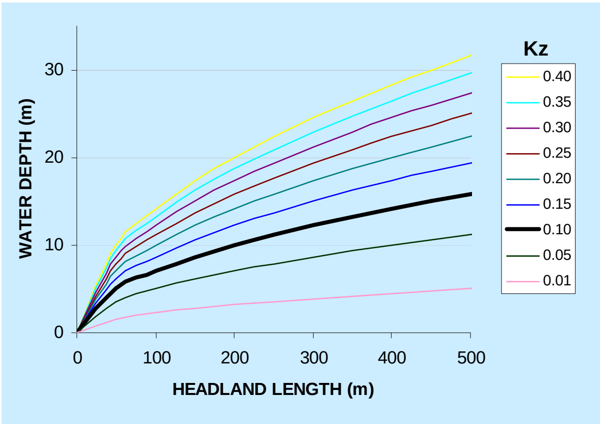


Figure 9.12 Sensitivity analysis showing relationship between vertical eddy diffusion coefficient (K_Z) and flow separation (Wake Parameter = 1) for various headland lengths and water depths (blue section expanded).

NSW *Triangular Headland* dimensions plotted in Figure 9.11 reveal that flow separation and wake effects are unlikely in water depths less than 15m and likely for headlands in water depths greater than ~35m. In this way, Figure 9.11 can operate as a screening level assessment tool to evaluate headland settings for their inherent propensity for wake effects. Generally, the worst case for pollutant trapping would be associated with discharges in to attached re-circulation cells which are indicated by Wake Parameter values of ~1.

Two adjacent headlands form a ***Bay*** when their flow fields interact by affecting the flow incident on the other headland or by constraining respective wake effects. Previous studies of headlands (e.g. Chapter 7 and Figure 9.10) indicate wakes typically extend at least a headland/island length downstream of the headland/island.

In summary, the following simple process based understanding and practical assumptions are critical in assessing the propensity for re-circulation and particle trapping in the wake of a headland or island:

- free stream flows (offshore) are typically driven by alongshore pressure gradients
- low velocity flows follow isobaths around the headland (frictional forces dominate)
- high velocity flows separate from the tip of the headland (inertial terms dominate)
- separation results in a flow downstream of the headland, which decelerates, spreads and re-attaches with the coastline at some distance downstream
- eddies occur in a wake region delimited by the offshore protrusion of the headland and the downstream flow which re-attaches with the coast
- Recirculation can occur in the wake due to a number of contributing factors.
    - the Bernoulli effect can produce a depression of sea level near the tip of the headland, and high vorticities generated by friction in a narrow boundary layer at the tip of the headland are injected into the interior of the flow at the point of separation as the source of the eddies vorticity (Signell and Geyer, 1991).
    - differences in the dynamic response to reversing pressure gradients may cause 'phase eddies' to spin up (Black and Gay, 1987). That is, a phase eddy evolves when flow reversals occur earlier in the wake of the headland than in the free stream where currents are still continuing to decelerate. In this way the formation of phase eddies is governed by the inertia of the wake relative to the free stream flow.
- Recirculation is favoured by:
    - Wake Parameter values close to, or in excess of unity. That is, when inertial forces manifest (currents) begin to dominate over

    - very high Wake Parameter values (e.g. due to very high velocities) can cause unstable turbulent flows which disrupt re-circulation cells
    - sharp tipped headlands which promote flow separation and spawn vorticity within the wake (Signell and Geyer, 1991)
- Likewise recirculation can be inhibited by a number factors such as:
    - high levels of stochastically forced turbulence near the tip of a headland may prevent the formation of a single narrow headland jet, instead resulting in a wider turbulent shear layer which may be much less conducive to large-scale recirculation (Aiken et al., 2002**).** This, and other mixing processes, may be expressed by an eddy viscosity parameter which, when high, inhibits the formation of re-circulation / retention cells.

No indices are apparent in the literature for general morphological characterisation of particle retention (or 'flushing time') for *Island/Headland Wake* zones or for *Open Sweep, Open Square* and *Open Triangular* bays.

If a coastal configuration predisposes areas to the formation of a *Wake Zone* then a worse case re-entrainment scenario is assumed for screening level assessments using an *Eddy Retention Value* (ERV) which is proposed as the ratio of volume of effluent discharged during the lifetime of a re-circulating lee eddy to the volume of water within the eddy.

$$\mathbf{ERV} = \frac{\mathbf{E_F\, T}}{\pi\, \mathbf{R_L}^2\, \mathbf{H_A}}$$

where R_L = eddy dimension (m)

T = duration of eddy persistence (s)

H_A = average water depth in *Wake Zone*

R_L and T are preferably determined by observations and/or through model simulations but R_L may also be estimated as follows:

Wolanski et al. (1984) proposed eddy length scale (R_L).

$$R_L = \frac{UH_A^{1/2}}{\omega^{3/4} K_Z^{1/4}}$$

where K_Z = vertical eddy viscosity (m^2/s).

Pattiaratchi et al. (1986) noted that as the currents in the re-circulating region of the obstacle are of the same magnitude as the current approaching the obstacle the angular velocity of the eddy (ω) is ~ U/R_L Therefore, Wolanski et al.'s (1984) eddy length scale (R_L) becomes

$$R_L = UH_A^2 / K_Z$$

Not surprisingly this is equivalent to the Wake Parameter (P) multiplied by the length of the headland (L).

So the *Eddy Retention Value* (ERV) is given by

$$ERV = \frac{E_F\ T\ K_Z^2}{\pi\ U^2 H_A^5}$$

Other *Inner CBL* effects such as those associated with the *Wave Zone* typically exhibit extreme small scale spatial and temporal variability and are best dealt with by example (see Sections 9.3.2 and 9.5).

Most *Inner CBL* phenomena cannot be considered in isolation of *Outer CBL* processes because *Outer CBL* processes set the outer boundary condition for the *Inner CBL* and pre-condition for *Inner CBL* phenomena. For example, at a large-scale bottom boundary stress associated with *Outer CBL Boundary Jet*/EAC flow, shelf irregularities and regional *Winds* promotes cross-shelf currents which are constrained by the coastline, resulting in upwelling. These episodic upwelled nutrients can stimulate primary production. In some instances, decay of the resulting plankton and macroalgae plus organic material from coastal catchments (*River Plumes*) produce surfactants. *Waves* shoaling in the *Inner CBL* together with local *Winds* create sufficient small-scale turbulence for bubbles to form and coalesce, which in the presence of surfactants can form 'seafoam'. The coast can further act to constrain seafoam so it accumulates at the shoreline, as depicted by the graphic image of Yamba during August 2007, in the Preface of this thesis.

9.3.2 Impacts and Ecological Consequences of Inner CBL Processes

A range of *Inner CBL* processes shape biotic pathways as well as pollutant pathways, thus affecting a range of environmental values. Here *Inner CBL* processes are examined in relation to their roles in shaping both biological distributions and pollutant dispersion.

Island and Headland Wakes shape distributions of biota, often leading to high conservation value areas which can warrant special protection against impacts.

The influences and impacts of *Island and Headland Wakes* on biological communities and individual species are well reported in the scientific literature. As discussed in Chapter 8, regions of enhanced relative vorticity, like headland wakes, may aggregate prey and represent important foraging habitat for predators like cetaceans (Johnston, et al.,2005). Wake induced upwelling and plankton retention can result in high productivity (e.g. Roughan et al. 2005). Even in the absence of a well-defined eddy biological distributions can be affected by headland wakes; for example, Rankin et al. (1994) found that juvenile Gem clams were deposited just inside the wake perimeter, where shear velocities decreased to levels below critical erosion velocities of the clams. Re-circulation can also shape the benthic environment of infauna and epibiota by driving sand circulation such as that observed between sandbanks and headlands by Berthot and Pattiaratchi (2006).

The clockwise rotating cells observed in the embayments of northern NSW (**Pritchard** et al. 2007; Creswell, 1983) could have significant importance for genetic structuring of benthic invertebrates and other marine organisms (Banks et al. 2007). Investigations of source and sink regions do not necessarily identify the pathway that larvae take between spawning and settlement. The form and viability of both biological particles and pollutants vary with time along pathways from source to sink, for example: larvae caught in a rotating eddy may be more prone to predation, become starved of food, or subject to adverse environmental conditions for long periods of time; populations contained within re-circulation cells may experience extended periods of exposure to 'trapped' contaminants; and, over time bioavailable forms of nutrients may be transformed to less available (eg oxidization of inorganic) forms or inaccessible (eg conversion to organic) forms due to biogeochemical processes associated with algal successions, bacterial loops and trophic interactions.

Various studies have shown or speculated that sandy embayments can restrict macroalgae gene flow by acting as barriers to dispersal (Faugeron et al., 2001, Billot et al., 2003; Coleman and Kelaher; 2009). Other studies have revealed similar findings for species at higher trophic levels. Archambault et al. (1998) found higher abundance of zooplankton inside embayments compared to straight sections of the Canadian coast and confirmed retention and local production of larvae inside embayments. Diehl et al. (2007) observed recruitment of the sand crab *Emerita analoga* at sites distributed along > 800 km of the California coastline and suggested that the California coast may be composed of separate retentive cells of populations separated by headlands. Nicastro et al. (2008) showed that coastal configuration strongly affects selection, larval dispersal and haplotype diversity of mussel population in South Africa with differences in genetic structure on scales of 10s of kilometres. Their gene flow analysis based on mussel populations inside bays and on the open coast in South Africa showed that bays act as discrete sources.

Jessopp et al. (2007) found that flushing time due to the effect of coastline configuration (embayments) was a useful predictor for species richness and turnover of benthic marine invertebrate larvae along the Irish coast, particularly when combined with topographic variables, chlorophyll, tidal range and salinity.

Headland Wakes can interact with ***Effluent Plumes*** to retard dispersion of pollutants and increase the risk of environmental impacts.

Wakes effects, such as re-entrainment of effluent and pollutant trapping, were likely to be a contributing factor leading to observed impacts at Boulder Bay in central NSW. Within 3 months of the commissioning of the outfall, significant reductions in the cover of crustose and foliose algae, and several species of sponge were apparent at the outfall location when compared to control locations (Roberts *et al.,* 1998). The overall composition of the community at the outfall changed from one in which algae and sponges were well represented to an assemblage dominated by silt and ascidians. After commissioning of the outfall, the cover of a nondescript matrix comprising silt and microorganisms doubled its representation to almost 60%. A before/after/control/impact (BACI) investigation of the impacts of the newly commissioned Boulder Bay outfall on fish found declines in species richness and in the abundances of eastern hulafish (*Trachinops taeniatus*), yellowtail (*Trachurus novaezelandiae*) and the urchin (*Centrostephanus rodgersii*) at the outfall location together with increases in the abundances of some cryptic fish species (Smith et al., 1999).

The anticlockwise residual circulation in the wake to the south of Corambirra Point (**Pritchard** et al., 2007) may explain some of the unusually extensive impacts observed along the entire length of the point when sewage was discharged at the base of the headland. Prior to the commissioning of a deepwater outfall at Coffs Harbour, treated sewage effluent was discharged at the shoreline at the landward (south-western) end of Corambirra Point. Smith (1996) and Smith and Simpson (1993) found that effluent discharged through this shoreline outfall had an impact on the benthic communities on Corambirra Point: the cover of *Ulva lactuca* was increased for the full length of Corambirra Point (approximately 600m) and within 400m of the outfall there was a reduction in intertidal algal species richness and a change in the pattern of dominance in the animal community inhabiting kelp holdfasts.

Headland Wakes can interact with ***River Plumes*** to shape patterns of exposure to pollutants derived from coastal catchments and the fate of sediments exported from rivers and estuaries.

There are few reported studies of the interactions between headland wakes and *River Plumes* although small rivers commonly discharge into coastal settings with topographic complexities such as headlands and islands. A notable exception was the recent study by Warrick and Stevens (2011) in the Strait of Juan de Fuca on the American/Canadian west coast, which found that tidally induced transient eddies in the lee of a headland were responsible for the Elwha *River Plume* being directed eastward, and shoreline attached, twice as frequently as it was directed westward. Clearly, headland induced flow separation and transient eddies can strongly influence the sediment dispersal pathways and behaviour of buoyant plumes emanating from coastal catchments.

River Plumes strongly influence fish larvae and may play a significant role in the recruitment of local fishes (Grimes and Kingsford, 1996). Physical dynamics support high productivity, act to accumulate biomass in frontal waters, and transport organisms across the shelf and along the front. Temperate estuaries that feed the east Australian coastal zone have the most variable seasonal freshwater inputs in the world (Gillanders and Kingsford 2002), which has a strong effect on estuarine and coastal fisheries (Gillson et al. 2009).

Although a focus of this section has been on wake effects it is clear from the case studies presented above that a broad range of CBL processes determine the fate and potential impacts of pollutants, including those associated with the ***Wave Zone, Tides*** and ***River Plumes***.

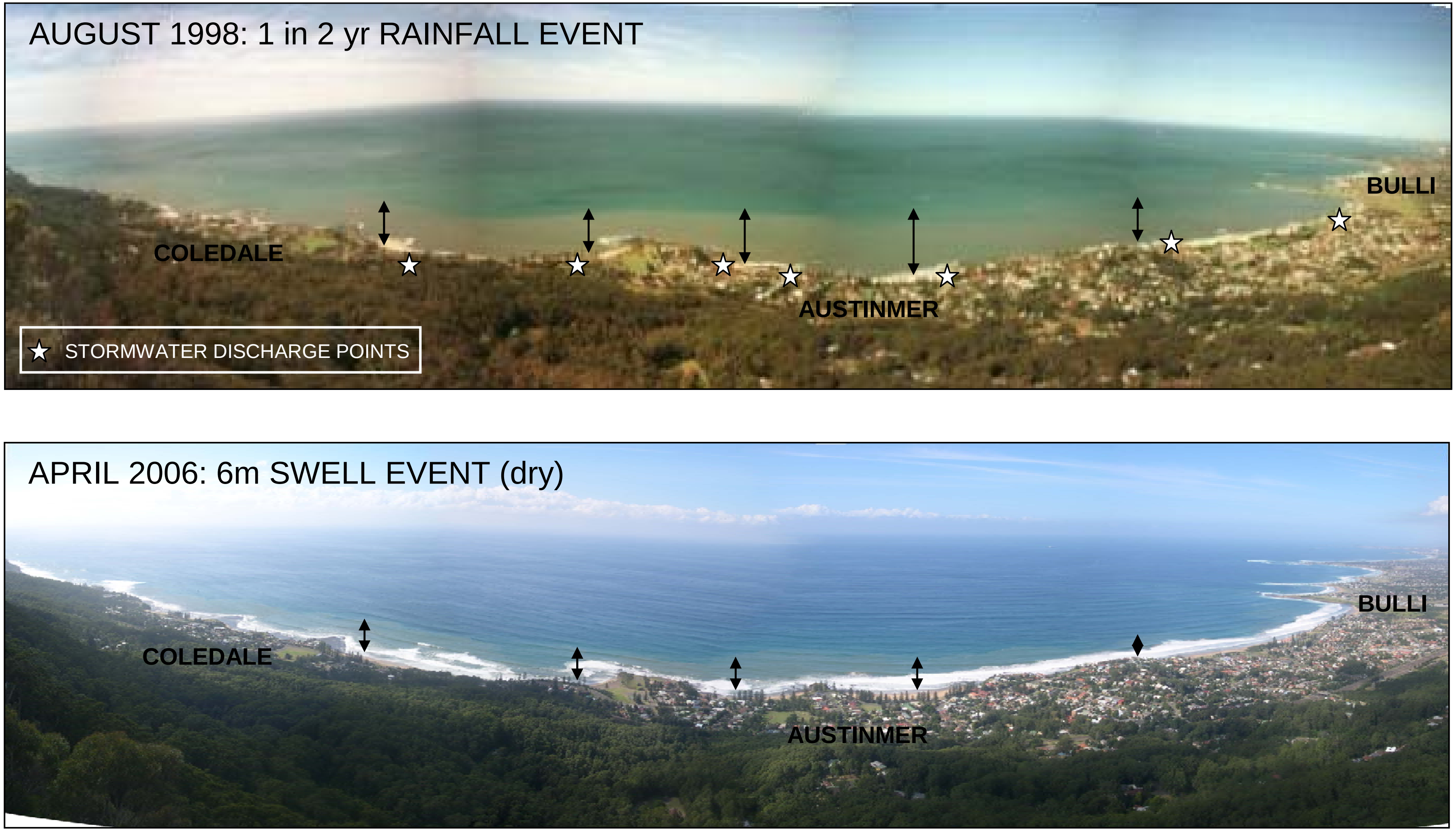
River Plumes emanating from NSW coastal catchments were discussed in Chapter 5, especially in relation to studies of a high rainfall event in 1998 when Lee and **Pritchard** (1999) mapped turbid plumes from five coastal catchments in south east Australia, extending over a total area of over 3000 km^2 .

Wave Zone processes can directly impact recreational amenity and beach user health risks. For example, Riddle (1994) and Large et al. (1994) found effluent, from Cronulla Sewage Treatment Plant (STP), discharged at Potter Point was drawn in to the northern end of Bate Bay by wind and waves breaking over Merries Reef (see Section 9.5.4 below). This anticlockwise circulation left the northern most beach of Boat Harbour contaminated by sewage under high wave conditions with a strong gradient of improving beach water quality running southward from Boat Harbour (Riddle, 1994).

Wave Zone effects also have the ability to re-suspend sediments together with any contaminants that may be sorbed to sediment particles. For example, major turbid plumes developed in the absence of any significant coastal catchments outflows, during a period of high wave activity in April 2006 in the Illawarra region south of Sydney (Figure 9.13). Erosion and sediment re-suspension by large long period swells, and the subsequent persistence of sediment plumes, indicated limited cross shelf movement of sediments which appear to be constrained within a shore attached coastal boundary layer. Sediment plumes were equally persistent in a shoreline attached coastal boundary layer when *River Plumes* emerged from these small,'flashy', coastal catchments abutting the Illawarra escarpment following extreme local rainfall in August 1998; these plumes merged and remained attached to the shoreline for several days to weeks (Figure 9.13).

Interestingly, sediment transport studies in California by Curran et al (2002) found that suspended sediment concentrations were set in the surf zone rather than at the river mouth (Eel River) where similarly small rivers discharged sediment laden run-off to coastal water. They suggested that the surf zone may play a significant role in the cross-shore re-supply of sediments to the river plume, highlighting the need for accurate measurements of sediment concentration, currents, waves, and boundary shear stress in energetic near-shore environments.

CBL Fronts and Convergence (Accumulation) Zones (see Section 4.2.4) may explain the "recruitment problem" of marine population dynamics (Roughgarden et al., 1991); that is, why larvae arrive at an adult population in large discrete pulses rather than in a continuous trickle. Roughgarden et al. (1991) hypothesised that barnacle larvae from central California accumulate along an offshore front, separating the California Current from upwelled water adjacent to the coast, with the front eventually colliding with the coast to deposit clumps of larvae.



APRIL 2006: BELLAMBI (068228) MONTHLY RAINFALL = 4.4mm

Photos by Pritchard from Sublime Point

Figure 9.13 Stable turbid waters trapped in a coastal boundary layer attached to the Illawarra shoreline, New SouthWales.

9.4 Case Studies

The importance of a process based understanding of Inner CBL dynamics on the fate of pollutants is further illustrated by the following examples:

- ***Sydney:*** *Outer CBL* (see also Chapter 6 and Pritchard et al., 1997)
- ***Coffs Harbour***: *Inner CBL Headland Wake* (see also Chapter 8)
- ***Boulder Bay***: *Inner CBL Headland Wake* with re-circulation cells and embayment quiescence limiting dispersion of effluent released from an outfall just inside the shear zone at the outer limit of the bay.
- ***Bate Bay***: *Inner CBL Headland Wake* (HW) and *Wave Zone* (WZ) with episodic wave induced circulation plus flow separation, shear & quiescent zones affecting pollutants released at the northern extremity of Bate Bay.

9.4.1 Sydney

The Sydney Case Study is located in the *Outer CBL* where NSW's greatest loads of sewage derived pollutants are discharged via three deepwater outfalls shown in Figure 9.14 (**Pritchard** et al., 2001).

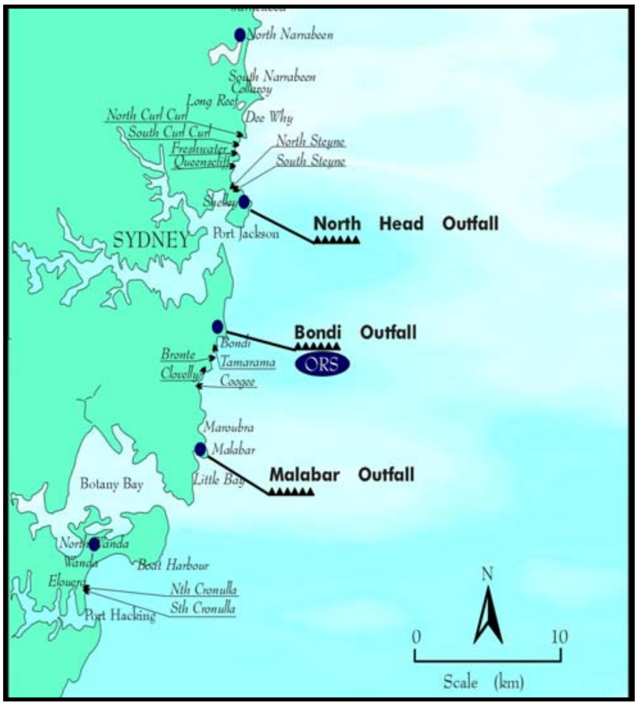


Figure 9.14 Sydney's deepwater outfalls

The specific findings from the Sydney Case Study have been reported in two published papers (**Pritchard** et al., 2001 and 2005) which appear in Chapter 6; these findings are not repeated in detail here. Sewage effluent is discharged from three deepwater outfalls after high rate primary treatment at a combined rate of over 12m^3/s. The locations of Sydney's deepwater sewage outfalls are shown in Figure 9.14. Prior to the commissioning of these deepwater outfall 1990/91, effluent from sewage treatment plants at North Head, Bondi and Malabar was discharged to the *Inner CBL* from cliff face outfall resulting in spectacular water quality impacts (Figure 9.15). The findings of a $24M, multi-disciplinary Environmental Monitoring Program which assessed the performance of Sydney's deepwater outfalls during the first two years of their operation are published in **Pritchard** (1997) which is provided in Appendix 3.

A

B

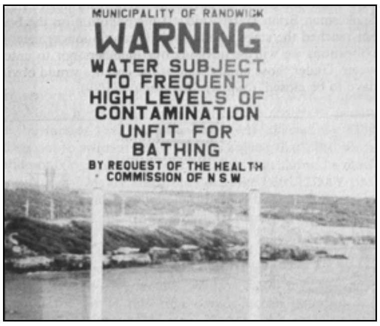


Figure 9.15 Former shoreline outfall plumes such as at North Head (A) prompted health warnings at local beaches such as at Malabar (B).

Not surprisingly, *Headland Wake* effects do not interact with Sydney's deepwater *Effluent Plumes* because the three major deepwater outfall systems are located well beyond the effects of the *Inner CBL*. Indeed the *Effluent Plumes* generally follow free stream flow and achieve high initial dilutions as demonstrated by EMP models (Wilson et al., 1995) and direct observations shown in Figure 9.16 (**Pritchard** et al., 1993).

Current reversals have been observed in the current record (see Figure 5 in **Pritchard** et al., 2005 in Chapter 6) which presents an opportunity for re-entrainment of effluent as plumes 'blow-back' over the diffuser systems with some reduction in the potential dilution of effluent. However, high initial mixing (due to deep water), rapid advection away from the outfall (see Figure 9.16), and the rotation of currents during reversals reduce the effect of re-entrainment, as was evident when current reversals were observed during tracer studies (see Table 2.1 in Chapter 2 based on **Pritchard** et al., 1993). The long term effect of 'blow-back' was assumed negligible for the purpose of the analysis below.

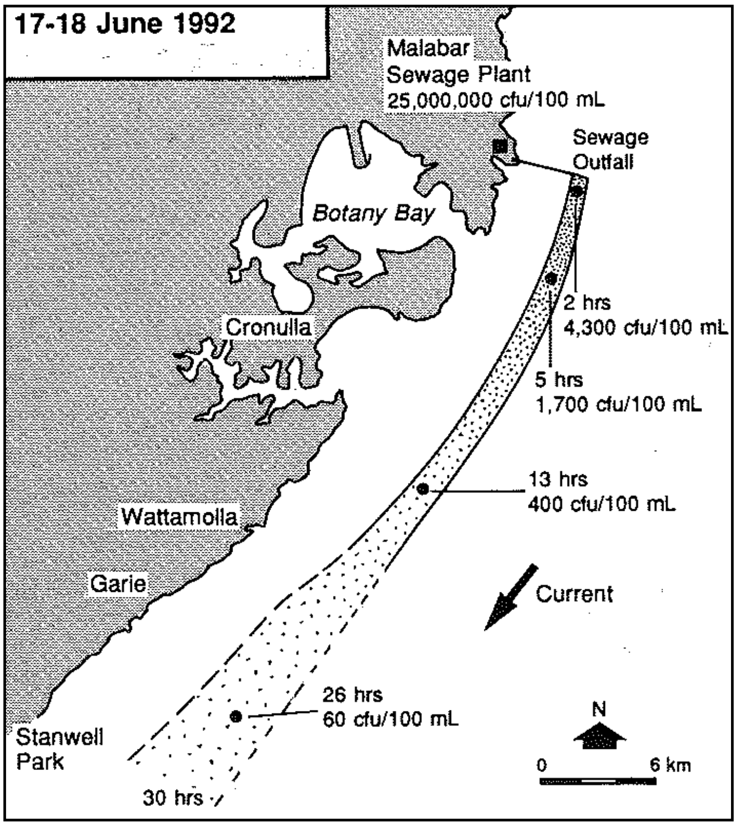


Figure 9.16 Malabar plume behaviour illustrating effects of dilution and die-off for thermo tolerant faecal coliform indicator bacteria from **Pritchard** et al. (1993)

Average (median) initial dilutions based on validated near-field models (from Pritchard et al., 1997) achieved by Sydney's three deepwater outfalls
are provided in Table 9.1. Compared to the former shoreline outfalls which they replaced, the deepwater outfalls provided more than a ten fold increase in initial dilutions and avoided boundary contact (shoreline and sea floor). Figure 9.17 illustrates that the deepwater outfalls (Bondi in this case) are optimally located to maximise buoyancy driven mixing by exploiting the steep inner shelf gradient.

Table 9.1 Sydney's deepwater ocean outfalls

	Deepwater Outfall / STP		
	North Head	Bondi	Malabar
Average Effluent Flow (m^3/s)	4.46	1.91	5.67
Diffuser Length (m)	765	510	720
Water Depth (m)	60	60	80
Average Upper Current (m/s)	0.22	0.22	0.22
Average Lower Current (m/s)	0.14	0.14	0.14
Median Modelled Dilutions TRAPPED PLUME	349	414	513
Median Modelled Dilutions SURFACE PLUME	817	1193	636

Based on information provided by **Pritchard** et al., (1997): median initial dilutions were based on hourly near-field model results (JETLAG) using measured hourly effluent flow rates and ambient currents and vertical temperature stratification observed at the Ocean Reference Station for the period from March 1991 to March 1994. Average current speeds are based on ORS data for the same period. The innermost diffusers at North Head and Malabar are both 2900m from shore.

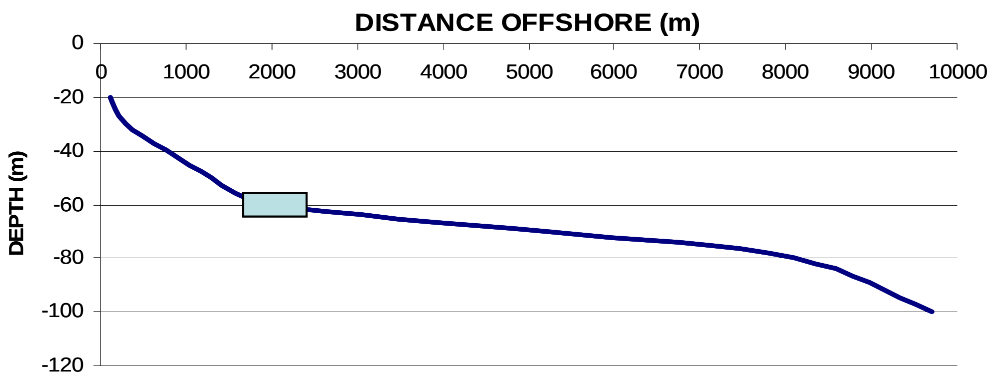


Figure 9.17 Cross-shelf bathymetry profile along a transect passing through Bondi deepwater outfall (shown as blue box).

Observed and potential impacts of Sydney's three deepwater outfalls, which together contribute nearly 75% of the nutrient loading to coastal waters from NSW coastal sewage treatment plants, have been described in detail by **Pritchard** (1997) and **Pritchard** et al. (1993, 1996, 1997, 1999, 2001, 2003) and others. For these deepwater outfalls, a consideration of effluent pollutant loads and concentrations alone would suggest a considerable potential for adverse effects, including algal blooms. However, physical processes facilitate rapid dispersion of sewage pollutants which alleviates many potential impacts. Ongoing monitoring including a major, long-term, ocean sediment and benthos monitoring program designed by Krogh, **Pritchard** & Rendell (1998), has been unable to detect major environmental impacts associated with these discharges to the *Outer CBL* off Sydney (SWC 2010).

Given the magnitude of these discharges, ongoing vigilance and possibly further investigations are warranted with a focus on emerging pollutants and more subtle, second order ecosystem effects such as possible changes to trophic dynamics and species composition. Such investigations can be targeted and informed by studies such as those described in Chapter 6 which concluded that the greatest risk of nutrient driven outfall impacts would be in surface waters during late summer when the contributions from outfalls are large with respect to ambient nutrient concentrations, and especially when ambient concentrations are low relative to saturation levels for phytoplankton growth.

9.4.2 Coffs Harbour

The Coffs Harbour Case Study is located in the *Inner CBL* where a new ocean outfall was required to implement a regional effluent management strategy (CHEIS, 2000) which recognised unacceptable impacts of former shore line outfalls (Figure 9.18).

The specific findings from the Coffs Harbour Case Study have been reported in two published papers (**Pritchard** et al., 2001 and 2007) which appear in Chapter 6; these findings are not repeated in detail here.

Key characteristics of the Coffs Harbour discharge and its morphological setting are provided in Table 9.2.

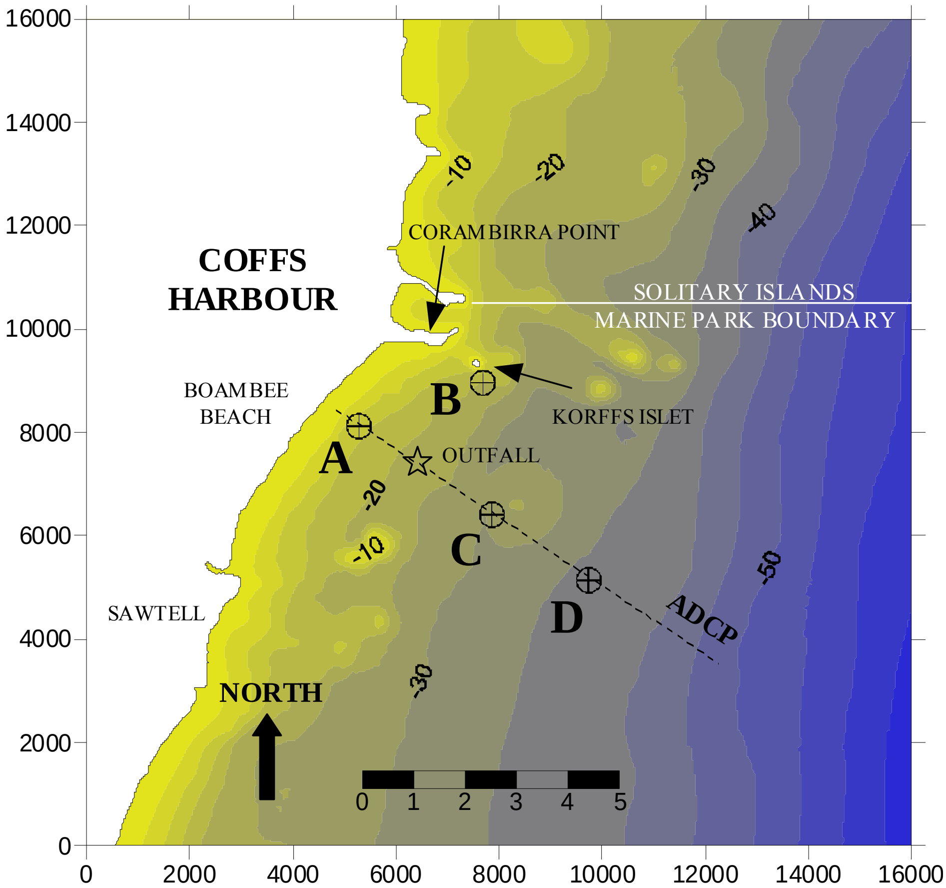


Figure 9.18 Study location showing local bathymetry, ADCP deployments (A-D) and transects (dotted lines). From **Pritchard** et al. (2007)

The Wake Parameter indicates borderline conditions for wake formation which is consistent with observations of only transient re-circulation cell formation.

The calculated and observed eddy length scales are remarkably similar (800m vs 1000m respectively). Expansion south of Corambirra Point due to the clockwise rotation of the coastline may contribute to the slight underestimation of eddy size by the Eddy Length Scale Parameter (R_L).

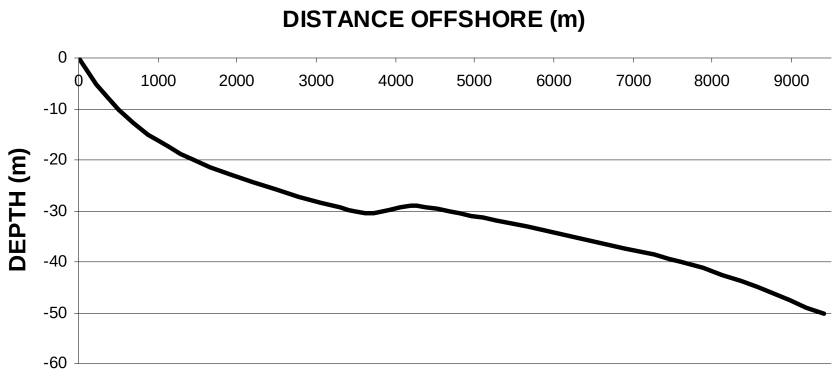
A cross-shelf bathymetry profile and shore parallel residual currents along the prescribed alignment of the new outfall are shown in Figure 9.19. For the residual current scenario, the wake is clearly shown with significant horizontal shear across the interval from 1.5 to 2km offshore. The propensity for a lee eddy offers only limited potential for pollutant trapping (ERV = 0.02%).

Table 9.2 Coffs Harbour Case Study Morphological and Discharge Characteristics

Observed and Assumed Characteristics	
CBL Type:	*Inner CBL Headland Wake*
Bay Type:	*Open Sweep* (Boambee Beach)
Headland Type:	*Triangular* (complex) : broad scale *Coastal Step ($S_{step}W$)*
Key Features:	Complex headland bathymetry (Harbour and Korffs Islet)
Headland Length (Corambirra Point)	L = 860m
Water Depth (Wake Parameter calculation)	H = 20m
Assumed vertical eddy diffusion coefficient	Kz = 0.1 m^2/s
Assumed current velocity	= 0.2 m/s
Observed/simulated eddy length scale	Obs R_L = ~1000m (radius)
Outfall (as constructed)	
Diffuser Length	D = 185m
Outfall length (from shore)	= 1500m
Effluent Flow Rate	E_F = 0.24 m^3/s

Calculated Parameters		
Wake Parameter	P	= 0.93
Eddy length scale	R_L	= 800m
Eddy Retention Value	ERV	= 0.02%

A



B

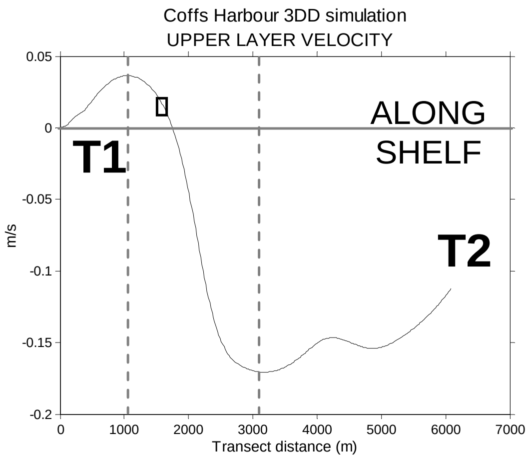


Figure 9.19 Cross-shelf bathymetry (A) and residual current (B) profiles along the prescribed alignment of the outfall (T1-T2). Outfall located at 21m water depth shown as box on T1-T2. Derived from data presented in Figures 1 and 8 in Pritchard et al. (2007).

A short sequence of current and wind reversals is shown in Figure 9.20, which illustrates a phase difference in the response of offshore currents compared to free stream flows. Visualisation of the complete time series is available via the tool provided in Appendix 4. Clearly, in some cases the more rapid response of near shore waters to changes in local drivers promotes shear and occasionally re-circulation in the lee of Corambirra Point.

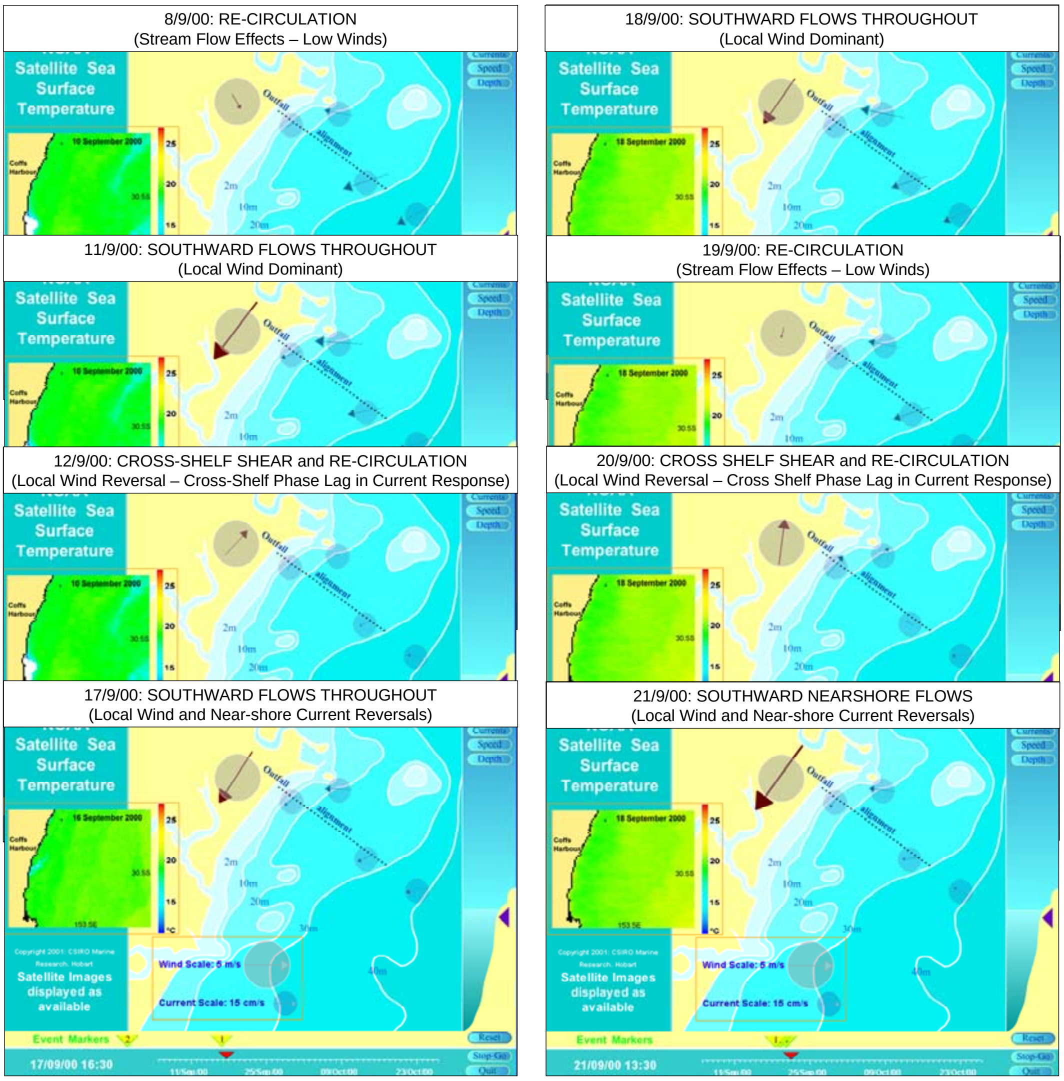


Figure 9.20 Time series wind and surface current data observed during the Coffs Harbour Case Study – images from OFS data visualisation tool in Appendix 4.

9.4.3 Boulder Bay

Boulder Bay is located within the *Inner CBL* in the Port Stephens Great Lakes Marine Park, 150 km north of Sydney. The complex bathymetry of Boulder Bay is bounded by obstacles, the largest of which is Snapper Island which extends up to 200m offshore (Figure 9.21). Snapper Island was not picked up as a significant 'headland' in the morphological classification in Chapter 7, due to its relatively small scale and complex morphological setting.

A

B

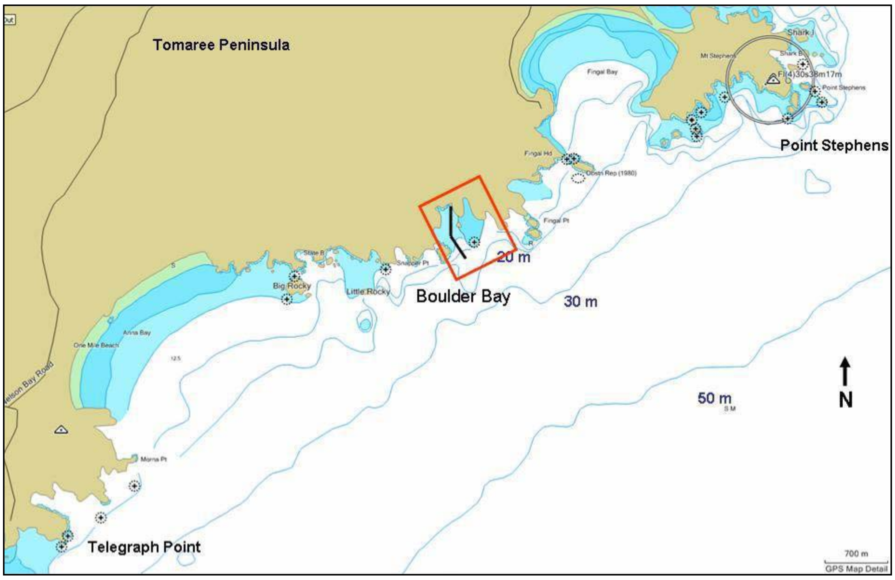


Figure 9.21 A: Bay dimensions and outfall location (GoogleEarth image).
B: Location of Boulder Bay outfall and regional bathymetry (CEE, 2010).

The Boulder Bay Waste Water Treatment Works accepts waste water from Port Stephens and nearby towns. In November 1993, an offshore outfall was commissioned with three rose head diffusers with eight ports each located in 16 to 20 m water depth, just east of Snapper Island. The outfall diffuser is on the upper section of a steep undersea escarpment which extends between the 15 and 27 m depth contours (Figure 9.22).

At a regional scale divergence of southward EAC flows associated with the change in the orientation of the coastline and continental shelf south of Port Stephens ($S_{step}W$ in Figure 9.4B) promotes a northward flowing *Counter Current* past Boulder Bay (Laurie, Montgomery and Pettit, 1977a,b; Figure 9 in Pritchard and Koop 2005 in Chapter 5), while at a local scale wind stress can dominate local circulation (AWACS, 1991).

Key characteristics of the Boulder Bay discharge and its morphological setting are provided in Table 9.3. Current effluent discharge rates are 0.1 – 0.15 m^3/s with a summer peak (CEE, 2010).

Table 9.3 Boulder Bay Morphological and Discharge Characteristics

Observed and Assumed Characteristics		
CBL Type:	*Inner CBL Headland Wake*	
Bay Type:	Complex *Open Rectangular*	
Headland Type:	Rugged *Triangular*	
Key Features:	Complex bathymetry within and outside the bay	
Headland Length (Snapper Island)		L = 200m
Water Depth (Wake Parameter calculation)		H = 17m
Typical Current Velocity (observed median)		U = 0.09 m/s
Assumed vertical eddy diffusion coefficient		Kz = 0.1 m^2/s
Assumed duration of re-circulation (weatherband)		T = 6.048 x 10^5s
Observed eddy radius (n=13)		Obs R_L = ~75m (median)
Outfall (as constructed)		
Diffuser system length (3 diffusers)		D = 99m
Outfall distance offshore		= 500m
Effluent Flow Rate (summer peak)		E_F = 0.15m^3/s
Calculated Parameters		
Wake Parameter	P	= 1.3
Eddy length scale	R_L	= 260m
Eddy Retention Value	ERV	= 0.51

The bathymetry of the coastline either side of Boulder Bay, from Telegraph Point to Point Stephens is complex (Figure 9.22), with a series of rocky headlands and small rocky coves. There are also a series of small rocky islands and submerged reefs scattered across steeply sloping seabed, with the 20 m depth contour between 300 and 500 m offshore in the proximity of Boulder Bay. Offshore from the 20m isobath the seabed is less steep, with 50 m depth contour more than 2 km offshore.

The Wake Parameter, based on the configuration of the shoreline, indicates a propensity for wake effects (1.3). This belies simple interpretation due to the complex bathymetry, especially the broad, offshore, gully ending in a steep escarpment immediately south east of Snapper Island (Figure 9.22).

Near field dilution modeling generally fails to take in to account the re-entrainment of effluent which may have been trapped or re-circulated in vicinity of the discharge point and thus can overestimate the degree of pollutant dilution (underestimates pollutant concentrations in receiving waters).

A series of oceanographic investigations were undertaken during the 1980's to assist with the design and placement of the offshore outfall at Boulder Bay, as illustrated in Figure 9.23 (CEE, 1987; AWACS,1991). Current meters and drogue deployments revealed two zones: within Boulder Bay (inshore from Snapper Island) where trapped anticlockwise eddies of variable size often developed and were observed for up to several hours. Eddies were at times small and generally confined to the northern and western parts of the bay but some extend across most of the bay influenced by stronger, predominantly shore-parallel offshore currents. Median currents within the bay were ~0.06 m/s, while currents near Snapper Island averaged 0.08 m/s and currents outside the bay in 27 m depth averaged 0.09 m/s.

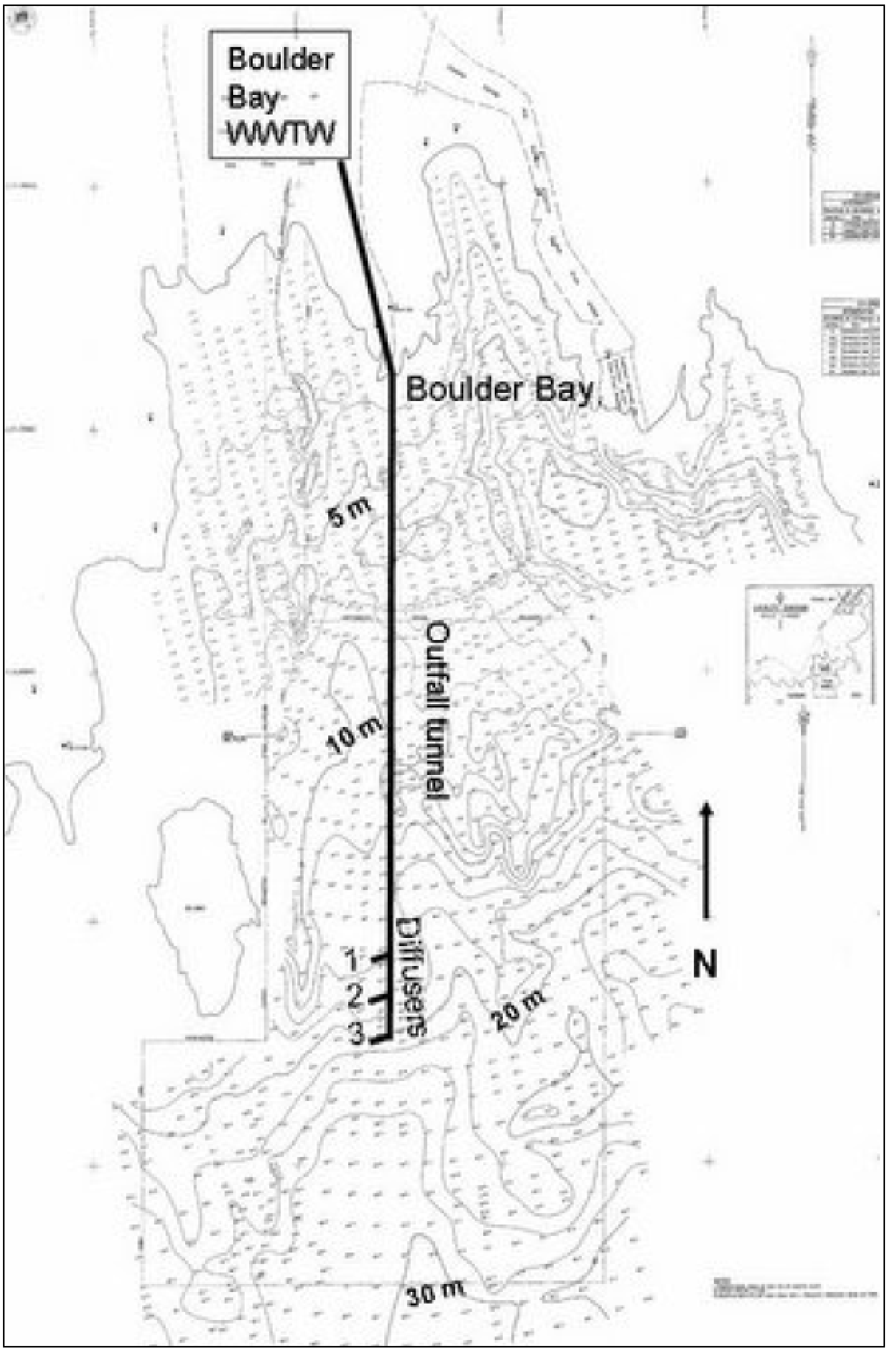


Figure 9.22 Detailed local bathymetry of Boulder Bay outfall (CEE, 2010).

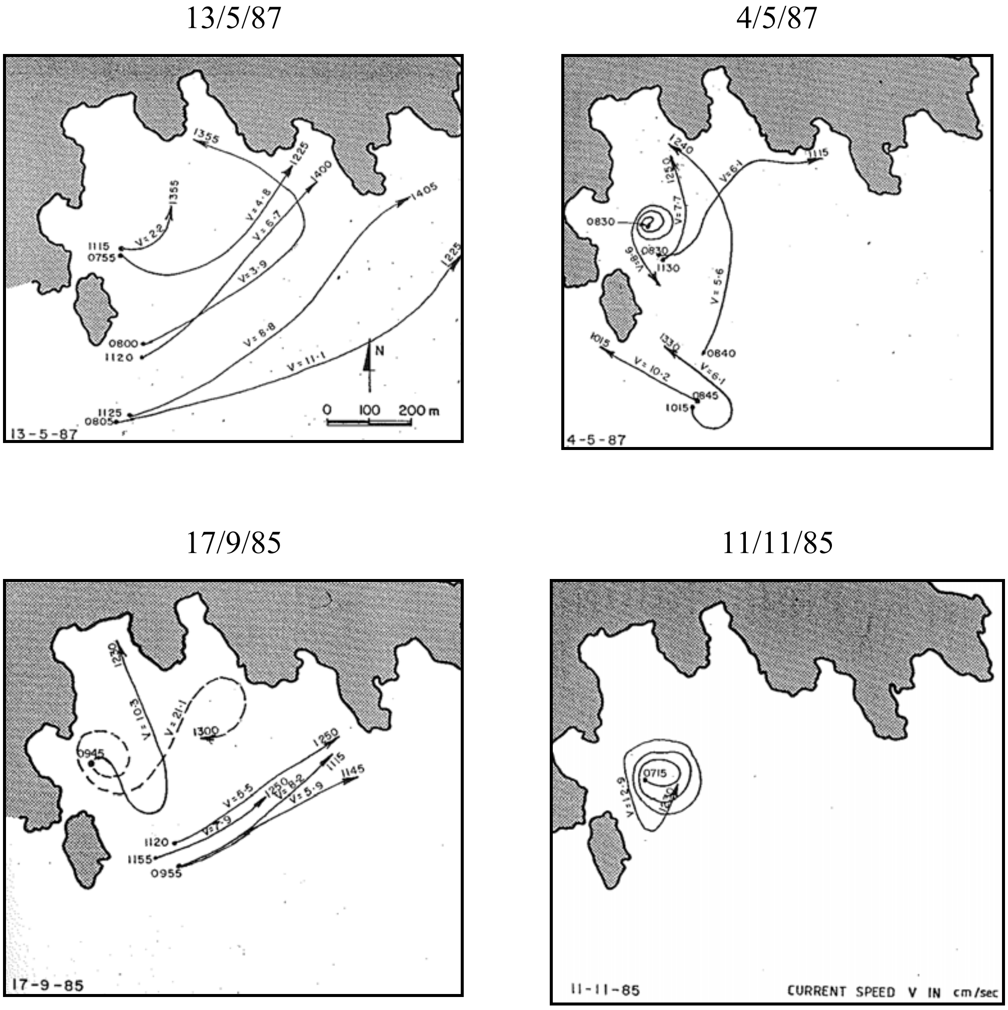


Figure 9.23 Examples of drogue paths in Boulder Bay modified from MHL (1991).

Current shear and anticlockwise rotation of offshore currents was frequently observed (eg 13/5/87). Interestingly the rotation of the recirculation cell is invariably anticlockwise, often in small intense cells to the north east of Snapper Island (eg 4/5/87 and 11/11/85). These anticlockwise rotating cells persist even under the influence of complex, reversing offshore flows (eg 4/5/87), presumably due to channeling of flows across the complex bathymetry of the Bay. Unfortunately, current meter deployments did not coincide with drogue experiments and detailed high resolution hydrodynamic modeling is unavailable to explore interactions with bay morphology.

Soon after commissioning of the outfall in 1993 impacts were detected due to discharge of secondary treated sewage effluent from the outfall shown in Figure 9.22 including:

- increased the abundance of both adult and juvenile kelp plants immediately after the commissioning of the extended outfall (Ajani et al., 1999);
- decreased the abundance of the eastern hulafish (*Trachinops taeniatus*), yellowtail (*Trachurus novaezelandiae*) and the urchin (*Centrostephanus rodgersii*), decreased the abundance and species richness of fish at the outfall compared to fish assemblages at the control locations, and increased the abundance of some cryptic (small, cave dwelling or camouflaged) fish species over time at the outfall (Smith et al., 1999); and,
- significantly reduced the cover of crustose and foliose algae at the outfall location compared to control (Port Stephens and Tomaree Head) locations within 3 months of the commissioning of the outfall; decreased the cover of several species of sponge, including *Cymbastela concentrica*, *Geodinella sp*. and *Spongia sp*., however, declines in the cover and number of species of sponges or total fauna did not change significantly; increased the cover of a nondescript matrix comprising silt and microorganisms doubled its representation to almost 60%; and, changed the overall composition of the community at the outfall from one in which algae and sponges were well represented to an assemblage dominated by silt and ascidians (Roberts et al., 1998).

Subsequent impact assessment studies by Roberts and Murray (2006) found no detectable impact on sessile biota although silt was a major component of cover on all reefs.

Identification and delineation of the turbulent retention zone within Boulder Bay at an early stage in the wastewater system planning and decision making process would allow optimisation of the outfall location. In this case a relatively short extension of the outfall beyond the extremities of the Bay would have resulted in a considerable reduction of the ERV with a corresponding improvement in the performance of the outfall system. This in turn would alleviate some of the concerns about potential impacts in the vicinity of the outfall, especially as effluent flows increase with population growth in the sewerage catchment.

9.4.4 Bate Bay

Bate Bay in southern Sydney is an *Open Sweep* bay type with a sewage outfall at its northern extremity at Potter Point and a major reef called Merries Reef running 2km southwestward between the outfall and popular sandy beaches inside the Bay (Figure 9.24), with potential for *Wave Zone*, *Wake Zone* (flow separation) and *Bay* effects.

A. B.

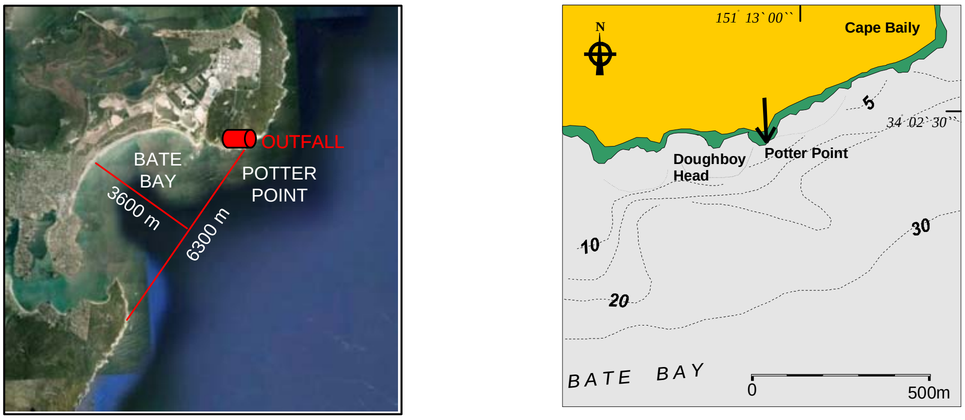


Figure 9.24 Bate Bay
A: Dimensions and outfall location (GoogleEarth image); B: Local bathymetry (from Ingleton and Large, 2002).

The seabed in the vicinity of Potter Point is characterised by a series of sandstone shelves stepping down to a depth of 30m approximately 500m offshore. Effluent from Cronulla Sewage Treatment Plant is discharged into 6m of water from a shoreline outfall located at Potter Point outfall on the southern side of the Kurnell Peninsula (Ingleton and Large, 2002).

In the early nineties, just after the bulk of Sydney's sewage effluent was transferred from offshore via deepwater outfalls (**Pritchard** 1997), the beach at the northern end of Bate Bay (Boat Harbour) was the beach most frequently affected by sewage contamination in Sydney with a very strong gradient of improving water quality in Bate Bay from north to south (Riddle, 1994). In the 1990's Sydney Water Corporation (then Sydney Water Board) committed to a comprehensive assessment program to determine the sources and causes of occasional pollution incidents in the Cronulla Region (Riddle, 1994).

Key characteristics of the Bate Bay discharge and its morphological setting are provided in Table 9.4.

Table 9.4 Bate Bay Morphological and Discharge Characteristics

<u>Observed and Assumed Characteristics</u>	
CBL Type:	*Inner CBL Wave Zone* and *Wake* (flow separation)
Bay Type:	*Open Sweep*
Headland Type:	*Coastal Step* (Potter Point = $N_{step}E$)
Key Features:	Wave effects/complex internal bathymetry/riverine inputs
Headland Length (Potter Point)	L = 3600m (N_{step}E)
Water Depth (for Wake Parameter calculation)	H = 20m
Indicative Current Velocity	U = 0.2 m/s
<u>Outfall (as constructed)</u>	
Diffuser system length	D = point source
Outfall distance offshore	shoreline
Effluent Flow Rate	E_F = 0.63 m^3/s
<u>Calculated Parameters</u>	
Wake Parameter	P = 0.2

Potter Point does not present a significant obstacle to southward flows although flow separation is favoured at Potter Point by the sudden expansion associated with the *Coastal Step* in to Bate Bay, albeit complicated by the presence of Merries Reef. Indeed the presence of this reef system signals a need to consider *Wave Zone* effects.

Extensive studies (Riddle, 1994; Large et al., 1994) found that cross-shelf flows were limited near Bate Bay except under high wave conditions when an anticlockwise circulation was driven by winds and waves breaking across Merries Reef. Under such conditions effluent from a sewage outfall at Potter Point was drawn over Merries Reef and into Bate Bay, impacting recreational water quality. In contrast, under calm wave conditions Merries Reef appeared to act as a barrier so water to the west of the reef had a greater residence time than throughout the rest of the Bay.

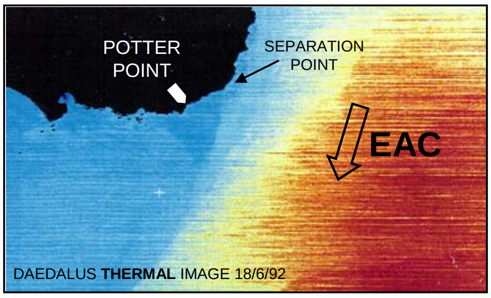
Currents at the entrance of Bate Bay were predominantly southward and flowed parallel to isobaths, consistent with observations off Coffs Harbour and Sydney (presented in Chapters 6 and 8). On occasions Large et al. (1994) found evidence of northward *Counter Currents* off the Royal National Park to the south of Bate Bay (weak) and along the Kurnell Peninsula (stronger), possibly associated with divergence of regional southward flows as the orientation of the shelf rotates clockwise in the proximity of Bate Bay. A significant near shore shear zone was observed with typically low and variable current velocities inside the Bay and energetic synoptic weather band (2-30 days) currents offshore. Salinity observations indicated higher residence times within the Bay.

Interestingly the Bate Bay study (Riddle, 1994) found no evidence of pollutants entering Bate Bay from sources outside the Bay, although discharges of sewage effluent from Malabar deepwater outfall were detected offshore (east) of Bate Bay. Other pollutant discharge points outside but in close proximity to Bate Bay included industrial outfalls with localized impacts detected at Tabbigai and Yena gap on the Kurnell Peninsula to the north of Bate Bay.

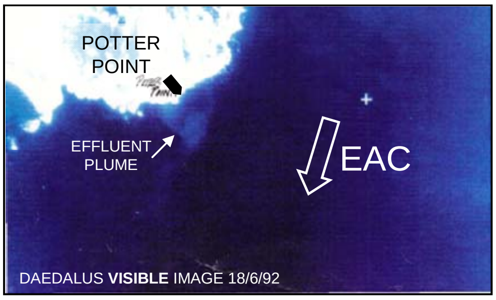
High resolution Daedalus airborne scanner imagery shows the flow separation to the northeast of Potter Point with a front constraining the then primary treated sewage plume discharged at Potter Point (Figure 9.25). This flow separation is the likely explanation for the isolation of Bate Bay from other external pollutant sources (Riddle, 1994) although it serves to constrain effluent discharged from Potter Point outfall, placing it at the head of any wave induced circulation across Merries Reef and in to the northern part of Bate Bay.

Early consideration of CBL effects would provide an efficient pathway to rapidly focus on the primary factors leading to pollutant impacts in Bate Bay, identify possible solutions (eg upgraded treatment at Cronulla STP in 2001) and dispel the notion that the offshore transfer of Sydney sewage to deepwater outfalls was responsible for pollution incidents in Bate Bay.

A



B



C

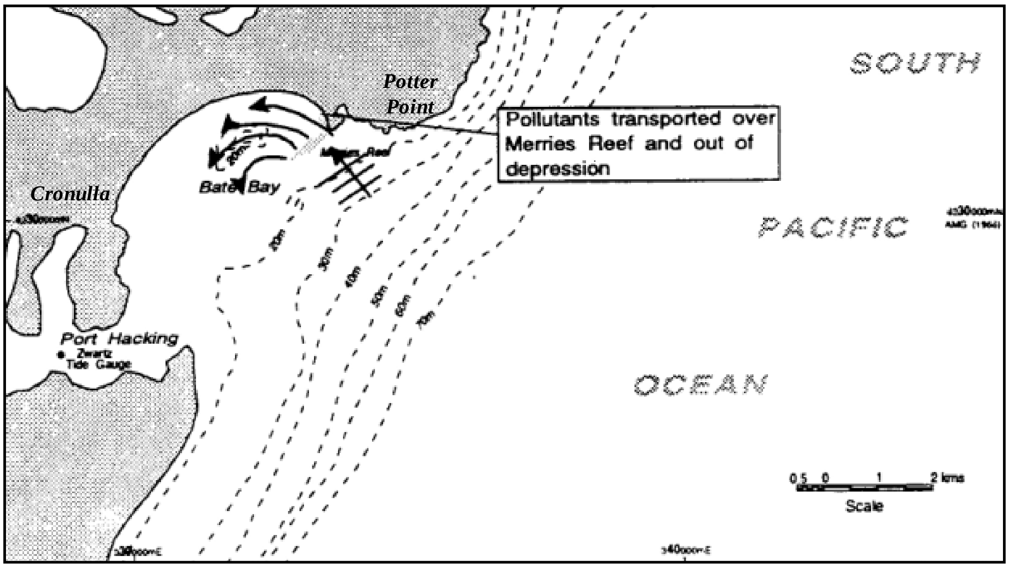


Figure 9.25 Bate Bay circulation

A. Separation of the southward EAC driven flow at Potter Point, depicted by sea surface temperature Daedalus airborne multispectral scanner image
B. Effluent trapping in the lee of Potter Point, depicted in the visible sprectrum by Daedalus airborne multispectral scanner image. The shoreline outfall is indicated by the block arrow.
C. Schematic of wave induced anti-clockwise circulation in Bate Bay (from Anderson and Gordon, 1993) based on extensive moored and profiling (ADCP) current meter deployments, drogues, aerial photography, satellite observations, salinity, temperature, and water quality observation together with modeling (Riddle, 1994; Large *et al*., 1994).

(Daedalus image from Wilson *et al*., 1995 – a component of the Sydney EMP described by **Pritchard**, 1997).

9.5 Management Implications

This thesis has provided a new understanding of the way that the interactions between flows and coastal morphologies in the *Coastal Boundary Layer* can affect both pollutant dispersion and the distributions of marine communities and species that are potentially impacted by these pollutants.

Explicit recognition of the *Coastal Boundary Layer*, including *CBL Modifiers* and *CBL Oscillators*, provides an opportunity to improve the management and regulation of human actions to deliver better outcomes for the marine environment. Specific management applications include but are not limited to approvals, regulation and management of: point source discharges of pollutants to the ocean; algal blooms including biotoxins issues; and, marine protected areas.

9.5.1 Discharges of pollutants to the ocean

Wastewater managers are required to pursue a range of wastewater management objectives such as source control, beneficial re-uses, and minimisation of overall impacts to a socially acceptable level while complying with legislative requirements (POEO, 1997). Australia and New Zealand share a set of comprehensive water quality guidelines (ANZECC/ARMCANZ, 2000) which guide users to identify environmental values, develop water quality objectives (e.g. DEC, 2005), and assess potential impacts in a risk based framework.

Even when stringent effluent limits are set and strict waste minimisation is practiced, sewage effluents are generally of poorer quality than the receiving water (**Pritchard** et al., 2003). It has been accepted practice to apply the concept of the mixing zone as outlined in national guidelines (ANZECC/ARMCANZ, 2000). That is, an explicitly defined area around an effluent discharge where certain environmental values are not fully protected. Although mixing zones have this special status they remain subject to assessment criteria to provide minimum levels of protection for local environmental values which preclude major irreversible impacts, acute toxicity and unacceptable long term accumulation of contaminants. In such circumstances, early investigation and definition of mixing patterns and potential effluent dispersion are of paramount importance in order that outfalls are located and configured to minimise potential impacts.

For many decades there has been intense scrutiny of sewage discharges to the ocean; a long standing NSW Government policy 'opposes ocean outfalls except in instances where the environmental and public health risks of alternative sewage managements systems would be demonstrably greater' (P.Marczan pers com, 2010). Despite this emphasis on environmental and public health risks, options for ocean outfalls can be artificially constrained by a limited prescribed range of assumed engineering solutions and a failure to recognise heterogeneous flow regimes within the CBL early in the planning process.

Two of the case studies identified above – Coffs Harbour and Boulder Bay - illustrate the need for early screening level assessments to scope an appropriate range of possible solutions. Initial assessments at both locations failed to explicitly consider re-circulation and headland/bay wake effects.

Ironically, as recently as 2010 an environmental assessment suggested that the recirculation cell observed in Boulder Bay may be advantageous: "…. drogue studies revealed a regular recirculation current within Boulder Bay. The study found that effluent was likely to be entrained in these eddies within the Bay which would allow time for dilution of effluent with seawater, before it was transported away from the bay." (CEE, 2010). This demonstrates an ongoing limited understanding of both CBL effects and the regulatory context.

The sampling design for initial current meter deployments to characterise local circulations for the assessment of Coffs Harbour outfall options was not suitable to describe wake effects in the lee of Corambirra Point. Likewise, initial assessment of engineering options for the offshore outfall at Boulder Bay focused on mixing through turbulence and entrainment due to jet effects and buoyant rise of the effluent plume, with little consideration of the potential for re-entrainment or the benefit-cost analysis of a small extension of the outfall to clear the wake effects.

High levels of treatment prior to discharge are often necessary but not sufficient to minimise environmental impacts associated with wastewater discharges. Impacts can occur even with high levels of sewage treatment if effluent is trapped within the CBL. For example, failure to extend the Boulder Bay discharge point to beyond the extremity of the embayment, and associated recirculation, fundamentally limits the environmental performance of the system; Roberts et al. (2006) showed through a series of manipulative field experiments that decreasing salinity impacted sponge dominated marine assemblages.

Many sewage discharges to the ocean prior to 1990 were designed with little regard to the dispersion characteristics of the coastal boundary layer (see Appendix 4); indeed many outfalls appear to have been designed for remote concealment rather than dispersion. For example, ten of the thirty two regulated NSW ocean outfalls were designed with so little consideration of mixing processes that they could not be represented for standard dispersion models such as United States Environmental Protection Agency's hydrodynamic mixing zone model CORMIX (Ingleton and Large, 2004).

This approach would be useful to scope options for other poor performing NSW outfalls (described by Krogh, Pritchard and Holden in Appendix 4) within embayments such as:

- Janies Corner outfall inside a small embayment near Forster; and,
- Merimbula/Pambula outfall at the shoreline within a large semi enclosed bay.

and in the lee of headlands such as at:

- Sawtell inshore on the southern side of Boambee Head
- Camden Haven on the southern side of Camden Head/Perpendicular Point

Wastewater management solutions inevitably balance environmental/scientific factors with social-economic factors. After exploiting feasible source control and re-use opportunities all foreseeable 'solutions' for coastal sewerage systems require a proportion of the wastewater to be discharged to the environment. A hierarchical screening of risks driven by an understanding of CBL processes is particularly relevant to highly dynamic marine environments, and promotes transparent decision making which in turn promotes cost effective solutions.

Some of the factors contributing to environmental exposure to high concentrations of pollutants are fundamental (beyond human control) while other factors are readily controllable such as:

- location of the discharge point to avoid sensitive habitats and wake zones with high *Eddy Retention Values*; while maximising water depth and exposure to high ambient current velocities at the point of discharge.
- level of wastewater treatment prior to discharge to minimise initial concentrations and loads of pollutants.
- hydraulic design of the outfall to maximise initial mixing potential

Pollutant concentrations tend to increase with improvements to sewerage systems (less as rainwater ingress) and with increasing re-use (higher pollutant concentrations in waste streams). Likewise, waste streams associated with de-salination plants have increased in recent times due to major droughts in Australia during the first decade of this century. This increased coupling of water supplies and wastewater disposal systems across the *Inner CBL* further emphasises the need to understand and map CBL processes, especially near centers of human population where engineering solutions tighten local ocean loops in the water cycle .

Feasible, cost efficient, options can be scoped by performing screening level assessments, based on readily available data, early in the planning and budgeting process. Screening level assessments can be focused through consideration of CBL processes outlined in Chapter 4 and can exploit existing basic data sets such as: morphological assessments proposed in Chapter 7; readily available remote sensed data described in Chapter 5; existing time series data such as from the long term CSIRO Port Hacking monitoring stations used in Chapter 6; recent observational data streams such as those from the recently established national Integrated Marine Observing System (IMOS); and, available coastal modeling such as emerging 'Ribbon' modeling approaches which are utilising global models by developing adequate turbulence closure and open boundary algorithms for broad scale characterisation of coastal processes (CSIRO, 2011). In this way, a set of rational options can be identified through screening level assessments and prioritised for more detailed assessments. Subsequent, targeted assessments may then require acquisition of additional data and more sophisticated modeling tools, as demonstrated in the case of Coffs Harbour in Chapter 8.

Having undertaken screening, and then more focused environmental assessments of outfall options, we have a sound platform for negotiations that lead to transparent decision making, taking in to account important socio-economic factors (i.e. explicit compromise).

For example, in the case of Coffs Harbour, the combination of observations and model simulations allowed the development of a benefit-cost curve, where benefits were expressed in terms of current speed (an agent of dispersion) and costs were expressed as incremental engineering costs of extending the outfall further offshore (Figure 9.26). Here a shear zone located ~2-3km offshore associated with the *CBL Wake* provided the greatest opportunity to optimize dilution benefits for relatively small additional cost increments. This benefit-cost curve assumed that outfall construction cost estimates would increase almost linearly with distance offshore although in many instances incremental offshore extension of outfalls could be expected to be less due to mobilization costs.

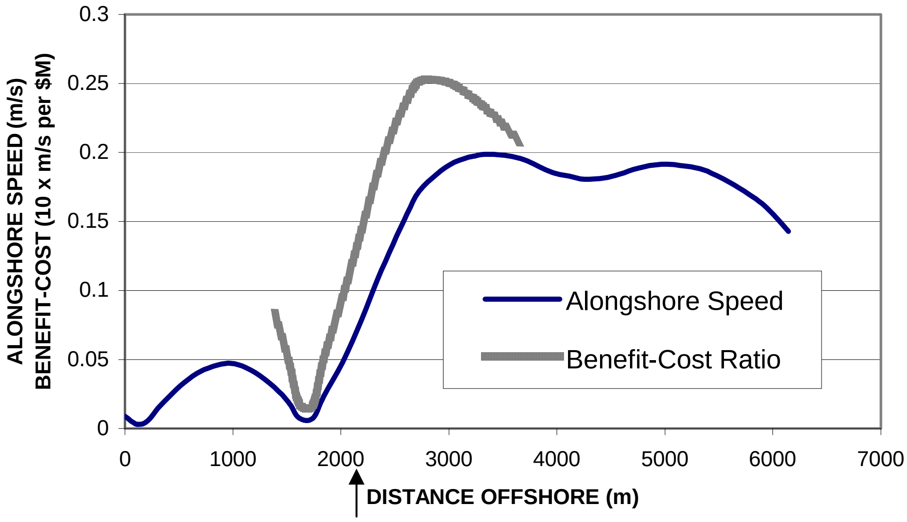


Figure 9.26: Indicative Benefit-Cost based expressed as a ratio of current strength to relative cost. Incident averaged current speed is plotted and the arrow indicates the Outfall location.

At a more conceptual level the identification of causal mechanisms to explain the correlation between bacterial contamination of beaches and wave induced circulation across Merries Reef at the northern end of Bate Bay implicated the discharge of sewage at Potter Point (see 9.5.4 above). This facilitated management action to improve the level of treatment at Cronulla STP to address beach pollution issues in northern Bate Bay, and avoided expenditure on ineffective 'solutions' to Bate Bay pollution issues such as massive expenditure to improve levels of treatment for sewage released via Sydney's deepwater outfalls.

Other *Inner CBL* effects such as the persistence of shoreline attached *River Plumes* (eg Figure 9.13) motivate stringent regulation and coastal management strategies, especially those associated with urban development and earth works in coastal catchments, stormwater management, and disposal of dredge material.

Understanding the interactions of CBL effects can be critical in predicting the spatial focus of potential impacts which must be monitored in order to inform decisions which contribute to cumulative pollutant loadings. For example, Warrick and Stevens (2011) noted the importance of the interaction of a *River Plume* with a *Headland Wake* where the Elwha River flows to the Strait of Juan de Fuca near the border of USA and Canada. Here the Elwha *River Plume* was directed eastward and shoreline attached twice as frequently as it was directed westward, due to tidally induced transient eddies which developed in the lee of a deltaic headland near the entrance of the Elwha River. This controlled the initial coastal sediment dispersal pathways following a dam removal project in Elwha River.

Many biological studies construct Before and After Control Impact (BACI) experiments (Green 1979, Underwood 1991, 1992, 1993) to detect environmental impacts. These impact assessments involve data collection before and after a putative impact at (where possible) replicated "control" and "impact" locations. In this way BACI designs take into account background variability that is common to both control and impacted sites. In many cases it is reasonable to assume that shifts in environmental factors in the ocean would affect the background variability at outfall and control sites equally. However, poorly selected 'Control' sites, combined with before-after shifts in the spatial structure of the CBL (and associated ambient factors), have the potential to bias results of real world impact assessments (Lee and **Pritchard**, 1996). Consider BACI assessments of the impact of a new ocean outfall on fish populations. Fish distributions are affected by East Australian Current (EAC) dynamics (Young et al., 2001) but EAC dynamics can exhibit significant spatio-temporal variability (Suthers et al., 2011). So for instance, fish carried with (or attracted to) warm East Australian Current (EAC) waters are likely to be present in similar numbers at both control and outfall sites if they receive EAC waters at similar times. However, if CBL processes result in EAC waters arriving at different times (spanning the before-after periods) then the experimental design is compromised. Therefore, control and impact sites should be selection based on an understanding of the inherent spatio-temporal variability of relevant CBL features.

9.5.2 Algal blooms including biotoxins

Visible and/or harmful algal blooms (HABs) have the potential to affect tourism in New South Wales (NSW), Australia, which is focused on coastal regions and is worth more than A$6 billion p.a. In NSW coastal waters, the magnitude and frequency of 'red tides' of the non-toxic dinoflagellate *Noctiluca scintillans* appear to have greatly increased since the early 1990's (Ajani et al., 2001a, 2011).

Phytoplankton have been implicated in seafood contamination and fish kills in NSW coastal waters. For example, during the summer of 1997-1998 *Dinophysis acuminata*, a producer of diarrhetic shellfish poisoning, was implicated in the contamination of edible surf clams (pipis /Donax sp) at Ballina some 700km north of Sydney and Newcastle just north of Sydney with a total of 82 cases of gastroenteritis in consumers (Ajani et al., 2001b). Recently, in February 2011, a toxic microalgae, *Karlodinium micrum*, was implicated in a massive fish kill in northern Jervis Bay which indiscriminately killed thousands of fish (N.Knott *pers comm*., 2010).

In Chapter 5, a predictive understanding of algal blooms was developed and illustrated based on an understanding of CBL processes, and available remotely sensed data complemented by established meteorological and oceanographic data streams. This was possible because natural upwelling/uplifting were identified as the principal driver of marine (offshore) algal blooms in NSW coastal waters despite significant sewage inputs near major urban centres (**Pritchard** et al., 2003; Ajani et al., 2001a; Hallegraeff and Reid, 1986). Furnished with this knowledge and an understanding of specific upwelling/uplifting processes, periods of increased risk of marine algal blooms can be identified to inform timely management responses, through established procedures such as those outlined by NSW Regional Algal Coordination Committees.

Developments in the capabilities and applications of satellite remote sensing reported by **Pritchard** and Koop (2005) in Chapter 5, and a subsequent review by McClain (2009) noted the feasibility of monitoring for HABs and red tides using ocean colour data streams. However, management applications must recognize limitations in coastal waters where coastal boundary layer phenomena lead to heterogeneous and complex optical properties that challenge the prescribed algorithms used to infer algal pigment concentrations. Although the limited spatial and spectral resolutions of freely available ocean colour data streams remains a limitation, initiatives are underway in NSW and elsewhere to improve ocean colour products through acquisition of relevant local validation data, and the development of more sophisticated algorithms based on observed optical properties of coastal ('Case 2') waters (P.Davies and A.Dekker pers comm. 2011).

Management responses to algal blooms include warnings and advisory alerts which rely on an understanding of the potential evolution and fate of algal blooms in the CBL. There have been precautionary oyster market closures (see Chapter 5 especially Figure 11, and **Pritchard** et al., 2001), and many NSW recreational beaches have been closed due to perceived or actual risks of red tides. Although *Outer CBL* processes drive upwellings of nutrient rich waters as shown in Chapter 4, *Inner CBL* processes determine the fine scale distribution of algal blooms and the tendency for coastal trapping where they become a greater risk to recreation and aquaculture. Recent high-resolution spatial and temporal resolution observations in California emphasise the role of *Inner CBL* physical dynamics in controlling the duration and intensity of red tide exposure to coastal habitats (Omand, et al., 2011). A red tide forming dinoflagellate (*Lingulodinium polyedrum*) initially developed as a subsurface layer before internal wave-breaking vertically mixed it to the surface where it formed an alongshore surface band which remained 500m from shore as it was blocked by a density barrier of warm water adjacent to the beach.

9.5.3 Connectivity – managing Marine Protected Areas and marine pests

The identification of CBL types and their spatial distribution is critical for marine protected area planning and management of marine pests because CBL processes determine the inherent physical connectivity across coastal waters.

The management importance of marine connectivity was recent highlighted by an independent expert review of marine park science in New South Wales (Fairweather et al., 2009) which found that "Movement and population connectivity for most organisms is poorly understood. The effectiveness of the network (in terms of size, location and zonation) is therefore unknown". This statement recognises that a key component for designing networks of marine reserves is connectivity (Palumbi 2003). By understanding scales of connectivity we can enhance our ability to predict population dynamics and our ability to manage for population recovery or rehabilitation (Coleman et al., 2011 submitted). Mace and Morgan (2006) argued that larval accumulation zones should be included in networks of marine reserves based on dominant settlement of benthic invertebrates (crabs, barnacles and mussels) in the lee of a small headland in California.

The majority of marine organisms produce pelagically-dispersing larvae so connectivity between populations is strongly influenced by dispersal mechanisms, thus highlighting the importance of CBL current patterns, together with knowledge of life histories and key habitats distributions. Metapopulation analyses incorporating the dynamics of local oceanography and the life histories of protected species have demonstrated how the spacing of protected areas can be optimised to maximise population persistence across the geographic range of the population (Botsford et al. 2003; Palumbi 2003). Configurations of marine protected areas that facilitate connectivity amongst individual protected areas, and with non-protected areas, build biodiversity resilience and contribute to conservation outcomes.

Connectivity varies spatially and temporally and can be related to CBL processes and their interactions with coastal morphology. For example, assessments of proposed networks of marine protected areas across Australia's Southwest Marine

Region included simplified modelling which indicated contrasting dispersal patterns between shallow (0-100m) and upper slope (100-500m) waters and stronger connectivity in autumn months and La Niña years when Leeuwin Current flow is maximal (England et al., 2009).

Similar connectivity issues were investigated through modelling on the east coast of Australia in relation to the potential for spread of marine pests. These studies (Roughan et al., 2011) indicated that particles released inshore of the EAC jet exhibited a greater coastal connectivity than those released offshore of the EAC front, and the separation point of the EAC strongly influenced connectivity patterns with more sites being connected (with lower concentration) downstream of the separation point of the EAC. El Niño Southern Oscillation patterns were also evident with La Niña periods having a tendency to increase summer time connectivity and El Niño periods increasing winter connectivity.

Roughan et al (2011) point out that the although propagules of marine pests can remain in the water column for periods of weeks to months, the dispersal of marine pests has typically been assessed in relation to more easily measured vectors such as ships (hulls and ballastwater), or aquaculture infrastructure. A systematic identification of the coastal boundary layer and an understanding of CBL processes can profoundly affect the ways we manage (limit) the spread of marine pests. For instance, by quantifying connectivity we can optimise rules for maximum distances from shore for the release of ballast water, and following known releases we can identify appropriate surveillance targets. von der Meden et al. (2008) found that coastline topography and local processes affected the dynamics of invasive and indigenous intertidal species in South Africa due to wave exposure being strongly dependent upon coastline topography (bays and headlands) and differential environmental preferences of invasive (Mytilus galloprovincialis) and indigenous (Perna perna) mussels.

9.6 Conclusion

Within the *Coastal Boundary Layer* (CBL), oceanographic processes operating at various scales drive flows which interact with complex shelf and coastal morphologies to shape dispersion pathways and fates of pollutants released in to the CBL, as well as structuring the biological communities that are affected by these pollutants. The *Coastal Boundary Layer* classification presented here, as applied to NSW marine waters, provides a useful framework to focus research and assessments of the potential impacts of pollutants.

Simple, readily available, data can be used for initial screening level assessments to identify the critical processes and factors contributing to potential impacts, for subsequent more detailed research and assessment of options within a risk based framework. For example, NSW *Triangular Headland* dimensions plotted in Figure 9.11 revealed that flow separation and wake effects were unlikely in water depths less than 15m and likely for headlands in water depths greater than ~35m.

Case studies have been presented to illustrate approaches to address the different impact assessment issues that arise due to the morphological setting within the *Inner CBL* (Coffs Harbour – Chapter 8) or the *Outer CBL* (Sydney – Chapter 6). The various parameterisations developed in this thesis are calculated for these cases.

They demonstrate how the CBL classification can focus and improve impact assessments to reveal options that deliver cost-effective outcomes for the marine environment.

9.7 References

Aiken, C.M., Moore, A.M. and Middleton, J.H. (2003) Non-normal perturbation growth in idealised island and headland wakes. Dynamics of Atmospheres and Oceans. 37, 171–195

Aiken C.M., Moore, A.M. and Middleton, J.H (2002) The non normality of coastal ocean flows around obstacles, and their response to stochastic forcing. Journal of Physical Oceanography 32 (10): 2955-2974.

Ajani, P., Ingleton, T., **Pritchard, T**. and Armand, L. (2011). Microalgal blooms in the coastal waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales 133, 15-31.

Ajani, P.A., Lee, R.S., **Pritchard, T.R**., and Krogh, M. (2001a) Phytoplankton patterns at CSIRO's long-term coastal station off Sydney, Journal Coastal Res., 34, 60-73.

Ajani, P.A., Hallegreaff, G.M., **Pritchard, T.R.** (2001b) Historic overview of Algal blooms in marine and estuarine waters of New South Wales, Australia, Proc. Linn. Soc. NSW, 123, 1-22.

Ajani,P.A. Roberts, D., Smith, A and Krogh, M. (1999) The effects of sewage discharge on tow bioindicators at Port Stephens, NSW, Ecotoxicology 8(4), pp 253-267.

Anderson, P.G. and Gordon, A. (1993) Bate Bay pollution study field data collection. Australian Water and Coastal Studies, Report 93/20.

ANZECC/ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment & Conservation Council and Agriculture & Resource Management Council of Australia & New Zealand.

Archambault P., Roff J.C., Bourget E, Bang B, Ingram GR (1998) Nearshore abundance of zooplankton in relation to shoreline configuration and mechanisms involved. Journal of Plankton Research, 20, 4, pp671-690.

AWACS (1991) Boulder Bay offshore ocean outfall investigation review of existing oceanographic data. Australian Water and Coastal Studies Report 90/18.

Banks, S.C., Piggott, M.P., Williamson, J.E., Bove, U., Holbrook, N.J., Beheregaray, L.B. (2007) Oceanic variability and coastal topography shape genetic structure in a long-dispersing sea urchin. Ecology, 88(12), 2007, 3055–3064

Barton, E.D. (2009) Island Wakes. In Ocean Currents: A Derivative of the Encyclopedia of Ocean Sciences, Ed: Steele,J.H., Thorpe,S.A., Turekian, K.K., Elsevier, pp470-475.

Berthot, A. and Pattiaratchi, C. (2006) Field measurements of the three-dimensional current structure in the vicinity of a headland-associated linear sandbank. Continental Shelf Research 26, 295–317.

Billot C, Engel CR, Rousvoal S, Kloareg B, Valero M (2003) Current patterns, habitat discontinuities and population genetic structure: the case of the kelp, Laminaria digitata in the English Channel. Mar Ecol Prog Ser 253:111–121

Black, K. P. and Gay, S. L. (1987) Eddy formation in unsteady flows. Journal of Geophysical Research, 92: 9514–9522.

Botsford, L.W., Micheli, F. & Hastings, A. (2003). Principles for the design of marine reserves Ecol. Appl., 13, S25-S31.

Botsford, L.W. (2001) Physical influences on recruitment to California Current invertebrate populations on multiple scales. ICES Journal of Marine Science, 58, 5, pp1081-1091

Branagan, D.F. and Packham, G.H. (2000) Field Geology of New South Wales. Department of Mineral Resources New South Wales, Sydney, Australia.

CEE (2010) Design of the Marine Environmental Assessment Program for the Ocean Outfall at Boulder Bay. Consulting Environmental Engineers, August 2010.

CEE (1987) Oceanographic investigation Boulder Bay for Hunter Water Board Port Stephens Shire Council, Report No. H.S.P. 8713, Consulting Environmental Engineers, October 1987.

CHEIS (2000) Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coff Harbour City Council, NSW, Australia.

Coleman, M.A., Chambers,J., Knott,N., Malcolm,H., Harasti,D., Jordan,A. and Kelaher,B. (2011 submitted) Connectivity within and among a network of temperate marine reserves. Submitted to Conservation Biology.

Coleman, M.A. and Kelaher,B.P. (2009) Connectivity among fragmented populations of a habitat-forming alga, Phyllospora comosa (*Phaeophyceae, Fucales*) on an urbanised coast. Mar Ecol Prog Ser, 381: 63–70.

Cresswell, G.R.,Ellyett,C., Legeckis,R., Pearce,A.F. (1983) Nearshore features of the East Australian Current system. Australian Journal of Marine and Freshwater Research, 34,105–114.

CSIRO (2011) The 'Ribbon' Model Concept. CSIRO Marine and Atmospheric Research, http://www.emg.cmar.csiro.au/www/en/emg/projects/-Ribbon--Model.html

Curran, K.J., Hill, P.S., Milligan, T.G. (2002) Fine-grained suspended sediment dynamics in the Eel River flood plume. Continental Shelf Research 22 (2002) 2537–2550

DEC (2005) Marine Water Quality Objectives for NSW Ocean Waters: Sydney Metropolitan and Hawkesbury–Nepean, Department of Environment and Conservation NSW, ISBN 1 74137 072 8, DEC 2005/584. http://www.environment.nsw.gov.au/water/mwqo/index.htm

Denniss, T., Middleton, J.H. and Manasseh, R. (1995), Recirculation in the lee of complicated headlands: A case study of Bass Point, J. Geophys. Res., 100(C8), 16,087–16,102.

Denniss, T. and Middleton, J.H. (1994) Effects of viscosity and bottom friction on recirculating flows. Journal of Geophysical Research, 99 (C5), 10183-10192.

Diehl, J.M., Toonen R.J., Botsford L.W. and Louis W. (2007) Spatial variability of recruitment in the sand crab *Emerita analoga* throughout California in relation to wind-driven currents. Marine Ecology-Progress Series, 350, pp 1-17.

England,P.R., Condie,S., Feng, M. & Slawinski, D. (2009) Modelling connectivity for resilient protected area design among areas for further assessment identified by DEWHA for the development of a Commonwealth MPA Network in the Southwest Marine Region. CSIRO Marine & Atmospheric Research / CSIRO Wealth from Oceans Flagship. http://www.ag.gov.au/cca

Fairweather, P., Buxton, C. and Robinson, J. (2009) Marine Park Science in NSW: An Independent Review. A report prepared for the Marine Parks Advisory Council, NSW. http://www.mpa.nsw.gov.au/pdf/Marine-Park-Science-in-NSW-An-Independent-Review.pdf

Faugeron S, Valero M, Destombe C, Martinez EA, Correa JA (2001) Hierarchical spatial structure and discriminant analysis of genetic diversity in the red alga Mazzaella laminarioides (Gigartinales, Rhodophyta). J Phycol 37: 705–716

Gaylord B. and Gaines S.D. (2000) Temperature or transport? Range limits in marine species mediated solely by flow. American Naturalist, 155, 6, pp769-789.

Gillanders B.M., Kingsford, M.J. (2002) Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. Oceanography and Marine Biology 40: 233-309

Gillson J, J Scandol, IM Suthers (2009) Estuarine gillnet fishery catch rates decline during drought in eastern Australia. Fisheries Research 99: 26-37

Green, R. H. (1979) In Sampling Design and Statistical Methods for Environmental Biologists. Wiley and Sons, New York.

Grimes, C.B. and Kingsford, M.J. (1996) How do riverine plumes of different sizes influence fish larvae: Do they enhance recruitment? Marine and Freshwater Research, 47 (2), 191-208

Hallegraeff, G. M. and Reid, D.D. (1986) Phytoplankton species successions and their hydrological environment at a coastal station off Sydney. Aust .J. Mar. Freshwater. Res. 37, 361-377.

Hassler, C.S., Djajadikarta, J.R., Doblin, M.A., Everett, J.D., Thompson, P.A. (2011) Characterisation of water masses and phytoplankton nutrient limitation in the East Australian Current separation zone during spring 2008. Deep-Sea Research II58(5), 664–677.

Ingleton, T. and Large, D. (2002) Modelling Coastal Discharges: Scoping Study. NSW Environment Protection Authority Report. pp77.

Jessopp, M., Mulholland, O.R., McAllen, R., Johnson, M.P., Crowe, T.P. and Allcock, A.L. (2007) Coastline configuration as a determinant of structure in larval assemblages. Marine Ecology-Progress Series, 352, pp67-75.

Johnston, D.W., Westgate, A.J. and Read. A.J. (2005) Effects of fine-scale oceanographic features on the distribution and movements of harbour porpoises Phocoena in the Bay of Fundy. Marine Ecology-Progress Series 295: 279-293

Jordan,A., Davies,P., Ingleton,T., Foulsham,E., Neilson,J. and **Pritchard,T.** (2010) Seabed habitat mapping of the continental shelf of NSW. DECCW 2010/1057, ISBN 978 1 74293 085 5.

Karman, T.V. (1931) Mechanical similitude and turbulence. National Advisory Committee for Aeronautics, Technical Memorandum 611, 1-21.

Kingsford, M. J., and Suthers, I. M. (1996). The influence of tidal phase on patterns of ichthyoplankton abundance in the vicinity of an estuarine front, Botany Bay, Australia. Estuarine Coastal and Shelf Science 43:33-54.

Krogh, M., **Pritchard,T.R**. and Rendell, P. (1998) Study Design for Long-term Monitoring of Benthic Ecosystems Near Sydney's Deepwater Ocean Outfalls. NSW EPA Technical Report Series 98/105. ISBN 0 7313 0202 8

Large, D., Holden, C., Xie, J.,Tate, P. (1994) Bate Bay Pollution Study Volume 2 Physical Oceanography Summary Report. Australian Water Technologies Water Board, Sydney.

Laurie, Montgomerie & Pettit Pty Ltd (1977a) Burwood Beach wastewater treatment works. Report on pre-design investigations. Report prepared for the Hunter District Water Board.

Laurie, Montgomerie & Pettit Pty Ltd (1977b) Boulder Bay ocean outfall. Abstract of report on environmental impact on marine communities. Report prepared for the Hunter District Water Board.

Lefebvre,A., Ernstsen,V.B., Winter,C. (2010) Influence of compound bedforms on hydraulic roughness in a tidal environment, Proceedings of the 15th Physics of Estuaries and Coastal Seas (PECS) Conference, Colombo, Sri Lanka, 14-17 September 2010.

Lee, R.S. Wallace, S.L., Holden C. and Black K.P. (2007) Scaling coastal upwelling features of the East Australian Current, Journal of Coastal Research, SI 50, 1152-1162.

Lee, R. S. and **Pritchard, T. R**. (1999) Extreme Discharges into the Coastal Ocean: A Case Study of August 1998 Flooding on the Hawkesbury and Hunter Rivers. Pacific Coasts and Ports ’99 Proceedings, Perth, W.A.

Lee, R.S. and **Pritchard, T. R.** (1996) How Do Long-term Patterns Affect Time-limited Environmental Monitoring Programmes ? Mar. Pollut. Bull. 33, 260-268.

McClain, C.R. (2009) A Decade of Satellite Ocean Color Observations, Annu. Rev. Marine. Sci. 1:19-42. [arjournals.annualreviews.org]

Mace, AJ; Morgan, SG (2006) Larval accumulation in the lee of a small headland: implications for the design of marine reserves. Marine Ecology-Progress Series, 318, pp19-29.

MHL (1991) Boulder Bay Offshore Ocean Outfall Investigation Review of Existing Oceanographic Data, AWACS Report 90/18, June 1991.

Middleton, J. H., Griffin, D. A. and Moore, A. M. (1993) Oceanic circulation and turbulence in the coastal zone, Cont Shelf Res, 13, , 143–168.

Moore, T.S., Matear,R.J., Marra,J., Clementson,L. (2007) Phytoplankton variability off the Western Australian Coast: Mesoscale eddies and their role in cross-shelf exchange. Deep-Sea Research II 54, 943–960.

Nicastro, K.R., Zardi, G.I., McQuaid, C.D., Teske, P.R., Barker, N.P. (2008) Coastal topography drives genetic structure in marine mussels. Marine Ecology-Progress Series, 368, pp189-195.

O’Byrne,M.J., Griffiths, R. W. and Hughes,G. O. (2007) Wake Flows in Coastal Oceans: An Experimental Study of Topographic Effects. 16th Australasian Fluid Mechanics Conference, Crowne Plaza, Gold Coast, Australia, 3-7 December 2007

Oke, P. R. and Middleton, J. H. (2001) Nutrient Enrichment off Port Stephens: the Role of the East Australian Current. Continental Shelf Research, 21, 587-606.

Oke, P.R. and Middleton, J.H. (2000) Topographically induced upwelling off Eastern Australia. Journal of Physical Oceanography 30, 512–531.

Omand,M.M., Leichter,J.J., Franks,P.J.S.,Guza,R.T., Lucas,A.J., Feddersen, F. (2011) Physical and biological processes underlying the sudden surface appearance of a red tide in the nearshore. Limnol. Oceanogr., 56(3), 787–801.

Palumbi, S.R.(2003) Population genetics, demographic connectivity, and the design of marine reserves. Ecol Appl , 13:S146-S158.

Pattiaratchi,C., James,A and Collins,M. (1986) Island wakes and headland eddies: a comparison between remotely sensed data and laboratory experiments. Journal of Geophysical Research, 92, C1, pp783-794.

POEO (1997) Protection of the Environment Operations Act 1997, NSW Government.

Pritchard, T.R. (1997) Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, 24/1.

Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

Pritchard, T.R. and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T.R, Lee,R.S., Ajani,P.A., Rendell.P.S., Black,K & Koop,K. (2003) Phytoptoplankton responses to nutrient sources in coastal waters off southeastern Australia. Aquatic Ecosystem Health and Management, 6(2): 105-117.

Pritchard, T. R., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Affect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.

Pritchard, T. R., Lee, R. S. and Ajani, P. (1999) Anthropogenic and Oceanic Nutrients in NSW's Dynamic Coastal Waters and Their Effect on Phytoplankton Populations. Pacific Coasts and Ports '99 Proceedings. 537-543. Institute of Engineers, Australia.

Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N. (1997) Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

Pritchard, T. R. Lee, R. S. and Davidson, A. (1996) Dispersion of effluent from Sydney's new deepwater outfalls Part 2: Observations of Sewage Plume Behaviour: Winter and Summer Examples. In Mixing Processes in Estuaries and Coastal Seas (C.Pattiaratchi, ed), American Geophysical Union, Washington, pp. 439-452.

Pritchard, T.R., Lee, R.S., Davison, A. (1993) Sydney Deepwater Outfalls: In Situ Observations of Plume Characteristics. 11th Australasian Conference on Coastal and Ocean Engineering: Coastal Engineering a Partnership with Nature, Institution of Engineers, Australia, 1993: 53-58.

Rankin, K.L.; Millineaux, L.S. and Geyer, W.R. (1994) Transport of Juvenile Gem Clams (Gemma) in a Headland Wake. Estuaries, 17, (3), 655-667.

Riddle, M. (1994) Bate Bay Pollution Study Volume 1 Summary of Bate Bay Pollution Study. Australian Water Technologies Water Board, Sydney.

Ridgway, K. R., and J. R. Dunn (2003) Mesoscale structure of the mean East Australian Current System and its relationship with topography. Progress in Oceanography 56:189-222.

Roberts, D. E., Davis, A. R., Cummins, S. P. (2006) Experimental manipulation of shade, silt, nutrients and salinity on the temperate reef sponge *Cymbastela concentrica*. Marine Ecology Progress Series, 307, 143–154

Roberts, DE, Murray, SR. (2006) Patterns in assemblages of macrobenthos associated with the ocean outfalls at Boulder Bay, Burwood Beach and

Belmont Beach, Report to HWC by BioAnalysis Pty. Ltd.

Roberts DE, Smith A, Ajani P, Davis AR (1998) Rapid changes in encrusting marine assemblages exposed to anthropogenic point-source pollution: a 'Beyond BACI' approach. Mar Ecol Prog Ser 163:213–224.

Rochford, D.J. (1975) Nutrient enrichment of east Australian coastal waters. II. Laurieton upwelling. Australian Journal of Marine and Freshwater Research 26, 233–243.

Roughgarden J, Pennington Jt, Stoner D, Alexander S, Miller K (1991) Collisions of upwelling fronts with the intertidal zone - the cause of recruitment pulses in barnacle populations of central California. ACTA Oecologica-International Journal of Ecology, 12, 1, pp 35-51.

Roughan, M.,Macdonald,H.S.,Baird,M.E.,Glasby,T.M.(2011) Modelling seasonal and interannual variability in a Western Boundary Current and its impact on coastal connectivity, Deep-Sea Research II, 58(5), 628–644.

Roughan M, Mace AJ, Largier JL, Morgan SG, Fisher JL, Carter ML (2005) Subsurface recirculation and larval retention in the lee of a small headland: A variation on the upwelling shadow theme. Journal Of Geophysical Research-Oceans, 110/C10, C10027.

Signell, R. P. and Geyer, W. R. (1991) Transient eddy formation around headlands. Journal of Geophysical Research 96(C2): 2561–2575.

Short, A. (1993) Beaches of the New South Wales Coast: a guide to their nature, characteristics, surf and safety. Australian Beach Safety and Management Program. ISBN 0 646 15055 3.

Smith, S.D.A. (1996) The Effects of Domestic Sewage Effluent on Marine Communities at Coffs Harbour, New South Wales, Australia. Marine Pollution Bulletin, Vol. 33 (7-12), pp. 309-316.

Smith AK, Ajani PA, Roberts DE (1999) Spatial and temporal variation in fish assemblages exposed to sewage and implications for management. Mar Environ Res 47:241–260

Smith, S.D.A. and Simpson, R.D. (1993). Effect of pollution on holdfast macrofauna of the kelp Ecklonia radiata: discrimination at different taxonomic levels. Marine Ecology Progress Series 96: 199–208.

Suthers, I.M., Everett,J.D., Roughan,M., Young, J.W., Oke, P.R., Condie,S.A., Hartog,J.R., Hobday, A.J., Thompson, P.A., Ridgway, K., Baird, M.E., Hassler, C.S., Brassington, G.B., Byrne, M., Holbrook, N.J. Malcolm, H.A. (2011) The strengthening East Australian Current, its eddies and biological effects — an introduction and overview. Deep-Sea Research II 58, 538–546.

Suthers, I, Roughan,M, Morris,B, Armand,L, Baird,M, Boomer,A, Booth,D, Brassington,G, Byrne,M, Cato,D, Coleman,M, Couriel,E, Creese,R, Doblin,M Figueira,W, Gladstone,B, Harcourt,R, Hill,K, Holbrook,N, McCauley,R, **Pritchard,T**, Ralph,P, Richardson,A, Robertson,R, Rogers,T, Speer,M, Steinberg,P, Taylor,M, Wang,H, Williams,W, and others. (2010) NSW-IMOS Node Science and Implementation Plan (NSIP) July 2009-June 2013. http://imos.org.au/fileadmin/user_upload/shared/IMOS%20General/EIF/NSIP_2010/NSW_IMOS_NSIP-Aug10-v10.pdf

SWC (2010) Sydney Water Annual Report 2010. http://www.sydneywater.com.au/annualreport/performance/sustainability/clean_waterways_si4.html

Tomczak,M. (1998) Shelf and Coastal Oceanography, V1.0 http://www.es.flinders.edu.au/~mattom/ShelfCoast/chapter07.html

Tomczak, M. (1988) Island wakes in deep and shallow water. J. Geophys. Res. 93 (12), 5153–5154.

Underwood, A. J. (1991) Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. Australian Journal of Marine and Freshwater Research 42, 569-587.

Underwood, A. J. (1992) Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. Journal of Experimental Marine Biology and Ecology 161, 145-178.

Underwood, A. J. (1993) The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. Australian Journal of Ecology 18, 99-116.

US EPA (1990) Technical Guidance Manual for Performing Wasteload Allocations, Book III: Estuaries – Part 2: Application of Estuarine Waste Load Allocation Models, EPA 823/R-92-003, May 1990.

von der Meden C.E.O., Porri F., Erlandsson J., McQuaid C.D. (2008) Coastline topography affects the distribution of indigenous and invasive mussels. Marine Ecology-Progress Series, 372, pp 135-145.

Ward, P.J. (1996) Japanese long lining in Eastern Australian waters 1962-1990. Bureau of Resource Sciences, 1-249.

Warrick, J.A. and Stevens, A.W. (2011) A buoyant plume adjacent to a headland-Observations of the Elwha River plume. Continental Shelf Research, 31/2, 85-97.

Wilson, J. R., Cox, D. R., Walker, J. W., Howden, M. I., Couriel, E. D. and Lee, R. S. (1995) Sydney Deepwater Outfalls Environmental Monitoring Program: Final Report Series: Volume 2: Sewage Plume Behaviour, NSW EPA Publication, 227p.

Wolanski (2007). Estuarine Ecohydrology, pp 17-39

Wolanski, E., Imberger, J. and Heron, M. L. (1984) Island wakes in shallow coastal waters. Journal of Geophysical Research 89(C6): 10,553–10, 569.

Young, J.W., Lamb,T.D., Bradford,R.W., Clementson,L., Kloser,R., Galea,H. (2001) Yellowfin tuna (Thunnus albacares) aggregations along the shelf break of southeastern Australia: links between inshore and offshore processes. Marine and FreshwaterResearch52,463–474.

10 SUMMARY AND CONCLUSION

The aim of this thesis was to investigate the processes within the coastal boundary layer that affect dispersal and advection of pollutants and, in doing so, develop conceptual models to facilitate coastal management. Six objectives were addressed to achieve this aim.

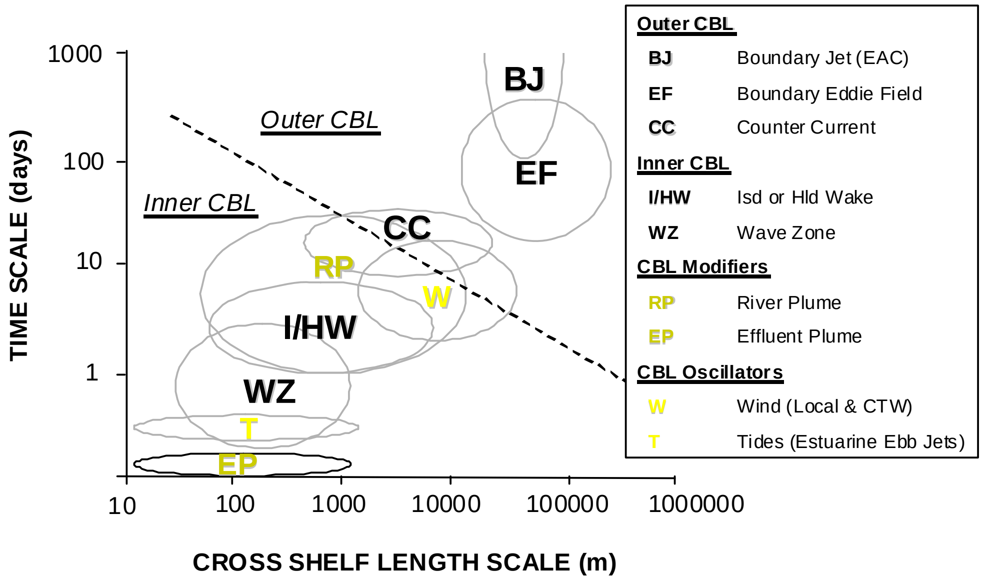
10.1 Attainment of thesis objectives

OBJECTIVE 1: Classify coastal boundary layer types observed off New South Wales based on coastal bathymetry, satellite sensed data, aerial photography, and observations of local and regional flow dynamics

This thesis presents the first classification of the Coastal Boundary Layer (Figure 10.l and Chapter 4), complemented by a new hydrodynamically relevant morphological classification of NSW headlands, islands and bays (Chapter 7). Together these classifications facilitate screening level assessments of pollutant impacts which highlight factors and processes contributing to potential environmental impacts, including impacts due to pollutant trapping in the Inner CBL (Chapter 9).

The *Coastal Boundary Layer* (CBL) is defined for the first time in this thesis as the turbulent interface between the coastline and the deep oceans, where regional currents and ocean waves are profoundly affected by changes in the orientation and variable morphology of the coastline and continental shelf. Concise, one-page summaries of CBL *Types*, *Modifiers* and *Oscillators* are provided in Chapter 4, with schematic conceptual models and selected examples from New South Wales.

No previous research is evident in published literature to characterise coastal domains through classification of the CBL and morphology.



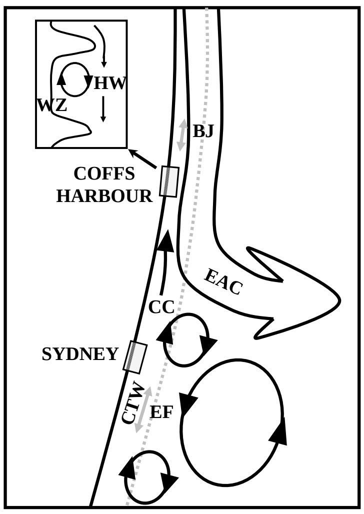


Figure 10.1 Coastal Boundary Layer types. Schematic representation of the temporal spatial scales of coastal boundary layer effects in NSW offshore waters. Ellipses represent indicative ranges of cross-shelf extents and dominant temporal expression of the CBL effects (above). Case study locations – Coffs Harbour and Sydney - are also shown (left).

CBL processes shape dispersion pathways and fates of pollutants released into the CBL, as well as structuring the biological communities that are affected by these pollutants. Therefore, the CBL classification, together with the morphological classification in Chapter 7, provides a logical framework to structure marine ecosystem studies. The CBL classification utilises readily available data to identify the critical processes and factors contributing to potential pollutant impacts, thus focusing subsequent more detailed investigations and assessment of options within a risk-based framework. Case studies demonstrate how subsequent detailed assessments relate CBL processes to potential pollutant impact assessments. Furthermore, these case studies reveal options that deliver cost-effective outcomes to understand and protect the marine environment (Chapters 6, 8 & 9).

OBJECTIVE 2: Determine the utility of remotely sensed ocean colour and sea surface temperature (SST) data to characterise broad scale ecosystem and coastal boundary layer processes and to investigate applications to support coastal management

Simple approaches to explain and predict algal blooms in NSW coastal waters are developed and demonstrated in Chapter 5, based mostly on freely available remotely sensed data streams. Broader applications are also explored, leading to a separate research agenda which is now developing algorithms capable of revealing and quantifying characteristics of the optically complex waters of the Inner CBL of NSW (see Section 10.3.3). Key research findings, relevant to NSW coastal waters, include:

- a great deal of mesoscale variability can only be observed using satellite remote sensing of ocean colour especially when combined with AVHRR SST and supported by some *in situ* observations
- satellite ocean colour imagery can provide cause-and-effect indicators at appropriate time and space scales for assessment and management of coastal systems
- a methodology is developed and demonstrated to forecast algal bloom risk and diagnose initiation sites (Chapter 5)
- quantitative remote sensing of Case 2 waters, such as the NSW coastal boundary layer, remains challenging although considerable scope exists for integration of regional or special case algorithms within an overarching branching algorithm
- the development of more sophisticated inverse modelling techniques for NSW coastal waters (& other coastal regions) requires precise multispectral radiances, with contemporary optical and concentration measurements of the water constituents.

OBJECTIVE 3: Investigate CBL processes, their relationship to coastal morphology, and their role in controlling the dispersion, fate and potential impacts of pollutants discharged to the New South Wales coastal waters

Together the findings presented in this thesis demonstrate the dominant role of *Coastal Boundary Layer* dynamics in determining the potential impacts of pollutants in high energy coastal marine environments.

The structural complexity and variable orientation of the continental shelf is described in Chapter 9, and ‘coastal roughness’ is classified across NSW in terms of types of headlands, bays and islands in Chapter 7 (see Objective 4). Dominant CBL processes and their role in controlling the dispersion of pollutants off Sydney and off Coffs Harbour are investigated in the context of their morphological settings in Chapters 6 and 8, respectively (see Objective 5). Likewise, the spatial extent of mesoscale CBL processes and their relationship to coastal morphology are demonstrated in Chapter 5, using mostly-remotely sensed ocean colour and sea surface temperature data.

Analysis of long term data sets such as the current and temperature time series data from the Sydney Ocean Reference Station and near field model results (Chapter 6) reveal CBL processes and patterns which affect the dilution and dispersion of pollutants at a range of temporal scales:

- ❖ high frequency internal waves are evident in the ORS record. Buoyant plumes rising through internal wave fields may differ significantly in height of rise and dilution compared to plume behaviour under mean stratification; likewise, biological and water quality sampling designs must recognise variability associated with these vertical displacements
- ❖ plumes generally surface (and achieve high effluent dilutions) when top-to-bottom temperature differences are less that 1°C
- ❖ de-stratification which can occur over time frames of hours promotes vertical mixing of nutrient rich bottom waters and allows effluent plumes to reach the surface

- ❖ temperature stratification exhibits seasonal and inter annual variability: peak stratification ranges from ~7°C in summer 1993 to ~4°C in summer 1994
- ❖ stratification minima and associated high plume surfacing frequencies were generally confined to El Niño (warm) episodes
- ❖ both winds and currents show prominent seasonal peaks due to latitudinal shifts in atmospheric pressure systems and seasonal differences in EAC effects (Section 6.3, Figure 6)
- ❖ the annual cycle is subtle in the current meter record and virtually absent in the wind record (Section 6.3, Figure 6)
- ❖ a low frequency signal is apparent when the directional current displacements are plotted for entire ORS time series; eastward deviations are apparent in the upper current meter record for events centered on 1996 and 2001 (Section 6.3, Figure 12).

OBJECTIVE 4: Develop a hydrodynamically relevant morphological classification of headlands, islands and open bays for New South Wales

A new hydrodynamically-relevant morphological classification of coastal features is developed, and applied to the New South Wales Inner CBL in Chapter 7, based on literature reviews, coastal maps, bathymetry charts and aerial imagery. A simple index - the Wake Parameter - is explored and applied to NSW headlands to indicate the propensity for various turbulent flow regimes for more detailed investigations (Chapter 9). The hydrodynamic implications of coastal features described in this morphological classification will be further explored through separate research collaboration (see Section 10.3).

At both small and large spatial scales the roughness and configuration of the shoreline/shelf appear to result in similar flow patterns. The new morphological classification of coastal features in New South Wales in Chapter 7 found:

- ❖ the majority of all types of bays are in the southern half of the State
- ❖ the length to width ratios of bays typically remains approximately constant irrespective of size, especially for *Open Rectangular* and *Open Sweep* bays (~1:2)

- headland morphologies range from sand dominated asymmetric cusp shaped headlands near Crowdy Head to rocky headlands with conspicuously fractal characteristics near Batemans Bay
- the median length of 114 headlands classified as *Triangular* is 624m (range 186-5768m)
- the median length of 30 headlands classified as *Coastal Step* (one-sided) is 1,324m (range 230-13,980m)
- standardised *Apex Angles* of both *Triangular* and *Coastal Step* headlands are remarkably consistent with mean apex angles of 70° (SD 24°) and 67° (SD 22°), respectively, and with identical ranges (20°to119°)
- wake effects are predicted by the *Wake Parameter* (P>1) for *Triangular* headlands in NSW coastal water depths greater than 35m. Conversely, NSW headlands in water depths less than 15m are unlikely to be associated with prominent wake effects
- Montague Island and North Solitary Island stand out from NSWs five largest offshore islands as targets for more detailed evaluation of wake effects as they appear most likely to be associated with large-scale wake effects. However, based on the *Wake Parameter*, Fish Rock, a small island about 2km offshore from Smoky Cape, has the greatest propensity for flow separation.

Based on literature reviews plus observations and modelling undertaken for the Coffs Harbour Case Study (Chapter 8), a simple process-based understanding was developed to assess the propensity for re-circulation and particle trapping in the wake of a headland or island.

OBJECTIVE 5: Investigate physical processes and dispersion characteristics for specific pollutant discharges to New South Wales coastal waters through case studies off Sydney (outer coastal boundary layer) and Coffs Harbour (inner coastal boundary layer)

The vast majority of New South Wales's sewage wastewater is discharged to the Outer CBL off Sydney. Processes affecting pollutant dispersion off Sydney are revealed and quantified in Chapter 6. Outer CBL processes also determine the outer boundary condition and regional drivers for Inner CBL dynamics which are explored in a second case study off the coast of Coffs Harbour. Here pollutant trapping and optimal initial mixing are quantified across the Wake Zone associated with a headland (Chapter 8).

SYDNEY

Sydney's three deepwater ocean outfalls were found to be the principal, continuous, anthropogenic source of nutrients to NSW coastal waters. Research findings based on new analysis of mostly existing long-term time series data, long term near field model simulations, and previous research found that:

- *Outer CBL* processes significantly mitigate many of the risk factors that lead to environmental impacts: high initial dilutions are possible and pollutant residence times are low in this high energy environment with limited flow disruption due to local bathymetric features (Chapter 6; **Pritchard** et al., 2001, 2005)
- consideration of sewage-derived pollutant loadings and concentrations discharged from Sydney's deepwater outfalls suggests a considerable potential for environmental impacts. However, significant outfall impacts remain undetected and, if present, are likely to be subtle (Chapter 6; **Pritchard** 1997; **Pritchard** et al., 1993, 1996, 1997, 1999, 2001, 2003 and others). Consistent associations between algal blooms and slope water intrusions and the lack of associations with proximity to major outfalls led **Pritchard** et al. (1999, 2003) to conclude that CBL processes leading to slope water intrusions ('upwellings') were the major factor responsible for phytoplankton blooms.

New analysis of long-term data from CSIRO sampling stations off Port Hacking (Chapter 6) found that prior to the commissioning of Sydney's deepwater outfalls nutrient patterns are consistent with winter overturning of shelf waters and episodic slope water intrusions, with enhanced biological (phytoplankton) activity depleting nutrients in surface waters during the warmer summer months. These analyses revealed that:

- relative nutrient enrichment due to extreme natural events is most marked within the upper half of the water column and up to an order of magnitude greater for nitrate than for phosphate (Section 6.4, Figure 5)
- ambient nutrient ratios suggest that nitrogen is a limiting nutrient.

When simulations of near field effluent plume behaviour were analysed in relation to long term ambient nutrient patterns it was found that:

- ❖ there is little evidence to suggest that plumes from Sydney's deepwater outfalls result in major shifts in the ratio of dissolved inorganic nitrogen to dissolved phosphorus
- ❖ discharges from Sydney's deepwater outfalls have the greatest opportunity to influence algal bloom development in the upper half of the water column during late summer.

Understanding of *CBL Modifiers* such as *Effluent Plumes* (Chapter 6) yielded the following insights:

- ❖ the entrainment and uplift of nutrient (nitrate) rich bottom waters in buoyant plumes results in a net upward flux of ambient nutrients irrespective of the contribution from the effluent
- ❖ ADCP data are vastly superior to extrapolation below the bottom ORS current meter. This is a critical finding given that investigations of plume behaviour (**Pritchard** et al., 2001) suggest that most initial mixing can occur within the bottom 10-15 m of the water column (i.e. below the bottom ORS current meter).

<u>COFFS HARBOUR</u>

Most pollutants originate in coastal catchments and outfalls in New South Wales discharge to the Inner Coastal Boundary Layer where heterogeneous pollutant dispersion patterns are structured by coastal roughness. Investigations of pollutant trapping due to wake effects are rare in the published literature.

Observational and modelling investigations found current shear, transient re-circulation, and heterogeneous patterns of pollutant dispersion capacity in the lee of Corambirra Point, immediately south of Coffs Harbour. These studies found that there is significant scope to increase offshore outfall performance (dilution and dispersion) by extending the outfall across the interval from 1.5km to 2.5km offshore. Specific findings include:

- the most profound wake effect is a persistent shear zone located ~2km offshore from Boambee Beach created by Corambirra Point
- consistent flow retardation (30-50% of free flow) and short duration cyclonic eddy re-circulation (<36hr; 2-3km diameter) in the *Wake Zone* to the south of Corambirra Point
- pollutant particle clearance and initial mixing increases rapidly across the shear zone along prescribed outfall alignment; the flux of ambient water flowing across the transect increases eighteen fold over a cross-shore distance of just 1.4km (1.6 to 3km offshore)
- current reversals are more frequent within the wake (inshore) compared to the free stream flow (offshore), thus increasing the likelihood of re-entrainment of previously discharged effluent into new plumes
- recirculation cells are not considered to be the most important wake effect limiting dilution of effluent discharged off Coffs Harbour because re-circulation cells occur sporadically and the re-circulation cell volume is typically four orders of magnitude greater than daily effluent discharged from the outfall; that is, the *Eddy Retention Value* is low.

Other findings which may have broader relevance include:

- prominent spectral peaks in all current meter data (Sites A, B, C & D) at ~12 and ~24 hours, highlight the relative contribution of the semi-diurnal tides, inertial motions and local land-sea breezes, while strong peaks at 2.5, 3.9 and 7.8 days appear to be associated with the regional weather band (Section 8.4, Figure 3)
- the vertical distribution of diurnal energy suggests that the pycnocline layer may act as a waveguide (Section 8.4, Figure 4)
- inshore currents (Site A) exhibit energy levels across the spectrum that are significantly lower than all other sites indicating quiescent wake effects; observed current strengths at Site A were 2-3 times less than those at sites further offshore (Section 8.4, Figure 3)
- along shore surface currents were correlated with local winds, typically corresponding to about 1% of the wind speed at the inshore site (13m depth) and 2-3% of the wind speed at the offshore site (35m depth)
- the study period may include a greater proportion of wind driven southward currents than would be expected based on long term wind data.

The Coffs Harbour case study provokes questions about the dynamics of re-circulation in the lee of headlands, especially the role of phase lagged responses to reversing alongshore pressure gradients. That is, sporadic recirculation may result from flow reversals when reversal occurs earlier in the wake of the headland than in the free stream where currents continue to decelerate; phase differences between the inertial responses of shallow, nearshore waters and offshore free flow promotes rotational effects.

OBJECTIVE 6: Identify applications of the coastal boundary layer classification for coastal management and develop and demonstrate simple risk assessment tools to identify factors and processes which can mitigate potential pollutant impacts

Past failures to consider the morphological settings of pollutant discharges to NSW coastal waters have resulted in gross inefficiencies of pollutant discharge systems and potential environmental impacts.

Chapter 9 explores the management implications of the interactions between flows and coastal morphologies in the *Coastal Boundary Layer* in relation to approvals, regulation and management of discharges of pollutants to the ocean. It also outlines how an understanding of CBL processes is a pre-requisite for effective management of algal blooms including biotxoins issues, configuration of networks of marine protected areas, and marine pest control.

The importance of a process-based understanding of CBL dynamics on the fate of pollutants and the application of simple risk assessment tools is illustrated by four examples:

- Sydney: *Outer CBL Effluent Plume*
- Coffs Harbour: *Inner CBL Headland Wake*
- Boulder Bay: *Inner CBL Headland Wake*

- Bate Bay: *Inner CBL Headland Wake (HW)* and *Wave Zone (WZ)*

Early consideration of CBL effects would provide an efficient pathway to rapidly focus on the primary factors leading to potential pollutant impacts for each of these examples.

Case studies off Sydney and Coffs Harbour demonstrate how coarse screening level frameworks, such as the CBL and coastal morphological classification can be used to structure site-specific assessments to address specific scientific and management issues.

For the Coffs Habour study, a new *Eddy Retention Value* (ERV) is applied to estimate an upper bound on the re-entrainment potential of re-circulation cells which may form in the *Wake Zone*. The ERV represents a hypothetical worst case re-entrainment scenario where ERV is the ratio of volume of effluent discharged during the lifetime of a re-circulating lee eddy to the volume of water within the eddy. In the case of Coffs Harbour, re-entrainment potential associated with re-circulation was found to be minimal. However, definition of the shear zone which formed in the *Wake Zone* in the lee of Corrambirra Point is found to be a critical factor in optimising location of the outfall to maximum dispersion efficiency. This is developed to form the basis for a simple cost benefit analysis.

The Sydney Case study supports the case for ongoing disposal of the majority of Sydney's sewage effluent without requiring significant upgrades to the level of treatment due to the benefits of relocating the discharge points to deepwater locations which provide greater opportunities for effluent dilution and are removed from the effects of coastal roughness. Potential eutrophication issues are assessed in Chapter 6, while analysis of remote sensed data streams in Chapter 5 explain the development of specific algal blooms in terms of *Outer CBL* dynamics.

This thesis focuses on New South Wales coastal waters although the approaches and findings are relevant to a broader range of applications.

This thesis deals with the minimisation potential impacts associated with the discharge of pollutant but also emphasises that a consideration of increasing human demands on resources in the context of the whole water cycle leads to the conclusion that water and nutrients in sewage are a valuable resource, which we must make concerted efforts to recover, irrespective of the lack of major impacts near the point of discharge.

10.3 Shaping research agenda

Although this thesis is successful in addressing the major research questions captured by the thesis objectives, it also exposes fundamental data gaps, stimulates further research questions, and motivates for the further development of management applications.

Research outlined in this thesis has already shaped a broader research agenda, mostly in collaboration with the author.

10.3.1 Bathymetry

Accurate near-shore bathymetry data are a fundamental pre-requisite for investigation of CBL processes. However, the morphological classification of headlands, bays and islands described in Chapter 7 of this thesis revealed highly variable bathymetry data coverage. As a consequence the classification of NSW headlands and bays was restricted to the subaerial expression of the coastline due to the inadequacy of near shore bathymetry. Improved near-shore bathymetry would facilitate representation of important sub-tidal morphological characteristics of NSW headland and bay types in future classifications.

Accurate near-shore bathymetry is also required as a fundamental boundary condition for all coastal hydrodynamic, wave propagation and sediment transport models. Turbulent effects, represented by the *Wake Parameter* (P) described in Chapter 9, are highly sensitive to water depth (i.e. $depth^2$). These are strong arguments to improve the quality and resolution of near shore bathymetry data.

The author is working with colleagues in the New South Wales Office of Environment and Heritage to establish a State Bathymetry Mapping Strategy to target critical mapping targets. This builds on the NSW HabMap Program which recently delivered the first marine habitat maps for NSW built on a compilation of best available bathymetry data together with 1,500 km^2 of newly acquired high resolution swath mapped bathymetry data (Jordan, Davies, Ingleton, Foulsham, Neilson and **Pritchard**, 2010). The NSW Government is currently investing in acquisition of offshore bathymetry data including LiDAR/LADS and hydroacoustic surveys to build an improved digital elevation model of the NSW coastal zone (**Pritchard** et al., 2011).

10.3.2 Near-shore flows

Few sustained observations or accurate model simulations are available to characterise near-shore flow fields. However, since 2007 a national Integrated Marine Observing System (IMOS) has invested in research infrastructure to observe the oceans around Australia, including the establishment of cross-shelf transects comprising moored instruments which observe the current and density profiles throughout the water column. In addition IMOS is investing in a High Frequency (HF) WERA Radar system to observe near-shore surface currents across an array off Coffs Harbour at ~30ºS. Furthermore, recent reviews of IMOS research plans (e.g. Malone, 2010) motivate a greater emphasis on coupling the observational systems with modelling initiatives to facilitate spatial and temporal extrapolation and interpolation of direct and remote sensed observations. The author has been actively engaged in shaping investments in this coastal research infrastructure through formal and informal engagement with the IMOS, and with the coastal components of the complementary Terrestrial Ecosystem Research Network (TERN). Observations of this type will be required to calibrate and validate broad scale modelling of the coastal boundary layer processes at appropriate resolution. Recent and developing broad scale coastal modelling relevant to the east coast of Australia initiatives include recent applications of Regional Ocean Model System by the University of NSW (Roughan pers comm 2011, http://www.myroms.org/) and Ribbon modelling by CSIRO in collaboration with the Bureau of Meteorology (http://www.emg.cmar.csiro.au/www/en/emg/projects/-Ribbon--Model.html).

At a more specific level, worthy areas for research include the development of techniques to extract information currently obscured in the uppermost bins of

Acoustic Doppler Current Profiler (ADCP) records. This information is important because effluents discharged to near-shore environments typically form surface plumes.

10.3.3 Satellite ocean colour products

Chapter 5 revealed the need for a systematic appraisal of existing ocean colour algorithms as applied to the optically complex (Case 2) waters of the NSW coastal boundary layer, including better multi-spectral characterisation of the optical properties of coastal boundary layer water masses. This motivated a successful application for research funding from the NSW Environmental Trust (2009/RD0016) to:

1. Quantify the uncertainty associated with application of existing ocean colour algorithms to NSW coastal waters for chlorophyll, suspended sediments (SS) and coloured dissolved organic matter (CDOM).
2. Investigate the complex optical properties of NSW coastal waters to determine the relative importance of various error factors in ocean colour estimates of chlorophyll, SS and CDOM
3. Initiate and maintain a spectral library for NSW coastal waters for improving ocean colour remote sensing algorithms in Coastal NSW.

This three year project will be completed in December 2012 although initial findings have been reported by Davies, Ingleton, **Pritchard**, Mesley and Wright (2010), and comprehensive bio-optical observations of a complex mélange of water masses originating from the EAC, shelf waters, slope intrusions and riverine inputs have been collected by Davies et al. (2011).

Ocean colour products will become increasingly valuable for CBL applications as spatial and spectral resolutions of ocean colour data streams improve and as more sophisticated algorithms incorporate observed optical properties of coastal waters.

10.3.4 Extending headland, bay and island classifications

Further development and investigation of the classification of headlands, bays and islands proposed in Chapter 7 of this thesis is required to evaluate and extend its application to pollutant dispersion.

Modelling is required to examine the spatial patterns of particle retention within embayments and headland wakes for

- idealised coastal morphologies based on the known range of types and characteristics (classes of headlands and bays identified in Chapter 7); and,
- actual NSW coastal morphology to map relative dispersion potential.

In the first instance a limited range of regional flow scenarios could be used to drive two dimensional model simulations, commensurate with the objective of determining relative residence times to indicate generalised dispersion potential for typical NSW coastal morphologies. Neutrally buoyant, conservative (numerical) particles released into each of these simulated flow fields would determine indicative extents of re-circulation cells and relative residence times. This is essentially a sensitivity analysis based on known ranges of NSW headland morphologies to target subsequent more detailed modelling and observational investigations of specific dispersion characteristics.

Similarly, the working definition of *Bays* in Chapter 7 warrants testing: "the area between adjacent headlands constitute a bay when the distance between adjacent headlands is less than twice the average length of headlands." This can be tested and refined when field observations and model simulations are available to rigorously determine relevant length scales at which hydrodynamic characteristics are principally determined by the interacting effects of adjacent headlands rather than the individual effects of two single headlands.

Montague Island and North Solitary Island stand out from NSW's five largest offshore islands as targets for more detailed evaluation of wake effects as they appear most likely to be associated with wake effects such as re-circulation cells. However, based on the *Wake Parameter*, Fish Rock, a small island about 2km offshore from Smoky Cape, has the greatest propensity for wake effects.

The training wall system at the entrance of the Clarence River at Yamba is an obvious candidate for more detailed evaluation of the influence that such structures may have on boundary layer dynamics. Training walls at Yamba extend the entrance of the Clarence River more than 0.8 km offshore and maintain the greatest coastal discharge of freshwater of any river in NSW. No other training wall protrudes further eastward from shore.

10.4 Closing Remarks

This thesis has provided a new framework to understand the ways in which flows interact with coastal morphologies within the *Coastal Boundary Layer* and how this determines both pollutant dispersion patterns and distributions of marine communities and species.

This knowledge is a prerequisite to understanding pollutant impacts, marine ecosystem functions and appropriate management responses.

10.5 References

Davies, P., Cherukuru, N., Anstee, J. (2011) Bio-optical Measurements of New South Wales Coastal Waters and the EAC, 48th Australian Marine Sciences Association Conference 2011 Perth, p 47.

Davies,P., Ingleton,T., **Pritchard, T**., Mesley, E., Wright, A. (2010) Chlorophyll distributions at Port Hacking stations: implications for ocean colour remote sensing. 47th Australian Marine Sciences Association Conference 2010 Wollongong.

Jordan,A., Davies,P., Ingleton,T., Foulsham,E., Neilson,J. and **Pritchard,T.** (2010) Seabed habitat mapping of the continental shelf of NSW. DECCW 2010/1057, ISBN 978 1 74293 085 5.

Malone, T. (2010) Review of the IMOS coastal node proposals. Report to IMOS, 14-23 September 2010, 1-12.

Pritchard, T.R. , 1997. Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, Vol 24, No.1. March/April 1997.

Pritchard,T.R., Turner, I.L, Goodwin,I.D., Davidson, M.A., Short, A.D., Lane, C., Cameron,D.W., MacDonald,T., Splinter,K.D., Mole,M., Kearney,E., Middleton,J.H. (2011) Prospects for a National Coastal Observatory, NSW

Coastal Conference Proceedings, Tweed Heads, NSW, 8-11 November 2011.

Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.

Pritchard, T.R, Lee,R.S., Ajani,P.A., Rendell.P.S., Black,K & Koop,K. (2003) Phytoptoplankton responses to nutrient sources in coastal waters off southeastern Australia. Aquatic Ecosystem Health and Management, 6(2): 105-117.

Pritchard, T.R., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Refereed Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

Pritchard, T. R., Lee, R. S. and Ajani, P. (1999) Anthropogenic and Oceanic Nutrients in NSW's Dynamic Coastal Waters and Their Effect on Phytoplankton Populations. Pacific Coasts and Ports '99 Proceedings. 537-543. Institure of Engineers, Australia.

Pritchard, T.R., Lee,R.S. and Ajani,P. (1997) Oceanic and Anthropogenic Nutrients and the Phytoplankton Response: Preliminary Findings. Pacific Coasts and Ports '97 Proceedings,V1, Published by CAE University of Canterbury, Christchurch, New Zealand. Institute of Engineers, Australia.

Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N. (1996) Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

Pritchard, T.R., Lee, R.S. and Davison, A., 1993. Sydney's Deepwater Outfalls. In situ Observations of Plume Characteristics. In: Proceedings of 11th Australasian Conference in Coastal and Ocean Engineering, Townsville, 23-27 August 1993. Institute of Engineers, Australia.

APPENDIX 1: CONFERENCE PRESENTATIONS DURING T.PRICHARD CANDIDATURE

Only those papers personally presented by Tim Pritchard are listed here:

- 10 international conference presentations
- 1 international academic invited speaker presentation
- 7 national conference and invited speaker presentations

1. **Pritchard,T.R.**, Turner, I.L, Goodwin,I.D., Davidson, M.A., Short, A.D., Lane, C., Cameron,D.W., MacDonald,T., Splinter,K.D., Mole,M., Kearney,E., Middleton,J.H. (2011) Prospects for a National Coastal Observatory, NSW Coastal Conference Proceedings, Tweed Heads, NSW, 8-11 November 2011.

2. **Pritchard, T.R.** (2011) Coastal boundary layer effects on pollutant dispersion. Coasts and Port 2011 Conference, Perth, WA, 27-30th September 2011.

3. **Pritchard, T.**, Healy, T., Koop,K. and Black, K. (2010) Determining potential for pollutant impacts in dynamic coastal waters: comparing morphological settings. Refereed Proceedings of the 15th Physics of Estuaries and Coastal Seas (PECS) Conference, Colombo, Sri Lanka, 14-17 September 2010, pp 178-181.

4. **Pritchard, T.,** Krogh, M., Davies, P., Ingleton, T., dela Cruz,J., Holden,C., Suthers, I,, Roughan, M. (2009) Detecting climate change in the coastal waters off south east Australia – past, present and future. Greenhouse 2009: Climate Change & Resources, Perth, 23-26 Mar 2009.

5. **Pritchard, T**., Krogh, M., dela Cruz,J., Davies,P., Ingleton, T. (2009) The legacy of Sydney's long term monitoring stations and prospects for integrated monitoring of coastal waters. AMSA 2009: Marine Connectivity, Adelaide, South Australia, 5th - 9th July 2009.

6. **Pritchard, T**., Davies, P., Black, K. and Healy, T. (2008) Coastal boundary layer dynamics and their role in shaping pollutant dispersal and biotic distributions in the coastal waters. Coast to Coast Conference 2008, Darwin, 18-22 August 2008 (p93)

7. **Pritchard, T.R.,** Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, International Coastal Symposium, Gold Coast, Australia, 2007.

8. **Pritchard, T.R.,** Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

9. **Pritchard, T.R.**, Davies, P.L. and Healy, T., (2004). Predicting Risk of Algal Blooms and Coastal Boundary Layer Characteristics using Remotely Sensed Data. Eos, Transactions, American Geophysical Union, Vol.84, No. 52 [Presented 26th February 2004 - AGU Ocean Sciences Meeting, Portland, Oregon, USA]

10. **Pritchard,T.R.,** Holden,C., Davies,P.L. and Healy, T., (2004). Inter-annual variability of the coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Invited Seminar, Earth and Ocean Science Seminar Series, University of British Columbia, February 2004

11. **Pritchard, T.R.**, Baginska,B., Coade,G. & Lu.,Y., (2004). Linking landuse decisions to nutrient exports and their impact on the eutrophication of estuaries and coastal lakes. NSW Coastal Conference, Lake Macquarie.

12. **Pritchard, T. R.** (2004) NSW Coastal and Marine Issues: 'Water Quality' and Pollution, Invited speaker: Coastal Catchment Management Authorities Workshop, November 2004

13. **Pritchard, T. R.** (2004) Phytoplankton responses to nutrient sources in NSW coastal waters. Invited speaker: Department of Environment and Science Seminar Series, May 2004

14. **Pritchard, T.R**.& Black, K.P. (2002) Transient re-circulations affecting pollutant dispersion and ambient water quality in NSW coastal waters. Australian Marine Science Association Conference.

15. **Pritchard, T. R.,** Lee, R. S., Ingleton, T. and Black, K. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.

16. **Pritchard, T.R.** (2001) Oceanographic parameters in coastal pollution. Coastal Marine Seminar Series, University of Waikato, Hamilton, New Zealand.

17. **Pritchard, T. R.,** Rendell, P., Lee, R. S. and Ajani, P. (2000) How do Ocean Outfalls Effect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? International Coastal Symposium, Roturua, NZ, April 24-28 2000.

18. Ajani,P., Lee,R., **Pritchard,T.R.** and Krogh,M. (2000) Phytoplankton patterns at CSIRO's long-term coastal station off Sydney International Coastal Symposium, Roturua, NZ, April 24-28 2000. [presented by T Pritchard]

APPENDIX 2: PUBLICATIONS AUTHORED BY T.PRITCHARD AND USED IN THIS THESIS

Only those publications authored or co-authored by T.Pritchard and used in this thesis are listed here.

A2.1 Relevant Refereed Papers and Book Chapters (24)

A2.2 Relevant Refereed Reports (9)

A2.3 Relevant Formal Papers, Reports and Conference Proceedings (48)

NOTE: T. Pritchard authored or co-authored 17 refereed publications during candidature (indicated in **bold**).

A2.1 Relevant Refereed Papers and Book Chapters

1. **Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T. (2007) Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.**

2. **Pritchard, T.R., Holden, C. and Healy, T. (2005) Variability of coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Refereed Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia, 61-66.**

3. **Pritchard, T.R. and Koop, K (2005). Satellite Remote Sensing in Marine Ecosystem Assessments. Chapter 6 in: ed. den Besten, P.J. & Munawar, M. Ecotoxicological Testing of Marine and Freshwater Systems: emerging techniques, trends and strategies. Ecovision World Monograph Series, Taylor & Francis, 195-228.**

4. **Pritchard, T.R, Lee,R.S., Ajani,P.A., Rendell.P.S., Black,K & Koop,K. (2003) Phytoptoplankton responses to nutrient sources in coastal waters off southeastern Australia. Aquatic Ecosystem Health and Management, 6(2): 105-117.**

5. **Pritchard, T.R., Lee, R.S., Ingleton, T.C., and Black, K.P. (2001) Dispersion in the lee of a headland: a case study of circulation off Coffs Harbour. Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, Institute of Engineers, Australia.**

6. **Pritchard, T. R., Rendell, P., Lee, R. S. and Ajani, P. (2001) How do Ocean Outfalls Effect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? Journal of Coastal Research, 34, 96-109.**

7. Pritchard, T. R., Lee, R. S. and Ajani, P. (1999) Anthropogenic and Oceanic Nutrients in NSW's Dynamic Coastal Waters and Their Effect on Phytoplankton Populations. Pacific Coasts and Ports '99 Proceedings. 537-543. Institure of Engineers, Australia.

8. Pritchard, T. R., Lee, R. S. and Davison, A. (1996) "Dispersion of effluent from Sydney's new deepwater outfalls Part 2: Observations of Plume Behaviour: Winter and Summer Examples" In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), pp. 430-438. American Geophysical Union, Washington.

9. **Ajani, P., Ingleton, T., Pritchard, T. and Armand, L. (2011). Microalgal blooms in the coastal waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales 133, 15-31.**

10. **Ajani,P., Lee,R., Pritchard,T.R. and Krogh,M. (2001) Phytoplankton patterns at CSIRO's long-term coastal station off Sydney. Journal of Coastal Research, 34, 60-73.**

11. **Ajani,P. Hallegraeff, G. and Pritchard,T.R. (2001) Algal Blooms in Marine and Estuarine Waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales, 123, 1-22.**

12. **Baginska,B., Pritchard,T. and Krogh,M. (2003) Roles of land use resolution and unit-area load rates in assessment of diffuse nutrient emissions. Journal of Environmental Management 69, 39-46.**

13. **Baginska, B. Lu, Y and Pritchard, T. (2005) Modelling nutrient loads to better manage impacts of urbanization in Tweed catchment, New South Wales, Australia. Proceedings of International Congress on Modelling and Simulation Advances and Applications for Management and Decision Making, 2346-2352.**

14. **Dela-Cruz, J., Pritchard, T., Gordon, G. and Ajani, P. (2006) The use of periphytic diatoms as a means of assessing impacts of point source inorganic nutrient pollution in south-eastern Australia. Freshwater Biology 51, 951–972.**

15. **Dela-Cruz, J, Ajani, P, Lee, R, Pritchard, T and Suthers, I (2002), Temporal abundance patterns of the red tide dinoflagellate Noctiluca scintillans along the southeast coast of Australia, Marine Ecology Progress Series, 236, 75-88.**

16. **Lee, R.S., Pritchard, T.R., Ajani, P.A. and Black, K.P. (2007) The influence of the East Australian Current eddy field on phytoplankton dynamics in the coastal zone, SI 50, 576-584.**

17. **Lee,R., Ajani,P., Krogh,M. and Pritchard,T.R. (2001) Resolving climatic variance in the context of retrospective phytoplankton pattern investigations off the east coast of Australia. Journal of Coastal Research, 34, 74-86.**

18. **Lee, R.S., Ajani, P.A., Wallace,S., Pritchard, T.R. and Black, K.P. (2001). Anomalous Upwelling along Australia's East Coast. Journal of Coastal Research, 34, 87-95.**

19. Lee, R. S. and Pritchard, T. R., (1999) Extreme Discharges into the Coastal Ocean: A Case Study of August 1998 Flooding on the Hawkesbury and Hunter Rivers. Pacific Coasts and Ports '99 Proceedings, Perth, W.A. 341-346. Institure of Engineers, Australia.

20. Lee, R. S. and Pritchard, T. R. (1996) "Dispersion of effluent from Sydney's new deepwater outfalls Part 1: ocean processes". In Mixing Processes in Estuaries and Coastal Seas (C. Pattiaratchi, ed), 430-438. American Geophysical Union, Washington.

21. Lee, R.S. and Pritchard, T. R. (1996) How Do Long-term Patterns Affect Time-limited Environmental Monitoring Programmes ? Mar. Pollut. Bull. 33, 260-268.

22. Philip, N.A. and Pritchard, T. R. (1996) Australia's First Deepwater Sewage Outfalls: Design Considerations and Environmental Performance Monitoring. Mar. Pollut. Bull. 33, 132-139.

23. Rendell, P.S. and Pritchard, T. R. (1996) Physicochemical Conditions in Coastal Waters off Sydney, Central NSW, Australia. Mar. Pollut. Bull. 33, 132-139.

24. Turner,I.L., Goodwin,I.D, Davidson,M.A., Short,A.D., Pritchard,T.R., Lane,C., Cameron,D.W., MacDonald,T., Middleton,J.M., Splinter,K.D. (2011) Planning for an Australian National Coastal Observatory: monitoring and forecasting coastal erosion in a changing climate. Coasts and Ports Conference Proceedings, Perth, 2011.

A2.2 Relevant Refereed Reports

1. Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N. (1996) Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

2. Pritchard, T.R. (1993) Model Verification Experiments, In: Sydney Deepwater Outfalls Post-Commissioning Phase Period 1. Volume 2 Physical Oceanography.(Ed. J.Middleton).

3. Pritchard, T.R. (1992) Model Verification Experiments, In: Sydney Deepwater Outfalls Commissioning Phase Volume 2 Physical Oceanography.(Ed. J.Middleton). p17-24.

4. Pritchard, T.R. (1990) EMP Database. In: Sydney Deepwater Outfalls Environmental Monitoring Program Pre-commissioning Phase Progress Report. SPCC, ISBN 0 7305 5266 7. p259-268

5. Pritchard, T.R. (1990) Mathematical Modelling. In: Sydney Deepwater Outfalls Environmental Monitoring Program Pre-commissioning Phase Progress Report. SPCC, ISBN 0 7305 5266 7. p65-90.

6. **Baginksa, B. Lu,Y., Mawer,D. and Pritchard, T. (2004) Comprehensive Coastal Assessment - Linking Land Use Decisions to Nutrient Exports. NSW DEC.**

7. Krogh, M., Pritchard,T.R. and Rendell, P. (1998) Study Design for Long-term Monitoring of Benthic Ecosystems Near Sydney's Deepwater Ocean Outfalls. NSW EPA Technical Report Series 98/105. ISBN 0 7313 0202 8

8. **Jordan,A., Davies,P., Ingleton,T., Foulsham,E., Neilson,J. and Pritchard,T. (2010) Seabed habitat mapping of the continental shelf of NSW. DECCW 2010/1057, ISBN 978 1 74293 085 5.**

9. Suthers, I, Roughan,M, Morris,B, Armand,L, Baird,M, Boomer,A, Booth,D, Brassington,G, Byrne,M, Cato,D, Coleman,M, Couriel,E, Creese,R, Doblin,M Figueira,W, Gladstone,B, Harcourt,R, Hill,K, Holbrook,N, McCauley,R, Pritchard,T, Ralph,P, Richardson,A, Robertson,R, Rogers,T, Speer,M, Steinberg,P, Taylor,M, Wang,H, Williams,W, and others. (2010) NSW-IMOS Node Science and Implementation Plan (NSIP) July 2009-June 2013. http://imos.org.au/fileadmin/user_upload/shared/IMOS%20General/EIF/NSIP_2010/NSW_IMOS_NSIP-Aug10-v10.pdf

A2.3 Relevant Formal Papers, Reports & Conference Proceedings

1. **<u>Pritchard,T.R</u>., Turner, I.L, Goodwin,I.D., Davidson, M.A., Short, A.D., Lane, C., Cameron,D.W., MacDonald,T., Splinter,K.D., Mole,M., Kearney,E., Middleton,J.H. (2011) Prospects for a National Coastal Observatory, NSW Coastal Conference Proceedings, Tweed Heads, NSW, 8-11 November 2011.**

2. **<u>Pritchard, T.R.,</u> Black,K.P., Lee, R.S. and Koop, K. (2011) Coastal boundary layer effects on pollutant dispersion. Coasts and Port 2011 Conference, Perth, WA, 27-30th September 2011. Institute of Engineers, Australia.**

3. **<u>Pritchard, T</u>., Healy, T., Koop,K. and Black, K. (2010) Determining potential for pollutant impacts in dynamic coastal waters: comparing morphological settings. Refereed Proceedings of the 15th Physics of Estuaries and Coastal Seas (PECS) Conference, Colombo, Sri Lanka, 14-17 September 2010, pp 178-181.**

4. **<u>Pritchard, T</u>., Krogh,M. dela Cruz,J. Davies,P., Ingleton,T (2009) The legacy of Sydney's long term monitoring stations and prospects for integrated monitoring of coastal waters. Australian Marine Sciences Conference Proceedings, Adelaide 2009.**

5. **<u>Pritchard, T</u>., Krogh, M., Davies, P., Ingleton, T., dela Cruz,J., Holden,C., Suthers, I,, Roughan, M. (2009) Detecting climate change in the coastal waters off south east Australia – past, present and future. Greenhouse 2009: Climate Change & Resources, Perth, 23-26 Mar 2009.**

6. **<u>Pritchard, T</u>, Davies, P., Black, K. and Healy T., (2008) Coastal Boundary Layer Dynamics and Their Role in Shaping Pollutant Dispersal and Biotic Distributions in the Coastal Waters. Coast to Coast 2008, Darwin.**

7. **Pritchard, T.R., Davies, P.L. and Healy, T. (2004) Predicting Risk of Algal Blooms and Coastal Boundary Layer Characteristics using Remotely Sensed Data. Eos, Transactions, American Geophysical Union, Vol.84, No. 52 [Presented 26th February 2004 - AGU Ocean Sciences Meeting, Portland, Oregon, USA]**

8. **Pritchard, T.R., Baginska,B., Coade,G. & Lu.,Y. (2004) Linking landuse decisions to nutrient exports and their impact on the eutrophication of estuaries and coastal lakes. Coastal Conference, Lake Macqurie.**

9. **Pritchard,T.R., Holden,C., Davies,P.L. and Healy, T. (2004) Inter-annual variability of the coastal dynamics of New South Wales, Australia and its relevance to anthropogenic impacts. Invited Seminar, Earth and Ocean Science Seminar Series, University of British Columbia, February 2004**

10. Pritchard, T.R. (1998) Relative Significance of Slope Water, Estuarine Discharges and Sewage Outfalls for N utrients in Offshore Coastal Waters. Coastal Nutrients Workshop Research Aiding Nutrient Management in Coastal Rivers and Estuaries 30-31 October 1997. Published by AWWA. ISBN 0-908255-42-X.

11. Pritchard, T.R., Lee, R.S., Ajani, P., Rendell, P. Andrew, D., Krogh, M. and Large, D. (1998) Nutrient Enrichment of NSW Coastal Waters: Sources and Consequences. AMSA '98, Adelaide 8-11 July 1998. Institure of Engineers, Australia.

12. Pritchard, T.R. (1997) Environmental Performance of Sydney's Deepwater Outfalls, Journal of Australian Water and Wastewater Association, Vol 24, No.1. March/April 1997.

13. Pritchard, T.R., Lee,R.S. and Ajani,P. (1997) Oceanic and Anthropogenic Nutrients and the Phytoplankton Response: Preliminary Findings. Pacific

14. Pritchard, T.R., Lee, R.S. and Ajani, P. (1996) Early Results from the NSW EPA's Ocean Nutrient and Phytoplankton Project. AMSA '96, Hobart 10-13 July 1996.

15. Pritchard, T.R. (1994) Existing Environmental Conditions – Pacific Ocean Sydney. In: Existing Environmental Conditions, Water Board Report.

16. Pritchard, T.R. (1994) Existing Environmental Conditions – Pacific Ocean Illawarra. In: Existing Environmental Conditions, Water Board Report.

17. Pritchard, T.R., Lee, R.S. and Davison, A. (1993) Sydney's Deepwater Outfalls. In situ Observations of Plume Characteristics. In:Proceedings of 11th Australasian Conference in Coastal and Ocean Engineering, Townsville, 23-27 August 1993. Institure of Engineers, Australia.

18. Pritchard, T.R. (1992) Sewage Tracers. Environmental Effects of Sydney's Sewage Outfalls: Workshop on Recent Research. CSIRO Centre for Advanced Analytical Chemistry, Lucas Heights, June 1992.

19. Pritchard, T.R. (1992) Sewage Tracers. Environmental Effects of Sydney's Sewage Outfalls: Workshop on Recent Research. CSIRO Centre for Advanced Analytical Chemistry, Lucas Hts, June 1992.

20. Ajani,P., Lee,R., Pritchard,T. and Krogh,M. (2000) Phytoplankton dynamics at a long term coastal station off Sydney, Australia. Abstract for HAB 2000, Hobart, Tasmania.

21. Baginska, B. and Pritchard,T.R. (2000) Nutrient Emissions for Manni and Richmond Catchments (NSW). NSW Environment Protection Authority Report prepared for the National Pollutant Inventory Program.

22. Baginska, B. and Pritchard,T.R. (1999) Catchment Nutrient Export Techniques. AMSA Uni. Melbourne 6-9 July1999

23. Bagnska, B. and Pritchard,T.R. (1999) CMSS as a tool for assessment of aggregated catchment emissions - sensitivity testing. NSW Environment Protection Authority.

24. **Davies, P., Pritchard, T., Jorda,A., and Ingleton,T. (2008) Integrated Science Program to Inform Management of NSW Coastal Seas 35 , Coast to Coast Conference, Darwin.**

25. **Davies,P., Jordan,A., Ingleton, T., Pritchard, T., Boyd,R., and Ruming, K. (2007) Mapping Seabed geomorphology and habitat of the Clarence River, New South Wales. Sustainable Marine Resource Manangement Project. NSW DEC and University of Newcastle report to Northern Rivers CMA.**

26. **Davies, P., Bergerson, D., Jordan, A., Ingleton, T., Pritchard, T. (2007) Evaluation of a wide swath bathymetry, CUBE modelling, and 3D data visualisation for habitat mapping. Geohab Annual Conference. Marine Benthic Habitats of the Pacific and Other Oceans: Status, Use and Management, Noumea, 2-6 May, 2007.**

27. **Davies, P., Jordan, A., Ingleton, T., Pritchard, T., Boyd, R and Ruming, K. (2006) Mapping of seabed geomorphology and habitats off the Calrence River Northern New South Wales. Final Report for the Sustainable Resource Management Project, Part A. Northern Rivers Catchment Management Authority.**

28. **Davies, P., Jordan, A., Ingleton, T., Pritchard, T. (2006) Underwater discovery and understanding marine habitats using sonar and video techniques. DEC ON-DECK Conference Darling Harbour, September, 2006.**

29. **Ingleton, Tim, Davies,P., Jordan,A., Mesley,E., Nielson,J., Bergensen,D., Bergensen,N. and Pritchard,T. (2009) Use of interferometric sidescan techniques for seabed mapping – tools to improve data processing and resolution. Australian Marine Sciences Conference Proceedings, Adelaide 2009.**

30. **Jordan,A., Pritchard,T., Coleman,M., Harasti,D., Knott,N. and Malcolm,H. (2009) Marine park planning in NSW – research priorities and future directions. AMSA Adelaide 2009 Marine Connectivity.**

31. **Jordan,A., Davies,P., Ingleton, T., Pritchard, T. (2007) Application of swath acoustic mapping technology as a tool for seabed habitat mapping in coastal waters of New South Wales, Austrlaia. Wollongong GIS Conference 2006 – to be published in a special issue of the Journal of Spatial Sciences**

32. **Lee, R.S., Ajani, P.A., Pritchard, T.R. and Black, K.P. (2001) Western boundary current dynamics and the phytoplankton response in the coastal zone. AMSA 2001.**

33. Lee, R.S., Holden, C., Ajani, P., Pritchard, T. and Andrew, D. (1998) A temporal and spatial comparison of measurements from the CSIRO long term coastal stations off Sydney, Australia. NZ Marine Sciences Society Conference Abstracts, Dunedin, New Zealand, July 1998.

34. Lee, R.S. and Pritchard, T.R. (1992) Fate of Pollutant Introduced on the Continental Shelf of the Eastern Australian Coast. American Geophysical Union Conference, Montreal, EOS Supplement April 7, 1992. 052A-4.

35. Lee, R.S., Pritchard, T.R., Davison, A., and Pearson, W. (1991) Tracing of Effluent 4km off the Sydney Coast. Australian Physical Oceanography Conference, Canberra, January 1992.

36. Lee, R.S., and Pritchard, T.R. (1992) Influence of Oceanic Processes on an Introduced Pollutant Field on the Sydney Continental Shelf. 4th Air-Sea Interaction Conference, Melbourne, 1992.

37. **Lu Y., Baginska B. and T. Pritchard (2004) Applying Remote Sensing and GIS Techniques to Managing Impacts of Diffuse Sources of Pollution due to Land Use Change in Tweed Catchment, NSW ISCO 2004 - 13th International Soil Conservation Organisation Conference - Brisbane, July 2004 Conserving Soil and Water for Society: Sharing Solutions.**

38. **Lu,Y, Baginska, B. and Pritchard, T.R. (2004) Applying remote sensing to Managing Impacts of Diffuse Sources of Pollution due to landuse change in Tweed catchment, NSW, Australia. ISCO 2004, 13th International Soil Conservation Organisation Conference, Brisbane, July 2004.**

39. **Mesley, E., Jordan,A., Davies,P. Ingleton,T., Nielson,J., Frolich,M., Pritchard, T. (2009) Mapping of seabed habitats on the NSW continental shelf at multiple scales. Australian Marine Sciences Conference Proceedings, Adelaide 2009.**

40. **Morris, B. M. Roughan, I. Suthers and T. Pritchard (2009) Cross-shelf Processes off the Coast of NSW; Preliminary Results from the NSW IMOS Array AMSA Adelaide 2009 Marine Connectivity.**

41. Nalty, C, Cathers, B., Pritchard, T., Lee, R., Allsop, D., Brown, D., Nippard, G., Peirson,W.L.,Wilson, J. (1992) Sydney Deepwater Outfalls Environmental Monitoring Program. Post-commissioning Phase. Cruise Report 17-19 December 1991, SPCC TR92/28. ISBN 0 7305 5277 2.

42. Nalty, C, Wilson, J., Peirson,W.L., Cathers, B., Pritchard, T., Lee, R., Allsop, D.,Brown, D., Nippard, G., and Woodrow, A. (1992) Sydney Deepwater

43. Nalty, C, Allsop, D., Peirson,W.L., Pritchard, T., Brown, D. (1992) Sydney Deepwater Outfalls Environmental Monitoring Program. Post-commissioning Phase. Cruise Report 16-18 June 1992. AWACS Interim Report 92/01/10.

44. Nalty, C, Peirson,W.L., Pritchard, T., Lee, R., Nippard, G., and Allsop, D. (1991) Sydney Deepwater Outfalls Environmental Monitoring Program. Post-commissioning Phase. Cruise Report 9 April 1991. AWACS Interim Report 91/01/06

45. **Richardson,A.J., Baird,M., Coman,F., Davies,C, Dela-Cruz,J., McLeod,D., Pritchard,T., Slotwinski,A., Suthers,I. (2009) Seasonal and inter-annual changes in the zooplankton community off Port Hacking,NSW. Australian Marine Sciences Conference Proceedings, Adelaide 2009.**

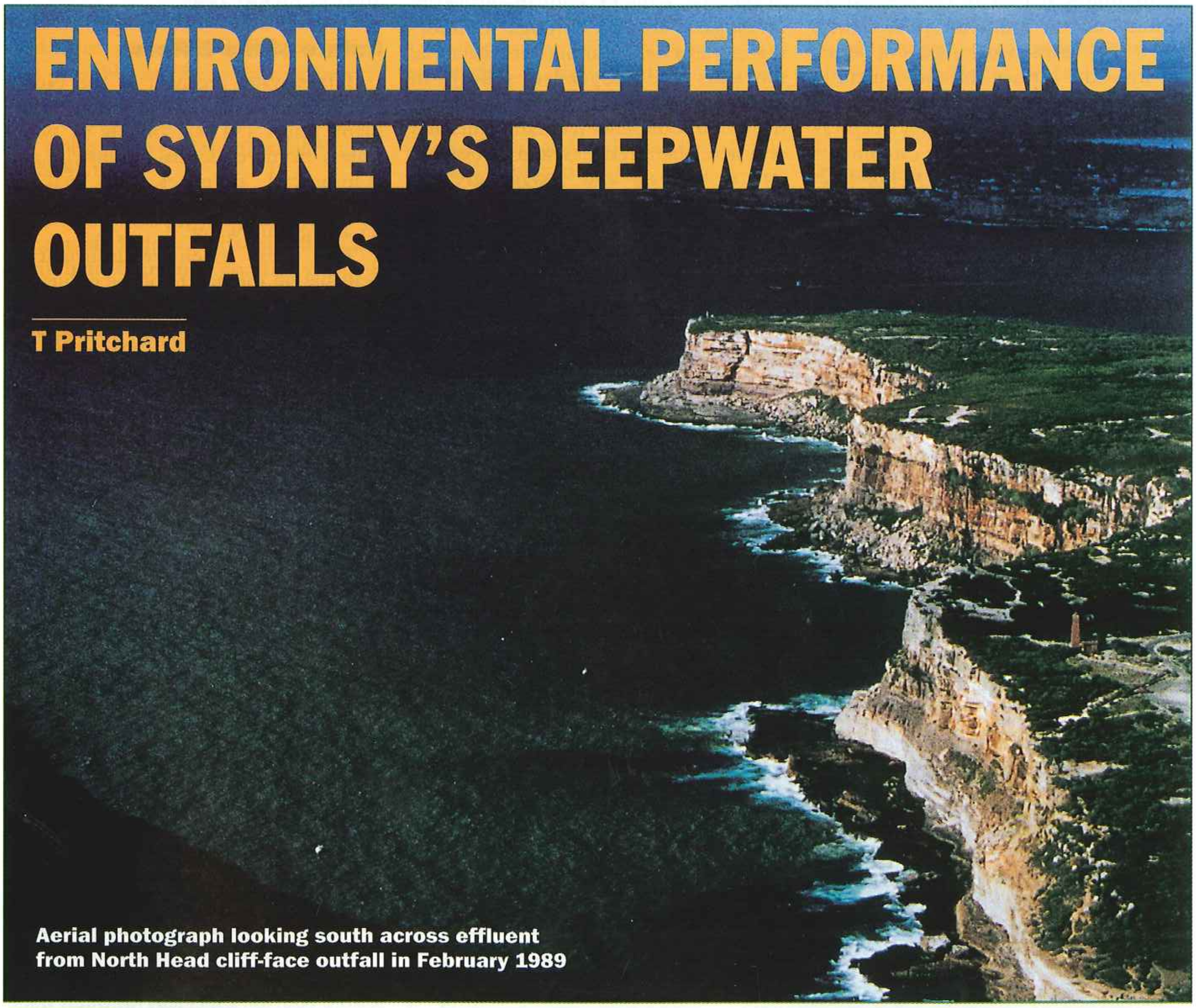
46. **Roughan, M., Suthers,I., Harcourt,R., Williams,S., Pritchard,T. (2009) Highlights from NSW IMOS. Australian Marine Sciences Conference Proceedings, Adelaide 2009.**

47. **Scanes, P. and Pritchard, T. (2003) Monitoring environmental impact of ocean disposal of sewage, experience from Sydney, Australia. Invited paper and presentation to Environment Protection Agency of Sao Paulo State (Brazil) at University of São Paulo**

48. **Scanes, P. and Pritchard, T. (2003) Environmental impact of ocean disposal and monitoring programmes. Invited paper and presentation to Environment Protection Agency of Sao Paulo State (Brazil) at University of São Paulo**

ENVIRONMENTAL PERFORMANCE OF SYDNEY'S DEEPWATER OUTFALLS

T Pritchard



Aerial photograph looking south across effluent from North Head cliff-face outfall in February 1989

Summary

A five year, multi-disciplinary Environmental Monitoring Program (EMP) has measured the environmental performance of Sydney's new deepwater outfalls against a wide range of criteria related to impacts on marine ecosystems and on human utilisation of marine resources. It also provided a baseline description of elements of the ecosystems found off Sydney and has developed an insight into some of the processes which determine the extent to which these ecosystems are exposed to, and affected by, effluent from the deepwater outfalls.

Generally, the EMP found that the deepwater outfalls are performing well: they have mitigated most of the environmental problems previously experienced when shoreline outfalls were operating without creating any major new problems in the ocean waters in the short term. Despite the generally good performance of the outfalls, there are a number of residual environmental issues associated with the operation of the outfalls including:

- potential for accumulations of sewage particles and associated contaminants in offshore sediments; and
- unexplained minor changes in abundances of certain bottom dwelling organisms and free swimming fish near outfalls.

Detailed results of EMP studies, an assessment of the performance of the deepwater outfalls and a summary of other monitoring are provided in the EMP Final Report Series published by the New South Wales Environment Protection Authority (EPA).

Sydney Deepwater Outfalls Environmental Monitoring Program

Titles in the Final Report Series.
ISBN 0 7310 3715 4 (series)

Vol 1. Assessment of the Deepwater Outfalls
Vol 2 Sewage Plume Behaviour
Vol 3 Water Quality
Vo 4 Trace Metals and Organochlorines in the Marine Environment
Vol 5 Impacts on the Marine Ecosystem
Vol 6 Database
Vol 7 Bibliography

Available from NSW EPA, PO Box 1135, Chatswood 2057

Introduction

About 80 per cent of Sydney's total sewage flow is discharged to the ocean after primary treatment at Malabar, North Head and Bondi sewage treatment plants (STPs). Over the last decade or more the community has voiced growing concerns about the effects of discharges of sewage to the ocean. One measure to address these concerns has been the construction of deepwater outfalls.

Before the commissioning of deepwater outfalls, discharges at cliff face outfalls often led to poor beach and bathing water quality (Robinson et al., 1996), high levels of some contaminants in certain fish (Lincoln-Smith and

Mann 1989a & b; McLean *et al* 1991) and reduced diversity of some biological communities at least in the immediate vicinity of the outfalls (Fairweather, 1990). The gross visual impact of effluent from the former cliff face outfall at North Head is clearly evident in Figure 1.

The locations of the Sydney deepwater outfalls and the sewerage catchments which they serve are shown in Figure 2. The first deepwater outfall was commissioned at Malabar in September 1990. This was followed by the commissioning of deepwater outfalls at North Head in December 1990, and at Bondi in August 1991. The outfalls are described in Table 1. Figure 2 also shows the reduction in the frequency of visible sewage pollution on beached following the commissioning of the outfalls, as discussed below

This paper presents a summary of the results from the EPA's Sydney Deepwater Outfalls Environmental Monitoring Program (EMP), the multidisciplinary study that measured the performance of the outfalls.

The EMP developed a predictive understanding of the behaviour of sewage plumes so it was possible to assess the extent to which monitoring sites were exposed to the sewage effluent during the EMP. The fate of a range of known effluent constituents were investigated directly through monitoring in the water column (faecal bacteria, nutrients and suspended solids), in deployed oysters and in fish (contaminants), in sediments (contaminants and sediment characteristics) and on beaches (faecal bacteria and sewage grease). Further studies measured the impacts of effluent on marine ecosystems (fish and benthos) and on human utilisation of marine resources (seafood contamination and recreation). These studies generally looked for changes which could be attributed to the commissioning of the deepwater outfalls by comparing changes observed at outfall sites with those at distant control (reference) sites using methodologies based, to varying degrees, on those espoused by Green (1979) and Underwood (1991, 1992, 1993).

The EMP was conducted mainly by the EPA and its consultants during the period from 1989 to September 1993 mostly in the area from Broken Bay to the Royal National Park and up to 15 kilometres offshore. This assessment of the performance of the deepwater outfalls relates largely to the first two years of their operation, that is, August 1991 to August 1993.

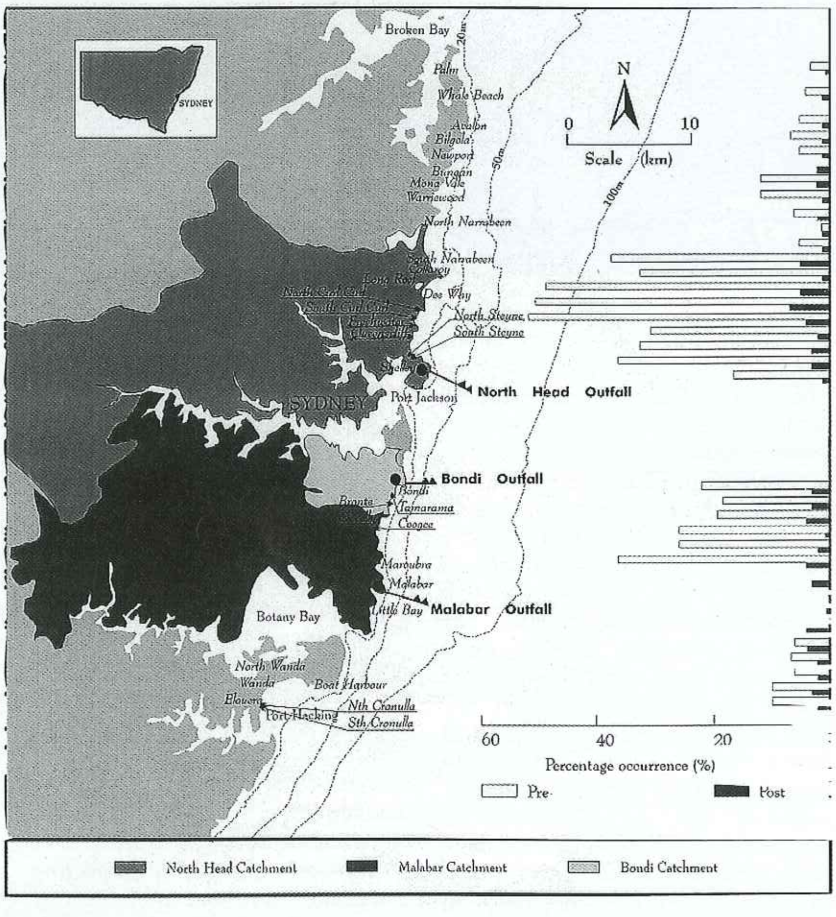


Figure 2 Map of the EMP's Sydney study area showing the deepwater outfall locations, sewage treatment plants and their catchments. Visible sewage pollution is also shown before and after commissioning of deepwater outfalls (based on EPA Beachwatch data from November 1989 to May 1993)

Nature of the Effluent

The sewage received at the North Head, Bondi and Malabar sewage treatment plants (STPs) consists of waste waters from residential, industrial and commercial premises, as well as substantial amounts at times of rainwater and groundwater.

The most extensive information available on the nature of the effluent is provided in licence compliance reports prepared by Sydney Water (or the then Water Board). Some of this information has been analysed by Pritchard *et al* (1996a). Comparisons between the three STPs were based on compliance data from 1994/95 when contaminant analyses were standardised across all STPs.

The concentrations of most of the measured contaminants were broadly similar at all three sewage treatment plants, at least in recent times. The composition of effluent from Malabar STP is shown in Table 2. Of the three plants, Malabar discharged the greatest volume of waste water and probably contributed the highest load of each contaminant.

The compliance monitoring data suggest that suspended solids and grease loads decreased by about 30 to 50 % during the course of the EMP (Figure 3). These reductions have been attributed to a combination of factors including improved treatment efficiencies, cessation of the discharge of digested sludge to the ocean and better source control, especially through trade waste agreements.

Dispersion of the Effluent

Effluent discharged from the deepwater outfalls undergoes rapid initial dilution, typically within 500 metres of the outfall, before reaching either a level of neutral buoyancy or the ocean surface. Median initial dilutions, based on hourly near field model results for the period from 1 March 1991 to 1 March 1994, are given for each deepwater outfall in Table 3. These initial dilutions, which have been verified by direct observations (Pritchard *et al* 1993, 1996b), are one to two orders of magnitude greater than those achieved at the former cliff face outfalls (Caldwell Connel, 1980). Model results also indicate that effluent plumes from the deepwater outfalls remain trapped below the sea surface for more than 80% of the time. Plumes reach the surface when the water column becomes unstratified, mainly during winter.

Typical far field plume behaviour is illustrated by the results of a radioisotope tracer experiment conducted from Malabar on June 17-18 1992 (Figure 4). On this occasion, initial dilutions were over 1:1000 and the plume remained submerged (depth >40 metres) and travelled parallel to sea floor contours to the south with slow subsequent (far field) dilution.

The key oceanographic processes that control the physical dispersion of effluent off Sydney, including the East Australian Current, coastal trapped waves, internal waves and tides and local wind-driven currents, have been described elsewhere (see Wilson *et al* 1996; Lee & Pritchard, 1996; Middleton *et al* 1997).

Some effluent constituents will be dissolved or neutrally buoyant and will therefore travel in an effluent plume while others will float or sink and therefore travel independent from the plume.

Simulations of settleable sewage particles, based on laboratory measurements (Baker *et al* 1995) and plume modelling (Wilson *et al* 1996), suggested that sewage particles would be initially deposited in a zone which forms a strip parallel to the coast, also with a southerly bias.

This zone of initial deposition, centred at water depths of 60 to 80 metres, falls just within the mid-shelf zone where previous studies (eg: Roy and Thom, 1981; Schneider and Davies, 1995) have indicated that fine sediment particles and associated contaminants are more likely to accumulate compared to the inner shelf where the former cliff face outfalls operated. Re-suspension and subsequent transport of sediments containing sewage material was not directly assessed.

Laboratory studies indicated that about three percent (by mass) of sewage effluent particles would be buoyant in seawater and would rise through at least 1.7 metres in 24 hrs (Baker *et al* 1995). Most of these floatable particles were less than 52 micrometres in diameter. Winds which could result in landfall of floating particles occurred about 20 percent of the time, mostly during the summer months (Wilson *et al* 1996).

Fate of Contaminants

Contaminants in the plume and in the floating and settling material may be transported out of the region or may accumulate in sediments or biota. Various studies examined aspects of these fates.

In the water column, monitoring data demonstrated substantial and almost immediate improvements in water quality (reductions in faecal coliforms, nutrients and suspended solids concentrations) at cliff-face outfall sites.

Trace contaminants were more difficult to measure in the water column. They were measured directly in surface waters and in the microlayer (air-sea interface) when the shoreline outfalls were operational (Rendell and Espey, 1996) and indirectly in fish and deployed oysters, both before and after commissioning of the deepwater outfalls (Scanes and Rendell, 1996a).

Microlayer studies sought to address concerns raised by overseas studies (e.g. Cross *et al* 1987) that contaminants can concentrate in the at the air-sea interface and can have lethal and sublethal effects on microscopic organisms, such as the eggs and larval stages of fish. EMP (Rendell and Espey, 1993) results indicated that, while the cliff face outfalls were still operational, contaminant concentrations in the microlayer were generally comparable to relatively unaffected areas in overseas studies. Because of this finding and the practical difficulties associated with this type of sampling in the ocean, no work was undertaken at the deepwater outfalls after commissioning.

In oysters deployed in the water column, elevated concentrations of organochlorines were associated with proximity to the cliff-face outfalls when they were operational (Scanes and Henry, 1992). Large decreases in organochlorine concentrations followed de-commissioning of cliff-face outfalls (Scanes, in press). Organochlorine concentrations were no longer elevated compared to reference sites. At the deepwater outfall sites, no significant changes were detected in trace metal or organochlorine concentrations in oysters.

At both offshore and inshore sites, no fish exceeded NFA MRLs for organochlorine compounds after the deepwater outfalls were commissioned (discussed later).

Fugacity and partition modelling was used to investigate the fate of specific organic contaminants across various environmental compartments (water, sediment, fish, etc) (Mortimer and Connel, 1995). This modelling predicted that organochlorine contamination of fish at inshore locations would be reduced to a very small percentage of pre-commissioning levels, while offshore concentrations would be an order of magnitude less than inshore pre-commissioning levels. These predictions were generally consistent with the results of the

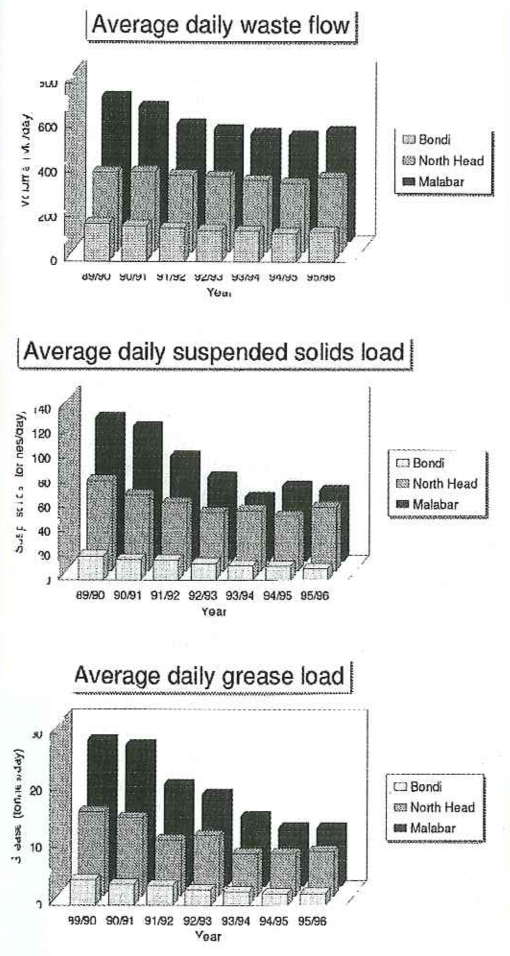


Figure 3 Effluent flows and loads from 1989 to 1996 based on licence compliance monitoring data

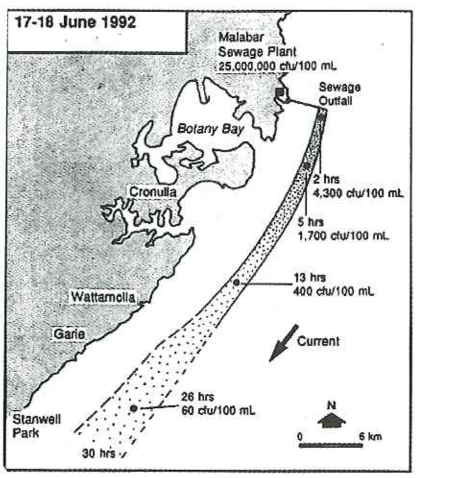


Figure 4 Malabar Plume Behaviour on 17-18 June 1992. Over a period of 26 hrs a labelled portion of the submerged plume was tracked and sampled for some 36 kms. Faecal coliform densities are geometric means (from Pritchard *et al* 1993)

contaminants in fish studies (Krogh and Scanes in press).

The recovery at the old cliff-face outfall sites was mainly reflected in reductions in the concentrations of organochlorines and lead measured in the flesh of red morwong (see Figure 5) and deployed oysters.

In the sediments, the proportion of fine grained sediments has increased at sampling sites near Malabar deepwater outfall, decreased at North Head outfall sites and remained essentially constant at Bondi outfall sites (Otway *et al* 1996). However, no changes in concentrations of organic carbon could be attributed to the commissioning of the deepwater outfalls (Gray, 1996).

A proportion of floatable sewage particles will still be stranded on beaches. However, concentrations of grease in sand at most beaches near the old outfalls (from South Curl Curl to Malabar) have decreased since commissioning of the deepwater outfalls and there is no evidence of an increase in beach grease at more distant beaches (Robinson *et al* 1996).

Impacts on Marine Ecosystems

At the deepwater outfall sites, the variety of habitats potentially affected by effluent include deepwater reefs, soft sediments and overlying waters. EMP studies attempted to characterise biological assemblages within each of these habitats. Changes in these assemblages at outfall sites, following commissioning of the outfalls, were compared with the 'natural variability' observed at a number of distant control or reference locations.

During EMP monitoring there were no sustained effects of the outfalls on the overall diversity (number of species) of biological communities found to be due to the operation of the deepwater outfalls. However, the outfalls have caused both increases and decreases in the abundance of a number of components of the soft bottom, planktonic and demersal fish communities near the outfalls (Scanes and Rendell (eds), 1996b).

Eleven species of fish (out of 65 analysed statistically) showed sustained changes in abundance around the deepwater outfalls - some species increased in abundance while others decreased. Significant changes in abundance were found for five types of fish larvae near the deepwater outfalls. Again, increases and decreases were found with no obvious pattern among outfalls. The types of larvae which changed were different from the adult fish which changed. This suggests no effects of altered recruitment at the time of sampling. There was no evidence that the presence/absence, abundance or proportional representation of deformed larvae were higher in Sydney than at far control locations (Terrigal or Greenwell Point).

Abundances and species assemblages of phytoplankton were not assessed in the EMP or any related studies although no significant changes in chlorophyll-a levels (used as a surrogate measure of phytoplankton abundance) that were consistent with an effect of the outfalls were detected following the commissioning of the deepwater outfalls. However, mean chlorophyll-a concentrations at both reference and outfall sites were generally higher after commissioning of the outfalls.

There were no significant changes in the numbers of species which comprise the assemblages living in sandy areas ('soft-bottom benthos'). There were, however, changes in abundances (both increases and decreases) of many taxa and the composition of species. A slight reduction in species richness of organisms living attached to deepwater reefs occurred near the North Head outfall, but no dominant taxa showed changes in abundance.

At the former cliff-face outfall sites, the rocky reef habitats are typically dominated by medium sized, attached or slow moving animals and attached algae with fish in the overlying waters. Other studies (Banwell, in prep) have shown that, following the diversion of effluent offshore, the impacted biological assemblages of intertidal areas near the cliff-face outfalls recovered to become much more like other intertidal assemblages along the rest of Sydney's coastline. It is interesting to note that the diversity and abundances of subtidal assemblages of fish and benthos near the cliff face outfalls were, in general, markedly unaffected by sewage discharge, despite the fact that the discharge had been occurring there for decades (Smith and Lincoln-Smith, 1993; Underwood *et al* 1993; Chapman et al. 1995).

Impacts on Human Utilisation of Marine Resources

At almost all Sydney beaches bathing waters are now suitable to swim in and beaches are free from readily visible sewage material for more than 90 percent of the time. The frequency and intensity of visible and bacterial sewage pollution has decreased with the commissioning of the deepwater outfalls, particularly at those beaches close to the former cliff face outfalls.

Table 1 Sydney's deepwater outfalls

Outfall	Water Depth (m)	Outfall Length (m)	Diffuser Length (m)	Outfall Capacity (ML/d)	Average Flow (ML/d)
North Head	60	2900	765	2400	385
Bondi	60	1700	510	700	165
Malabar	80	2900	720	2250	490

Table 2 Composition of effluent discharged from Malabar deepwater outfall

Effluent Constituent Concentrations [1,5]

Constituent	Concentration	Constituent	Concentration
Solids (mg/L)		**Organochlorines[2] (ug/L)**	
Suspended solids	133	Chlordane	0.04
Grease (oil and grease)	22	Dieldrin	0.02
		Heptachlor	0.04
Nutrients (mg/L)		Lindane	0.02
Ammonia N	27	PCBs	n.d (<0.1)
		Others[3]	n.d. (<0.01)
Metals[2] (ug/L)			
Arsenic	n.d. (<5)	**Polycyclic aromatic hydrocarbons[2] (ug/L)**	
Cadmium	n.d. (<5)	Total PAHs[4]	5.0
Chromium	32		
Copper	128	**Others (ug/L)**	
Lead	14	Cyanide	n.d. (<10)
Mercury	n.d. (<0.5)	Phenols	79
Nickel	34		
Selenium	n.d. (<5)		
Silver	6.0		
Zinc	172		

1 Median concentrations from licence compliance data for 01/04/94 to 31/03/95. Solids were measured daily while others were measured as 24 hr composites every 13 days.
2 Total concentrations.
3 Aldrin, BHC, DDD, DDE, DDT, endosulfan, endrin, hexachlorobenzene, methoxychlor.
4 Calculated by adding the concentrations of individual PAH compounds (not detected = 0).
5 n.d. = the median value was not detected.

Table 3 Median initial dilutions

	Surface Plume	Trapped Plume	All Conditions
North Head	817	349	379
Bondi	1193	414	456
Malabar	636	513	532

Although highly diluted effluent (containing faecal bacteria) and sewage grease may, on occasions, find its way to Sydney beaches, other pre-existing sources (e.g. smaller existing cliff face outfalls and stormwater) now stand out as issues of perhaps greater concern.

The reduction in the frequency of visible sewage pollution following commissioning of the deepwater outfalls is illustrated in Figure 2.

In fish there was no evidence that the commissioning of the deepwater outfalls has led to an increase in levels of chemical contaminants to the extent that they are of concern relative to the National Food Authority Maximum Residue Levels (NFA MRLs). If NFA MRLs are used as a guide, then, based on the mean level of contaminants found in fish associated with Malabar deepwater outfall (which discharges the greatest load of most contaminants), these fish are generally safe to eat. After the commissioning of the outfalls, no fish was found to have organochlorines present above the MRL although a small percentage of fish from both Sydney and distant central locations were found to contain some trace metals at concentrations above relevant MRLs. The frequency of detections of organochlorines increased slightly (possibly reflecting improved analytical techniques) although the proportion of fish with tissue concentrations of organochlorines which were high (greater than NFA MRLs) actually decreased to zero following the commissioning of deepwater outfalls.

All contaminant concentrations observed in red morwong at cliff-face outfall sites after decommissioning of the outfalls were 'low' when compared with NFA MRLs (Krogh and Scanes, in press). When cliff-face outfalls were in use, mercury, chlordane, heptachlor epoxide and HCB were sometimes found at concentrations greater than NFA MRLs in fish caught near cliff-face outfalls (Lincoln Smith and Mann, 1989a; McClean *et al* 1991).

Levels of faecal bacteria in offshore waters at and south of the deepwater outfalls (ie. locations in the path of the effluent plumes) necessitate proper storage and preparation of fish caught in this area if the intention is to consume them raw.

Discussion

Beach and bathing water quality have dramatically improved since effluent was diverted offshore to the deepwater outfalls, though some residual problems remain.

EMP studies have shown that contamination of sediments and biota in the vicinity of the new outfalls did not change to an extent that can be readily measured by the technology and methods utilised in these studies.

It appears from the computer modelling of plume behaviour and the studies of biota and sediments that the enhanced rate of dilution and dispersion has resulted in a decreased likelihood of any given organism or area of sediment encountering (and therefore accumulating) high loads of a contaminant, but concomitantly there has been an increased likelihood of more organisms accumulating small amounts of contaminants.

Ecological studies in the vicinity of the cliff face outfalls and the deepwater outfalls have shown that there have been some ecological impacts around the deepwater outfalls and some recovery of the intertidal assemblages previously affected by the cliff face outfall. The specific causes of the changes near the deepwater outfalls are unknown. There was little consistency among outfalls and no apparent relationship between abundances of predator and prey groups. The changes do not appear to be accounted for by the presence of toxicants. Based on effluent quality data and initial effluent dilutions, ANZECC (1992) guidelines for the protection of aquatic ecosystems have easily been met after initial dilution in recent times (1994/95). Likewise, contaminant concentrations in sediments near the deepwater outfalls were also below the levels considered to have the potential to cause biological effects.

These changes were observed at sites close to the outfalls. At this stage it is unclear how far the impacts may extend. But it is apparent that the observed changes are likely to extend considerably less than 10 to 20 kilometres from the outfalls, as this was the distance to control sites. This view is supported by the observation that changes at one outfall frequently differed from those at adjacent outfalls, yet the outfalls were only seven to eight kilometres apart. However, further studies are being implemented to establish whether the changes already identified persist and whether other chronic effects develop in the longer term.

Despite the generally good performance of the outfalls, a number of residual environmental issues have emerged. Some of these are associated with the deepwater outfalls while others are common to a broad area of NSW coastal waters. Pritchard *et al* (1996a) describe the ways in which these issues are being addressed.

Remaining deepwater outfall issues include:

- potential for accumulations of sewage particles and associated contaminants in offshore sediments;
- unexplained minor changes in abundances of certain bottom dwelling organisms and free swimming fish near outfalls;
- occasional presence of sewage grease on beaches
- faecal pathogens in sewage plumes.

Further general marine issues which have been raised or highlighted by the EMP, but not attributed specifically to the operation of the deepwater outfalls, include:

- occasional exceedances of NFA MRLs for some trace metals in fish from NSW coastal waters;
- possible nutrient enrichment of coastal waters and its effect on phytoplankton growth (algal blooms); and
- beach and bathing water pollution originating from stormwater sources and the remaining cliff-face outfalls discharging primary treated sewage.

Further monitoring and investigations to assess continued performance and to alert us to the development of possible longer term effects of the deepwater outfalls include the monitoring of sewage effluent, simulations of plume behaviour, the monitoring of ocean beaches and the regular monitoring of the quality of offshore sediments and the abundances of the organisms which are found living in and on these sediments.

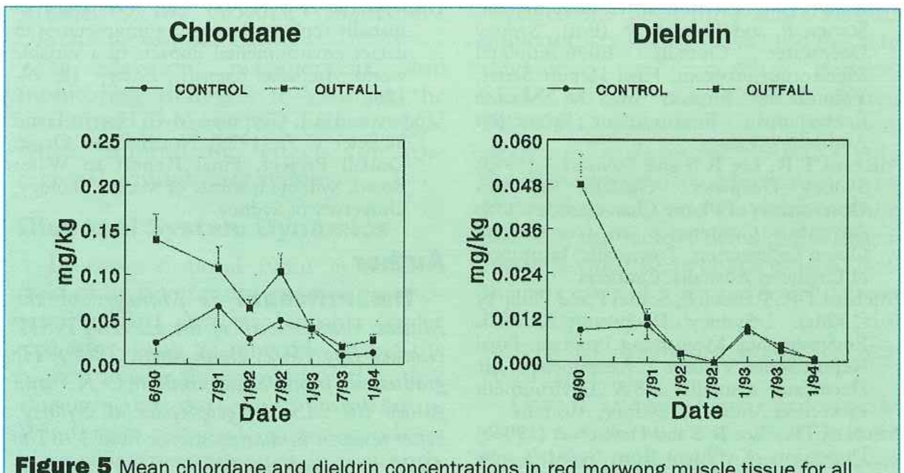


Figure 5 Mean chlordane and dieldrin concentrations in red morwong muscle tissue for all control and all outfall sites

Concluding Remarks

The legacy of the EMP is a better understanding of Sydney's coastal environment and a baseline data set against which the future environmental performance of the deepwater outfall systems can be assessed.

However, the results of the EMP contribute to just one element of a broader debate about effluent management which must be considered within the context of the entire water cycle. Over the last few years the NSW EPA, and many others, have concluded that we will have to regard water and nutrients in sewage as increasingly valuable resources which we should make concerted efforts to recover. Already, new legislation (the Sydney Water Board [Corporatisation] Act, 1994) places great emphasis on re-use of effluent and minimising the quantities of pollutants discharged to the ocean and other waterways.

The NSW Government has recently announced a public inquiry that will seek solutions to effluent management problems in coastal NSW. The Effluent Management Inquiry will assess the 'environmental costs' of ocean outfalls and other effluent disposal schemes and will consider options for further demand management and re-use.

Acknowledgements

This paper draws on the EMP Final Report Series particularly Volume 1: Assessment of the Deepwater Outfalls (Pritchard et al., 1996a), which, including its appendices, contains 194 pages. Paul Rendell's constructive criticism of an early draft of this paper is appreciated. Muriel O'Farrell produced the graphics for this article. The principal EMP contractors were Australian Water and Coastal Studies Pty Ltd and NSW Fisheries Research Institute. EMP pilot studies and much of the initial program design were undertaken by Sydney Water Corporation (then as Sydney Water Board) and its consultants. Throughout its life, the EMP was reviewed principally by the EMP Technical Review and Advisory Committees.

References

ANZECC (1992) Australian Water Quality Guidelines for Fresh and Marine Waters, Australian and New Zealand Environment and Conservation Council, Australia.

Baker E K, Harris P T, Kensett-Smith B, Bagster D F and Nobbs M N (1995) Physical properties of sewage particles in seawater, *Marine Pollution Bulletin* **30**, 247-252.

Banwell K (in prep) Effects of Sewage on Intertidal Assemblages, MSc Thesis, University of Sydney (Sydney).Caldwell Connel Engineers (1980) Analysis of Oceanographic Data and Review of Ocean Outfall Design Concepts. Report to Metropolitan Water, Sewerage and Drainage Board, Sydney.

Chapman M G, Underwood A J and Skilleter G A (1995) Variability at different spatial scales between a subtidal assemblage exposed to the discharge of sewage and two control assemblages, Journal of Experimental *Marine Biology & Ecology*, **189**, 103-122.

Cross J N, Hardy J T, Hose J E, Hershelman G P, Antrim L D, Gossett R W and Recelius E A (1987) Contaminant concentrations and toxicity of sea-surface microlayer near Los Angeles, California., *Marine Environ.Res.*, **23**, pp 307-323.

Gray L (1996) 'Contaminants in Sediments'. In: Scanes, P. and Rendell, P. (Eds). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 4: Trace Metals and Organochlorines in the Marine Environment. Environment Protection Authority. Sydney.

Green R H (1979) 'Sampling Design and Statistical Methods for Environmental Biologists'. Wiley & Sons (New York)

Fairweather P G, 1990 Sewage and the biota on seashores: assessment of impact in relation to natural variability. *Environmental Monitoring and Assessment,* **14**, 197-210.

Krogh M and Scanes P R (in press, 1997) Organochlorine Compounds and Trace Metal Contaminants in Fish Near Sydney's Ocean Outfalls. Marine Pollution Bulletin

Lee R S and Pritchard T R (1996) Dispersion of effluent from Sydney's new deepwater outfalls Part 1: Ocean Processes. In, 'Coastal and Estuarine Studies (50),: Pattiaratchi (Ed.) Mixing in Estuaries and Coastal Seas' American Geophysical Union, pp430-438. (Washington, DC)

Lincoln-Smith M P and Mann R A (1989a) 'Bioaccumulation in nearshore marine organisms. Organochlorine compounds in the red morwong Cheilodactylus fuscus, around Sydney's three major sewage outfalls' State Pollution Control Commission, Sydney

Lincoln-Smith M P and Mann R A (1989b) 'Bioaccumulation in nearshore marine organisms. Organochlorine compounds in the rocky reef animals near Malabar sewage ocean outfall' State Pollution Control Commission, Sydney

McLean C, Miskiewics A. and Roberts E (1991) Effect of Three Primary Treatment Sewage Outfalls on Metal Concentrations in the Fish Cheilodactylus fiscus Collected Along the Coast of Sydney, Australia. *Marine Pollution Bulletin*, **22**(3), 134-140.

Middleton J, Cox D and Tate P (in press, 1997) The Oceanography of the Sydney Region. *Marine Pollution Bulletin.*

Mortimer M R and Connel D W (1995) A model of the environmental fate of chlorohyrocarbon contaminants associated with Sydney sewage discharges. *Chemosphere,* **30**(11), 2021-2038.

Otway N M, Ling J E, McVae T A and Walker A R (1996) Soft-Bottom Community. In: Scanes, P. and Rendell, P. (Eds). 'Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 5: Impacts on the Marine Ecosystems' Environment Protection Authority. Sydney.

Pritchard T R, Lee R S and Davison A (1993) Sydney Deepwater Outfalls: In Situ Observations of Plume Characteristics. 11th Australian Conference on Coastal and Ocean Engineering, Townsville' Institution of Engineers Australia, Canberra

Pritchard T R, Rendell P, Scanes P and Philip N (1996a). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 1: Assessment of the Deepwater Outfalls. NSW Environment Protection Authority, Sydney, Australia.

Pritchard TR, Lee R S and Davison A (1996b) Dispersion of effluent from Sydney's new deepwater outfalls Part 2: Observations of Sewage Plume Behaviour: Winter and Summer Examples. In, 'Coastal and Estuarine Studies (50),: Pattiaratchi (Ed.) Mixing in Estuaries and Coastal Seas' American Geophysical Union, pp 439-452 (Washington DC).

Rendell P S and Espey Q (1993). Sydney Deepwater Outfalls Environmental Monitoring Program, Pre-Commissioning Report Series, Vol 8: Microlayer. EPA Sydney.

Robinson L, Heggie A and Coade G (1996). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 3: Water Quality. Environment Protection Authority. Sydney.

Roy P S and Thom B G (1981) 'Cainozoic shelf sedimentation model for the Tasman Sea margin of southwestern Australia' Geological Society of Australia Special Publication 18, 119-136.

Scanes P R and Henry G W (1992) Bivalve and Morwong Bioaccumulation, EMP Pre-commissioning Report Vol. 8, Environment Protection Authority, Sydney.

Scanes P R and Rendell P (Eds). (1996a). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 4: Trace Metals and Organochlorines in the Marine Environment. Environment Protection Authority. Sydney.

Scanes P R and Rendell P (Eds) (1996b). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 5: Impacts on the Marine Ecosystems. Environment Protection Authority. Sydney.

Schneider P M and Davey S B (1995) Sediment Contaminants off the Coast of Sydney, Australia: A Model for their Distribution. *Marine Pollution Bulletin*, **31**, 262-272.

Smith A and Lincoln Smith M (1993) Changes to Communities of Reef Fish Adjacent to the North Head and Bondi Cliff-face Sewage Outfalls Following Decommissioning, Final Report to Water Board, Sydney, The Ecology Lab., Sydney.

Wilson J R, Cox D R, Walker J W, Howden M I, Couriel E Dand Lee R (1996). Sydney Deepwater Outfalls Environmental Monitoring Program, Final Report Series, Volume 2: Sewage Plume Behaviour. Australian Water and Coastal Studies Pty Ltd. Sydney.

Underwood A J (1991). Beyond BACI: Experimental Designs for Detecting Human Environmental Impacts on Temporal Variations in Natural Populations. *Australian Journal of Marine and Freshwater Research*, **42**: 569-587.

Underwood A J (1992). Beyond BACI: The Detection of Environmental Impacts on Populations in the Real, but Variable, World. *Journal of Experimental Marine Biology and Ecology*, **161**: 145-178.

Underwood A J (1993) The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. *Australian Journal of Ecology*. **18**, 99-116.

Underwood A J, Chapman M G, Howitt L and Skilleter G A (1993) North Head Ocean Outfall Project, Final Report to Water Board, Sydney, Institute of Marine Ecology, University of Sydney.

Author

Tim Pritchard *is Manager of the Marine Waters Unit of the EPA of NSW (Locked Bag 1502, Bankstown, 2200). He graduated from Southampton, U.K. and gained his MSc in geophysics at Sydney. After research in marine science from 1981 to 1990 he joined the NSW EPA (then the SPCC) where he specialises in oceanography.*

Coastal boundary layer effects on pollutant dispersion

Tim Pritchard[1,2], Kerry Black[3], Randall Lee[4] and Klaus Koop[1]
1. NSW Office of Environment and Heritage, Sydney, Australia
2. University of Waikato, Hamilton, New Zealand
3. Melbourne University, Victoria, Australia
4. EPA Victoria, Australia

Abstract
Coastal Boundary Layer processes are investigated to assess how coastal and shelf morphologies affect flows which control the dispersion of pollutants discharged from coastal catchments on the New South Wales Coast, with case studies off Sydney and Coffs Harbour. Simple morphological risk assessment tools are presented to identify factors and processes which limit the exposure of sensitive environments to high pollutant concentrations and loads. A new *Maximum Dilution Potential* is developed and applied to case studies with contrasting morphologies in coastal waters. Eddy retention effects are generally not incorporated in existing near field models but, by including an *Eddy Retention Value*, the *Maximum Dilution Potential* incorporates potential re-entrainment effects in *Wake Zones*. Case studies illustrate specific *Coastal Boundary Layer* effects and indicate how an understanding of the spatial and temporal scales of *these* effects can be used to target more specific assessments of potential pollutant impacts. Although the approach presented here is focused on NSW coastal waters, the framework serves as a basis for general application elsewhere, and as a foundation for further refinement for application to NSW coastal waters.

Keywords: *Pollutant dispersion, coastal boundary layer, New South Wales*

1. Introduction

Pollutant loadings from coastal catchments enter coastal waters directly via regulated outfalls and unregulated stormwater drains, or indirectly via estuaries. These pollutants are advected and dispersed by coastal boundary layer (CBL) processes which result from interactions between flows and coastal/shelf morphologies including boundary jets, turbulent eddies, wake effects and tidal effects.

The aims of this study are to investigate the processes within the coastal boundary layer that affect dispersal and advection of pollution to facilitate coastal management.

In this paper we introduce the *Coastal Boundary Layer*, outline the results of a morphological classification of New South Wales (NSW) headlands in relation to their potential for wake effects, and develop a simple *Maximum Dilution Potential* index, which incorporates an *Eddy Retention Value* to take into account the effects of re-circulation in the lee of headlands. Case studies from NSW are discussed to illustrate this approach.

2. Background

2.1 The Coastal Boundary Layer

As early as 1972 Gabriel Csanady used the term ‘coastal boundary layer’ to describe a zone of dynamic features that were peculiar to near shore waters of the Great Lakes [6].

However, since then only occasional reference has been made to the coastal boundary layer [9,19,24] and no systematic CBL classification relevant to NSW coastal waters is evident in the scientific literature.

The coastal boundary layer (CBL) can be defined as the turbulent interface between the coastline and open water where regional currents and ocean waves are profoundly affected by changes in the orientation and variable morphology of the coastline and the continental shelf.

The CBL is analogous to the *Planetary* or *Atmospheric Boundary Layer* (PBL) albeit in the horizontal plane rather than the vertical plane. The CBL results from the interaction between regional currents and coastal bathymetry while the PBL results from interactions between regional winds and the planetary surface (e.g. [18]). Both are characterised by high levels of turbulence, strong gradients and rapid mixing with extreme variability and heterogeneity.

The physical characteristics of both the CBL and the PBL are important in dispersion of pollutants and transport of biological and anthropogenic materials (e.g. sewage discharges in the CBL and photo chemical smog and dust in the PBL).

This paper focuses on the *Inner CBL* effects associated with headland on pollutant dispersion (HW in Figure 1).

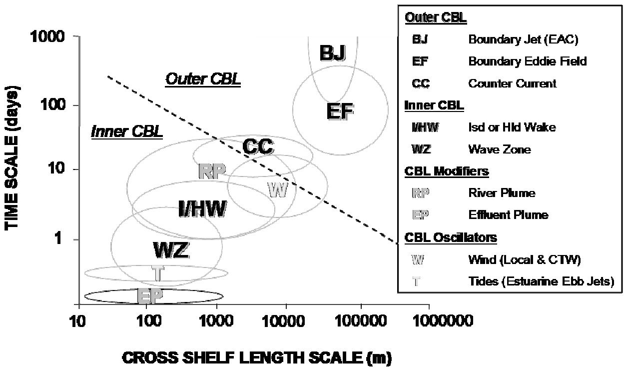


Figure 1 Schematic representation of the temporal and spatial scales of coastal boundary layer effects in NSW offshore waters. Ellipses represent indicative ranges of cross-shelf extents and dominant temporal expression of the CBL effects [10].

3. New South Wales Coastal Morphology

Various techniques have previously been employed to characterise coastal roughness such as fractal analysis [22] and various classification systems exist for coastal environments such as estuaries [16], beaches [17], coastal depositional environments [8] and sandbanks [7]. NSW bay shapes have previously been characterised in relation to likely differences in tsunami amplification and dissipation [2]. The results of the first morphological classification of NSW headlands [10] based on potential for retention and dispersion of pollutants have expanded on this earlier focussed impact study, and are summarised here.

One hundred and forty four NSW headlands were classified from Fingal Head just south of the Queensland border to Green Cape near the border with Victoria [7] (Figure 2). Of these one hundred and fourteen were identified as *Triangular* headlands with a median length of 624m (range 186-5768m), and thirty as *Coastal Step* (one-sided) headlands (length range 230-13,980m). *Cusp* headlands result from the expression of regional geology and the northward sediment transport which tends to fill the northern ends of bays, often producing iconic north facing cusp asymmetry. Sand dominated asymmetric cusp shaped headlands were conspicuous in northern NSW such as near Crowdy Head, while rocky headlands were more numerous in the south such as around Batemans Bay where coastal morphologies exhibited obvious fractal characteristics.

The standardised *Apex Angles* of both *Triangular* and *Coastal Step* headlands were remarkably consistent with mean apex angles of 70° (SD 24°) and 67° (SD 22°), respectively, and identical ranges (20°to119°).

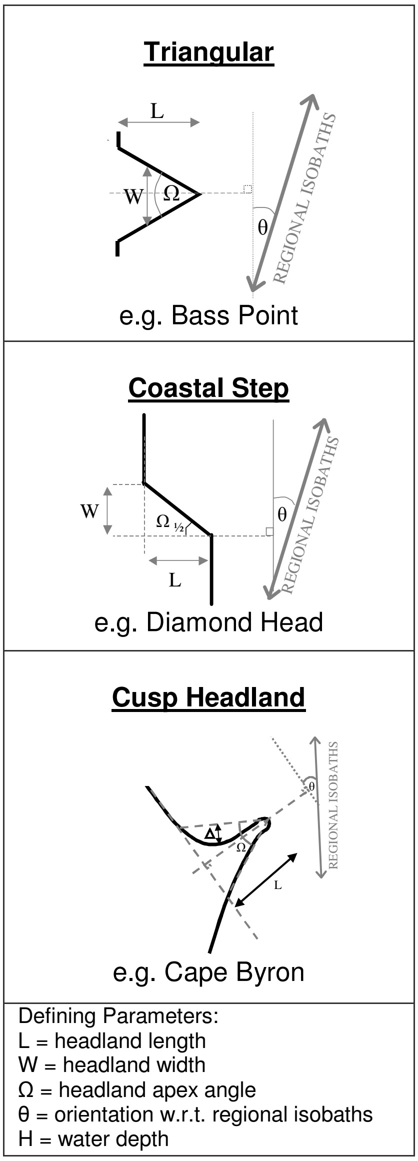


Figure 2 Simplified headland types relevant to NSW coastal morphologies

4. Pollutant Dispersion in the Inner CBL

4.1 Wake Effects

Although Cresswell et al. [4] noted the presence of weak clockwise cells in the embayments of northern NSW (e.g. between Smoky Cape and Korogoro Pt, Hat Head and Crescent Head; Crescent Head and Pt Plomer) there has been no systematic evaluation of the potential for wake effects in NSW coastal and shelf waters.

Turbulent flows, including eddies, are shed in the wakes of headlands, islands, shoals, man-made structures such as training walls, and in sudden expansions such as changes in the orientation of the coastline. The relative importance of inertial forces (advection of momentum) and frictional forces governs the nature of flow patterns in wakes of such obstacles [21, 23, 3, 18]. If the frictional force dominates the particles will be dragged along the obstacle but if the inertial force dominates the flow accelerate perpendicular to its intended path and separate from the obstacle resulting in a range of turbulent flow patterns. The ratio of inertial and frictional forces and associated flow patterns have been expressed by various indices such as the *Reynolds Number* and the *Wake Parameter* (P) which incorporates shallow water frictional effects [23].

$$\text{Wake Parameter,} \quad P = \frac{U H^2}{K_z L} \qquad (1)$$

where, U = shear velocity
H = water depth
K_z = vertical eddy diffusion coefficient
L = length of obstacle

The *Wake Parameter* was calculated for a range of NSW headland lengths and water depths as shown in Figure 3 by assuming a steady current of 0.2 m/s and a ubiquitous constant vertical eddy diffusion coefficient (Kz) of 0.1 m^2/s. The *Wake Parameter* is directly proportional to ambient current velocity and inversely proportional to vertical eddy diffusion coefficient so the pattern in Figure 3 can be readily scaled according to variations in these parameters. Based on this preliminary analysis, wake effects are predicted by the Wake Parameter (P>1) for *Triangular* headlands in water depths greater than 35m (Figure 3). Conversely, NSW headlands in water depths less than 15m are unlikely to be associated with prominent, large scale, wake effects where bottom shear stress and wave energy would be expected to be more dominant.

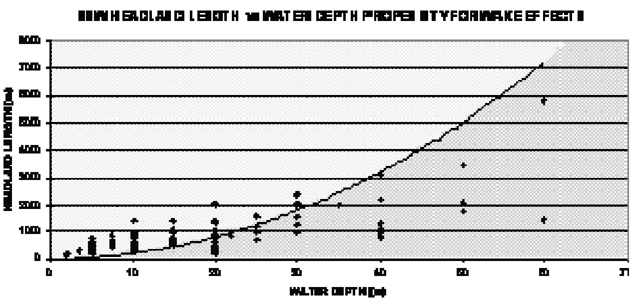


Figure 3 Headland length-depth distributions shown in relation to *Wake Parameter*, P = 1. Below P=1 (darker shade) flow separation and wake features such as re-circulation cells are favoured whereas above P=1 (lighter shade) frictional forces dominate to limit flow separation.

Indices such as the *Wake Parameter* were developed for simple morphologies and steady flows so real world factors associated with complex morphologies and unsteady flows must be expected to reduce the applicability of these indices. However, the *Wake Parameter* and other dimensionless flow indices provide a highly generalised relative measure of the propensity for various turbulent flow regimes. They signal important morphological parameters and can be used with caution to indicate broad classes of potential turbulent states and to spawn testable hypothesis for more detailed observational and modelling studies.

In general, recirculation is favoured by: deeper water due to lesser frictional effects; stronger currents although very high velocities can cause unstable turbulent flows; and, sharp tipped headlands which promote flow separation and spawn vorticity within the wake [18]. Likewise recirculation can be inhibited by a number factors such as: high levels of stochastically forced turbulence near the tip of a headland which may prevent the formation of a single narrow headland jet, instead resulting in a wider turbulent shear layer which may be much less conducive to large-scale recirculation [1]. This, and other mixing processes, may be expressed by an eddy viscosity parameter which, when high, inhibits the formation of re-circulation / retention cells.

4.2 Maximum Dilution Potential

Maximum Dilution Potential (MDP) is defined here in terms which incorporate both maximum mixing of effluent with ambient waters and potential (maximum) effluent retention due to re-circulation cells, which promote re-entrainment of previously discharged effluent in emerging effluent plumes.

Initial or near-field dilution of pollutants discharged to coastal waters is fundamentally limited by the availability of ambient water; therefore, fundamental limiting factors are the effluent discharge rate, the flux of ambient water available for dilution, and the degree to which the discharged effluent escapes re-entrainment. Engineering solutions such as well designed outfall diffuser systems with controlled exit velocities maximise initial dilutions in the near-field but often overlook the complexities of the receiving environment to fully optimise dilution capacity of the designed system [11].

If we can assume near complete vertical mixing through the water column, an upper limit on near field effluent dilution is given by a proposed *Maximum Dilution Potential* (MDP):

$$MDP(x) = \frac{U(x)\, H(x)\, D\, (1-ERV)}{E_F} \qquad (2)$$

where

U(x)	= ambient current velocity perpendicular to outfall orientation at a distance x from shore (m/s)
H(x)	= water depth at a distance x from shore (m)
D	= diffuser length (m)
E_F	= effluent flow (m^3/s)
ERV	= *Eddy Retention Value* (dimensionless)

If coastal configuration predisposes areas to the formation of a *Wake Zone* then a worse case re-entrainment scenario is assumed. Here an *Eddy Retention Value* (ERV) is proposed as the ratio of volume of effluent discharged during the lifetime of a re-circulating lee eddy to the volume of water within the eddy.

$$ERV = \frac{E_F T}{\pi R_L^2 H_A} \quad (3)$$

where

R_L = eddy dimension (m)
T = duration of eddy persistence (s)
H_A = average water depth in *Wake Zone* (m)

R_L and T are preferably determined by observations and/or through model simulations but, where water depth is well constrained, R_L may also be estimated as the Wake Parameter (Equation 1) scaled (multiplied) by the Headland Length (L) giving

$$R_L = \frac{U H_A^2}{K_Z} \quad (4)$$

So by substituting R_L in Equation 3 the *Eddy Retention Value* (ERV) becomes

$$ERV = \frac{E_F T K_Z^2}{\pi U^2 H_A^5} \quad (5)$$

Clearly, ERV is highly sensitive to H_A which limits its broader application to areas of simple and well defined bathymetry.

5. NSW Case Studies

Here two case studies are outlined for sewage discharges off Coffs Harbour and off Sydney.

5.1 Coffs Harbour

The Coffs Harbour Case Study is located in the *Inner CBL* where a new ocean outfall was required to implement a regional effluent management strategy [5] which recognised Poor environmental outcomes of former shore line outfalls (Figure 4).

The *Wake Parameter* here indicates borderline conditions for wake formation which is consistent with observations of transient re-circulation cell formation [11] and the characteristics listed below.

<u>Observed and Assumed Characteristics</u>

- Complex headland bathymetry (Harbour and Korffs Islet)
- Headland Length (Corambirra Point) (L) = 860m
- Water Depth (H) = 20m
- Assumed vertical eddy diffusion coefficient (Kz) = 0.1 m^2/s
- Assumed current velocity = 0.2 m/s

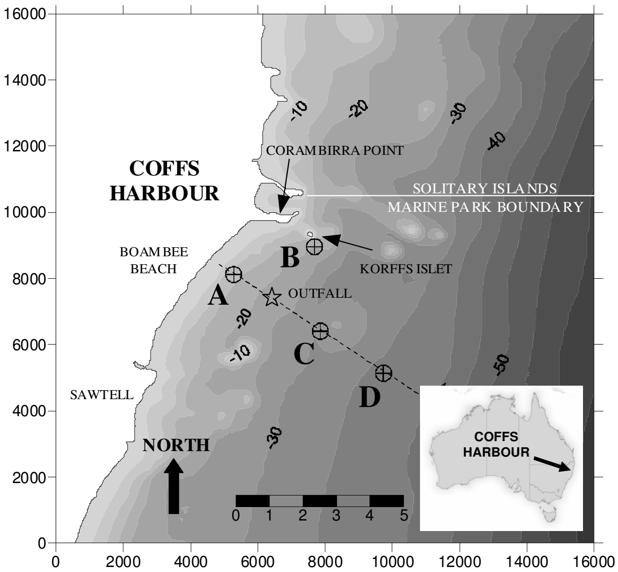


Figure 4 Coffs Harbour study location showing local bathymetry, ADCP deployments (A-D) and transect T1-T2 (dotted line). Modified from Pritchard et al. [11]

- Observed/simulated eddy length scale (Obs R_L) ~1000m
- Outfall diffuser length (D) = 185m
- Outfall distance from shore = 1500m
- Effluent Flow Rate (E_F) = 0.24 m^3/s

<u>Calculated Parameters</u>

- Wake Parameter (P) = 0.93
- Eddy length scale (RL) = 800m
- Eddy Retention Value (ERV)= 0.0002

The calculated and observed eddy length scales are remarkably similar (800m vs 1000m respectively). Expansion south of Corambirra Point due to the clockwise rotation of the orientation of the coastline may contribute to the slight underestimation of eddy size by the *Eddy Length Scale Parameter* (RL).

A cross-shelf bathymetry profile and shore parallel residual currents along the prescribed alignment of the new outfall are shown in Figure 5. For the residual current scenario, the average MDP increases from about 1:250 within the wake (0-2km offshore) to about 1:3,500 in the free stream flow (3-5km offshore), taking in to account an almost insignificant *Eddy Retention Value* (ERV = 0.02%); that is, the MDP is 14.4 times greater in the free stream than in the wake.

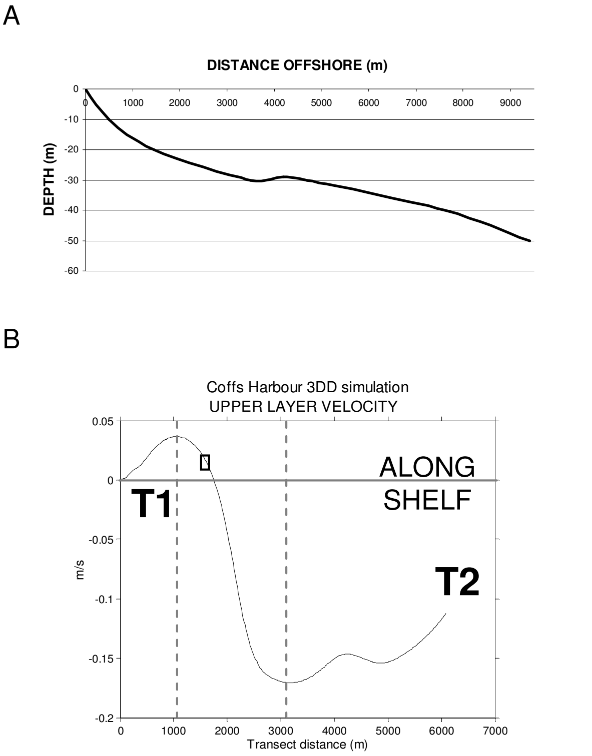


Figure 5 Cross-shelf bathymetry (A) and residual current (B) profiles along the prescribed alignment of the outfall (T1-T2). Outfall located at 21m water depth shown as box on T1-T2. Derived from data and model results presented in Pritchard et al. [11]

5.2 Sydney

The Sydney Case Study is located in the *Outer CBL* where NSW's greatest loads of sewage derived pollutants are discharged via three deepwater outfalls [12].

Not surprisingly, *Headland Wake* effects do not interact with Sydney's deepwater effluent plumes because the three major deepwater outfall systems are located well beyond the effects of the *Inner CBL*. Indeed the effluent plumes generally follow free stream flow and achieve high levels of dilution efficiency as demonstrated by models [24] and direct observations [14]. Therefore, the *Eddy Retention Value* (ERV) is zero. The *Maximum Dilution Potential* (MDP) was calculated for possible discharges along a cross-shelf transect that passes through the Bondi deepwater outfall (Figure 6B) as well as for each of the three actual outfalls (Table 1). The length of the diffuser was set at 510m (ie as constructed) and the effluent flow rate was fixed at 1.91 m^3/s [13]. Cross-shelf current speeds [U(x)] were based on extrapolation of data observed along the Sydney Integrated Marine Observing System transect, while cross-shelf bathymetry [H(x)] was based on Royal Australian Navy Charts (ISBN 1 86333 115 8). Based on the MDP cross-shelf profile Bondi deepwater outfall was located at an optimum distance from shore, at the base of a 'steep' inner shelf slope (Figure 6A). MDP calculations represented in Figure 6B account for stratification effects here by assuming that the maximum height of rise of plumes trapped by ambient stratification is half the water depth which is consistent with observed patterns [12,15].

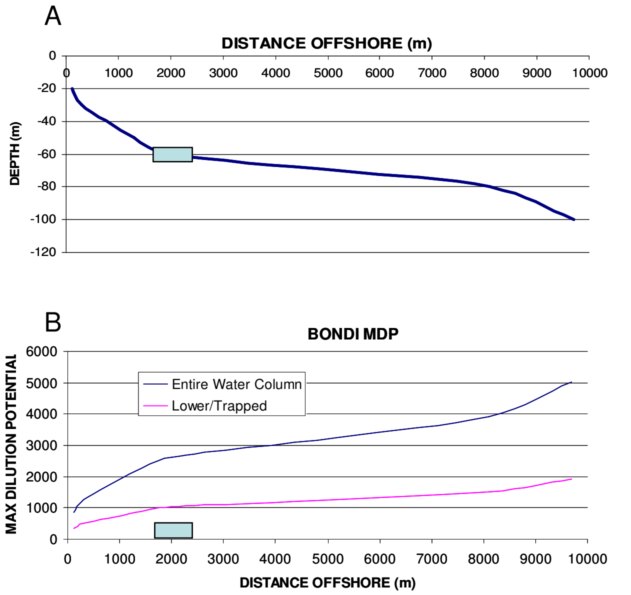


Figure 6 Profiles along a transect passing through Bondi deepwater outfall (shown as shaded box).
A: Cross-shelf bathymetry profile
B: *Maximum Dilution Potential* (MDP)

When actual average initial dilutions based on validated near-field models [13] are compared with the theoretical *Maximum Dilution Potential* it is clear that Sydney's three deepwater outfalls perform well, achieving 39% to 53% of their *Maximum Dilution Potential* (Table 1). It is notable that Malabar outfall has the lowest *Maximum Dilution Potential* but the greatest outfall efficiency.

Table 1 Maximum Dilution Potential calculation for Sydney's deepwater ocean outfalls

	Outfall / STP		
	NH	**BON**	**MAL**
Average Effluent Flow (m^3/s)	4.46	1.91	5.67
Diffuser Length (m)	765	510	720
Water Depth (m)	60	60	80
Median Dilutions TRAPPED	349	414	513
MDPTRAPPED	721	1122	711
Median Dilutions SURFACE	817	1193	636
MDPSURFACE	1854	2884	1828
Outfall Efficiency TRAPPED (%)	48%	37%	72%
Outfall Efficiency SURFACE (%)	44%	41%	35%
Outfall Efficiency AVERAGE (%)	**46%**	**39%**	**53%**

Based on information provided by Pritchard et al. [13]. The innermost diffusers at North Head and Malabar are both 2900m from shore.

6. Conclusions: Management Implications

Wastewater managers and regulators are required to pursue a range of wastewater management solutions, such as source control, beneficial re-uses, and minimization of overall impacts in order to achieve sustainable, socially acceptable outcomes.

A hierarchical screening of potential environmental impacts driven by an understanding of CBL processes is particularly relevant to highly dynamic marine environments, and promotes transparent decision making which in turn promotes cost effective solutions.

Feasible, cost efficient, options can be scoped by performing screening level assessments early in the planning and budgeting process based on readily available data such as coastal morphological and existing time series data. In this way, a set of rational options can be identified and prioritised for more detailed assessments. Subsequent, targeted assessments may then require acquisition of additional data and the use of more sophisticated modeling tools.

7. Acknowledgements

This project was supported by the Office of Environment and Heritage in the New South Wales Department of Premiers and Cabinet (and former agencies). The authors are grateful to the anonymous reviewer for helpful suggestions.

8. References

[1] Aiken C.M., Moore, A.M. and Middleton, J.H., 2002. The non normality of coastal ocean flows around obstacles, and their response to stochastic forcing. Journal of Physical Oceanography 32 (10): 2955-2974.

[2] Baldock, T.E., Barnes, M.P., Guard, P.A., Hie, T., Hanslow,D., Ranasinghe,D. & Neilson,O., 2007. Modelling tsunami inundation on coastlines with characteristic form. 16th Australasian Fluid Mechanics Conference, Gold Coast, Australia, pp 939-942.

[3] Black, K. P. & Gay, S. L., 1987. Eddy formation in unsteady flows. J. Geophys. Research, 92: 9514–9522.

[4] Cresswell, G.R.,Ellyett,C., Legeckis,R., Pearce,A.F., 1983. Nearshore features of the East Australian Current system. Aust. J. Mar. & Freshwater Res., 34,105–114.

[5] CHEIS, 2000. Coffs Harbour Sewerage Strategy Environmental Impact Statement. Vol 1-10. Coffs Harbour City Council, NSW, Australia.

[6] Csanady, G., 1972. The coastal boundary layer in Lake Ontario. J. Phys. Oceanography. 2:41-53, 168-176.

[7] Dyer, K.R. and Huntley, D.A., 1999. The origin classification and modelling of sand banks and ridges. Continental Shelf Research 19, pp. 1285-1330

[8] Harris P.T., Heap,A.D., Bryce, S.M., Porter-Smith, R., Ryan, D.A., Heggie, D.T., 2002. Classification of Australian clastic coastal depositional environments based upon a quantitative analysis of wave, tide and river power. J. Sedimentary Research; 72(6):858–70.

[9] King, B. and E. Wolanski, 1990. Coastal dynamics along a rugged coastline. Proceedings of the 5th Intemational Biennial Conference: Physics of estuaries and coastal seas. Gregynog, Wales.

[10] Pritchard,T.R., 2011. Determining potential for pollutant impacts in dynamic coastal waters: comparing morphological settings, PhD Thesis, University of Waikato, New Zealand.

[11] Pritchard, T.R., Holden, C., Lee, R.S., Black, K.P. and Healy, T., 2007. Dynamics and Dispersion in the Coastal Boundary Layer off Coffs Harbour in Eastern Australia. Journal of Coastal Research, SI 50, 848-857.

[12] Pritchard, T. R., Rendell, P., Lee, R. S. & Ajani, P., 2001. How do Ocean Outfalls Affect Nutrient Phytoplankton Relationships in Coastal Waters of New South Wales, Australia? J. Coastal Res., 34, 96-109.

[13] Pritchard, T.R., Rendell, P. Scanes, P. and Phillip, N., 1997. Volume 1: Assessment of the Deepwater outfalls, Sydney Deepwater Outfalls Environmental Monitoring Program Final Report Series. NSW Environment Protection Authority, Sydney.

[14] Pritchard, T.R., Lee, R.S., Davison, A., 1993. Sydney Deepwater Outfalls: In Situ Observations of Plume Characteristics. 11th Australasian Conference on Coastal and Ocean Engineering: Coastal Engineering a Partnership with Nature, IEA, Australia, 53-58.

[15] Pritchard, T.R., Lee, R.S., Davison, A., 1993. Sydney Deepwater Outfalls: In Situ Observations of Plume Characteristics. 11th Australasian Conference on Coastal and Ocean Engineering: Coastal Engineering a Partnership with Nature, IEA: 53-58.

[16] Roy P.S., Williams R.J., Jones A.R., Yassini I., Gibbs P.J., Coates B., West R.J., Scanes P.R., Hudson J.P., Nichol S., 2001. Structure and function of south-east Australian estuaries. Estuarine Coastal and Shelf Science, 53:351–84.

[17] Short, A., 1993. Beaches of the New South Wales Coast: a guide to their nature, characteristics, surf and safety. Australian Beach Safety and Management Program. ISBN 0 646 15055 3.

[18] Signell, R. P. and Geyer, W. R., 1991. Transient eddy formation around headlands. Journal of Geophysical Research 96(C2): 2561–2575.

[19] Stull, R., 1997. An Introduction to Boundary Layer Meteorology. Boston: Kluwer Academic Publishers. ISBN 9027727686.

[20] Thorrold,S.R. and McKinnon,A.D., 1991. Biological significance of the coastal boundary layer off Townsville, North Queensland. Bureau of Rural Resources Proceedings, 15, pp 104-109.

[21] Tomczak,M., 1998. Shelf and Coastal Oceanography,V1.0 http://www.es.flinders.edu.au/~mattom/ShelfCoast/chapter07.html

[22] Wessel, P., and Smith, W. H. F., 1996. A global, self-consistent, hierarchical, high-resolution shoreline database, J. Geophys. Res., 101, 8741–8743.

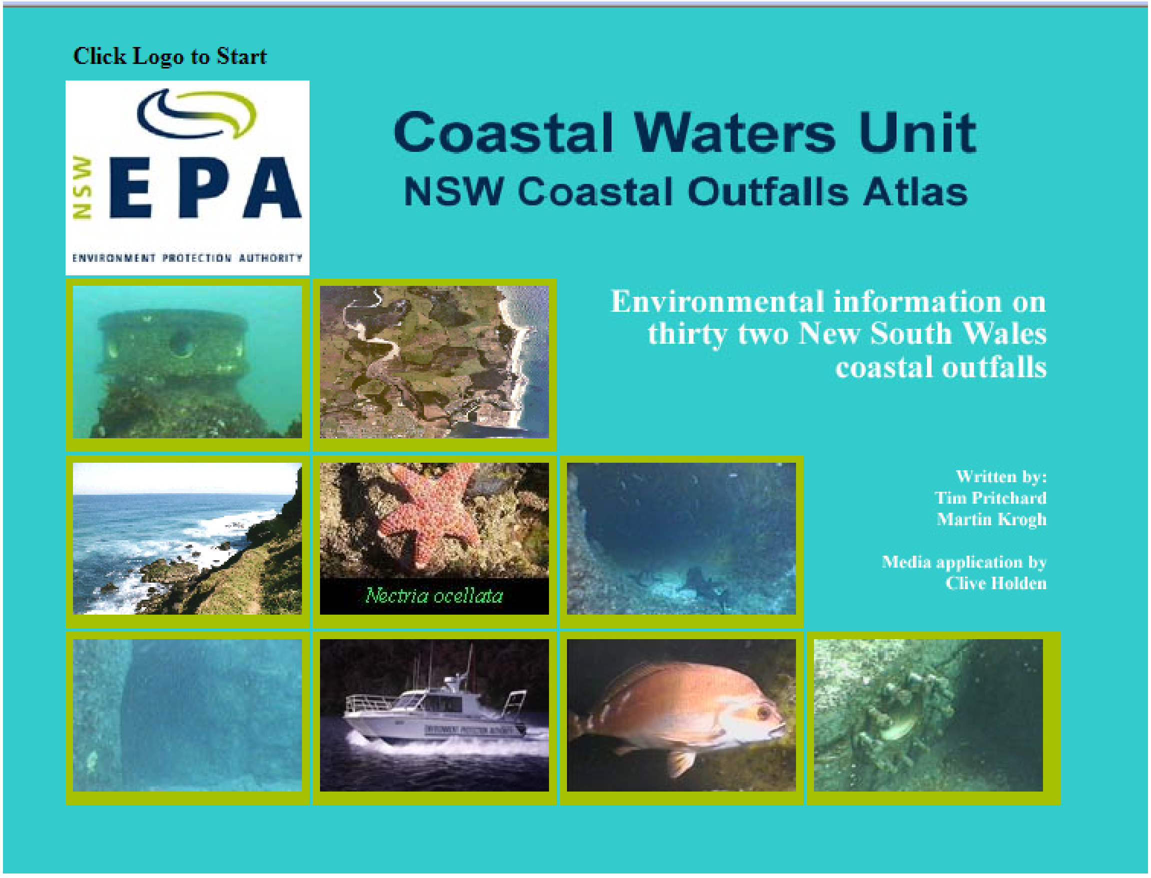
[23] Wolanski, E., Imberger, J. and Heron, M. L., 1984. Island wakes in shallow coastal waters. Journal of Geophysical Research 89(C6): 10,553–10, 569.

[24] Wilson, J. R., Cox, D. R., Walker, J. W., Howden, M. I., Couriel, E. D. and Lee, R. S., 1995. Sydney Deepwater Outfalls Environmental Monitoring Program: Final Report Series: Volume 2: Sewage Plume Behaviour, NSW EPA Publication, 227p

[25] Zaker, N. H., Imberger,J., Pattiaratchi,C., 2007. Dynamics of the Coastal Boundary Layer off Perth, Western Australia. J. Coastal Res., 23/5, pp. 1112-1130.

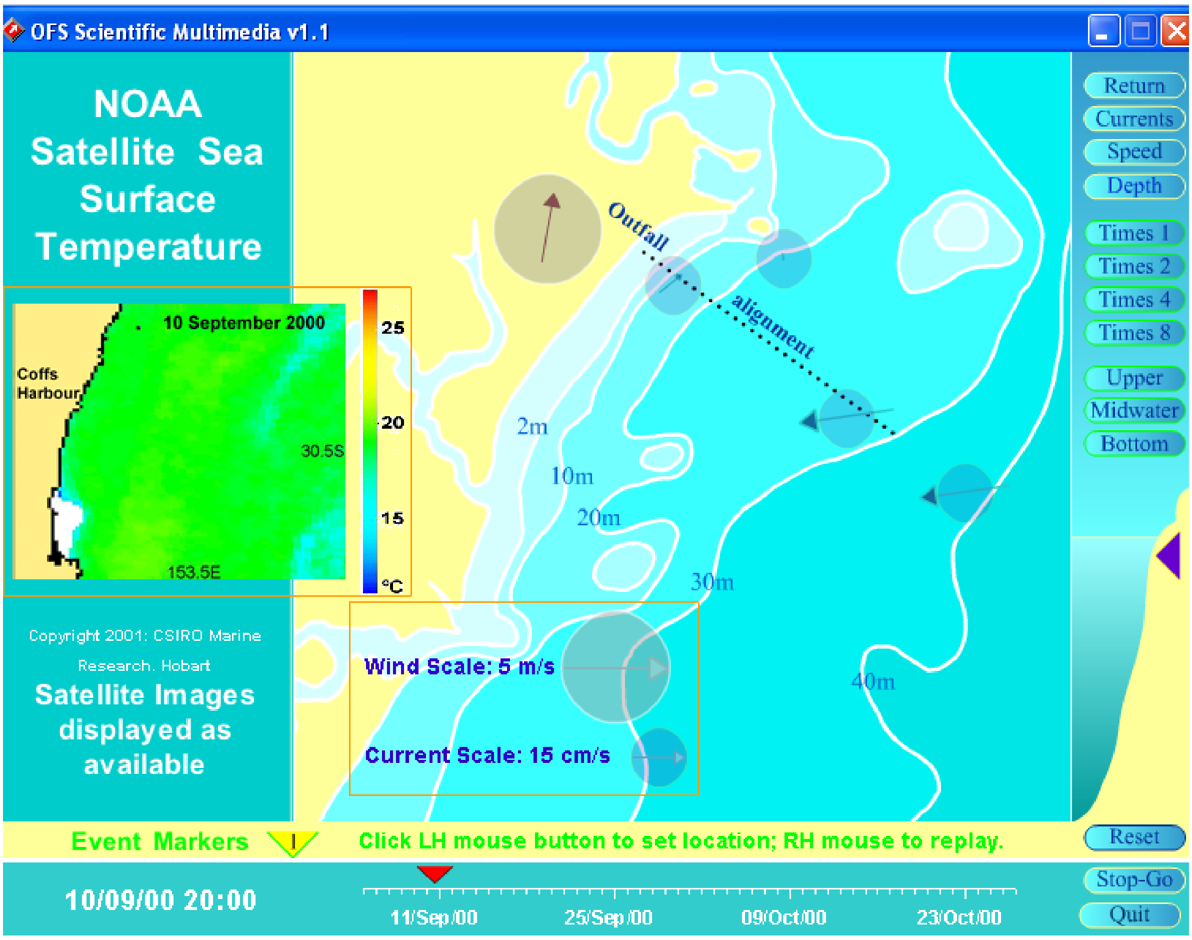
APPENDIX 4: DATA VISUALISATION TOOLS

A4.1 NSW Ocean Outfall Inventory



Available on attached USB

A4.2 Coffs Harbour Wind and Current Visualisation



Available on attached USB which includes data files