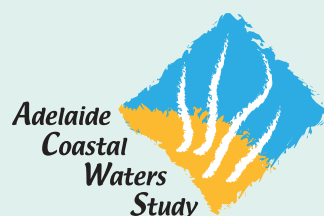


The Adelaide Coastal Waters Study

Final Report, Volume 1
Summary of Study Findings
November 2007



Prepared for

South Australian Environment Protection Authority

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The findings and recommendations presented in this report are derived primarily from information and data supplied to CSIRO by the Client and from the field investigations and research conducted by sub consultants. The passage of time, manifestation of latent conditions, or impacts of future events may require further exploration and subsequent data analysis, or re-evaluation of the findings, observations, conclusions, and recommendations expressed in this report.

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FOREWORD

I am pleased to present the Final Report of the Adelaide Coastal Waters Study.

In 2001, the Government of South Australia announced that the Environment Protection Authority (EPA) would manage the Study which sought to develop the understanding needed to redress the issues of seagrass loss, seafloor instability and poor water quality along Adelaide's metropolitan coast. This important work has delivered the ability to establish the targets that need to be achieved to manage our coast in a sustainable manner.

The Final Report of the ACWS integrates a large amount of knowledge derived through the Study, most of it delivered through local areas of expertise - original work that discovered important relationships between Adelaide's coastal ecosystem and its range of inputs. The report is underpinned by 20 Technical Reports, published during the course of the study and a Volume 2 report that summarises much of this work.

We established a partnership with CSIRO to ensure that the science associated with the study was rigorous and well focussed. I am indebted to Professor David Fox who directed the study and David Ellis who managed the project for CSIRO. The quality of the work reflects their skill and perseverance and that of the scientific team whose work underpins this study.

The ACWS Steering Committee, Technical Review Group and EPA officers including a former EPA employee, Dr John Cugley, put considerable time and effort into the guidance of this study, ensuring that the focus remained on developing a body of high quality knowledge about the key issues.

The findings of the report represent a challenge to all South Australians - but we always knew it would, and the different stakeholders have been getting on with implementing this new knowledge as the story began to unfold through the publishing of the technical reports and discussion about findings as they came to light. Even so, the sustainable management of Adelaide's coast and its range of contaminant inputs will take some time to achieve.

While it is crucial that the State Government takes a lead role in providing direction for the sustainable management of our coastal waters, it is equally important for the whole community to recognise that, collectively and individually, we all have a role to play. We must all take responsibility for Adelaide's coast and for its condition when future generations take over their management.

I encourage government, business and industry, peak bodies, academic and research institutions, community groups and individuals to consider and develop actions addressing the findings and suggested responses in this report. Through collaborative efforts we can generate positive change for a sustainable and valued coastal environment along Adelaide.

Dr Paul Vogel
CHIEF EXECUTIVE
Environment Protection Authority

ACKNOWLEDGMENTS

This report draws from and synthesises the results of a number of scientific investigations undertaken during 2003-2005 that defined the Adelaide Coastal Waters Study. We are indebted to the critical role played by our own Scientific Committee and the Client's independent Technical Review Group in ensuring the scientific integrity of the study and of its outputs.

This study could not have been undertaken without the significant contributions made by the researchers listed below who were part of the ACWS scientific research program. The dedication and commitment at both an individual and organisational level to the delivery of quality scientific outcomes is reflected in the pages of the ACWS task reports (listed below).

We are indebted to Alan Butler and his team at CSIRO Marine and Atmospheric Research who undertook the preliminary scoping study that provided invaluable background material and helped identify the research requirements of the present study. The ACWS Steering Committee provided valuable input throughout the study. Their contributions at all stages of the project were greatly appreciated.

We are most appreciative of the resources committed by the study Stakeholders to enable this study to proceed:

- South Australian Environment Protection Authority
- SA Water Corporation
- Torrens Patawalonga and Onkaparinga Catchment Water Management Boards
- Department for Transport Energy and Infrastructure
- Mobil Refining Australia Pty Ltd
- AGL Torrens Island
- South Australian Coast Protection Board
- Primary Industries and Resources SA (PIRSA)
- Ports Corporation.

Non-funding ACWS Steering Committee members include:

- Conservation Council of SA
- SA Fishing Industry Council Inc
- Local Government Association
- Department of Water Land and Biodiversity Conservation
- Planning SA.

We are particularly appreciative of the assistance provided by the Client's representatives, Dr John Cugley and Mr Peter Pfennig of the South Australian EPA.

ACWS Scientific Committee:

- Dr Graham Harris (Chair)
- Prof. David Fox (Study Director)
- Dr Graeme Batley (CSIRO Land and Water)
- Dr Simon Bryars (SARDI Aquatic Sciences)
- Prof. Anthony Cheshire (Science to Manage Uncertainty Pty Ltd)
- Prof. Howard Fallowfield (Flinders University)
- Prof. Peter Fairweather (Flinders University)
- Prof. Chari Pattiaratchi (The University of Western Australia)
- Dr Murray Townsend (SA Department for Environment and Heritage, Coastal Protection Branch)

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- Dr Rod Connolly (Griffith University)
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	Janet Anstee	CSIRO Land and Water

Adelaide Coastal Waters Study Technical Reports

Many of the researchers and support staff listed above contributed to one or more of the twenty ACWS Stage 2 Technical Reports prepared between 2005 and 2007. These technical reports are detailed below. Copies are available at <http://www.clw.csiro.au/acws>.

Report No.	Reference
ACWS TR 1	Wilkinson, J., Pearce, M., Cromar, N. and Fallowfield, H. (2003). <i>Audit of the quality and quantity of effluent discharging from Wastewater Treatment Plants (WWTPs) to the marine environment</i> . ACWS Technical Report No.1 prepared for the Adelaide Coastal Waters Study Steering Committee, November 2003. Department of Environmental Health, Flinders University of South Australia.
ACWS TR 2	Westphalen, G., Collings, G., Wear, R., Fernandes, M., Bryars, S. and Cheshire, A. (2004) <i>A review of seagrass loss on the Adelaide metropolitan coastline</i> . ACWS Technical Report No. 2 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences), Publication No. RD04/0073, Adelaide.
ACWS TR 3	Wilkinson, J., Hutson, J., Bestland, E. and Fallowfield, H. (2004). <i>Audit of contemporary and historical quality and quantity data of stormwater discharging into the marine environment, and field work programme</i> . ACWS Technical Report No. 3 prepared for the Adelaide Coastal Waters Study Steering Committee, June 2004. Department of Environmental Health, Flinders University of South Australia.
ACWS TR 4	Lamontagne, S., Le Gal La Salle, C., Simmons, C., James-Smith, J., Harrington, N., Love, A., Smith, A., Hancock, G., and Fallowfield, H. (2004). <i>Estimation of groundwater and groundwater N discharge to the Adelaide Coastal Waters Study area</i> . ACWS Technical Report No. 4 prepared for the Adelaide Coastal Waters Study Steering Committee. CSIRO Land and Water and Flinders University of South Australia, December 2004.
ACWS TR 5	Petrusevics, P. (2005). <i>Distribution of Suspended Matter in Adelaide Metropolitan Waters Using SeaWiFS Data - Final Technical Report</i> . ACWS Technical Report No. 5 prepared for the Adelaide Coastal Waters Study Steering Committee. Oceanique Perspectives, January 2005.
ACWS TR 6	Blackburn, D. T., and Dekker, A. G. (2006). <i>Remote sensing study of marine and coastal features and interpretation of changes in relation to natural and anthropogenic processes. Final Technical Report</i> . ACWS Technical Report No. 6 prepared for the Adelaide Coastal Waters Study Steering Committee, May 2005. David Blackburn Environmental Pty Ltd.
ACWS TR 7	Kaempf, J. (2005). <i>In-situ field measurements for Adelaide Coastal Waters Study</i> . ACWS Technical Report No. 7 prepared for the ACWS Steering Committee, July 2005. School of Chemistry, Physics and Earth Sciences, Flinders University.
ACWS TR 8	Pattiaratchi C. and Jones, R. (2005). <i>Physical and oceanographic studies of Adelaide coastal waters using high resolution modelling, in-situ observations and satellite techniques - PPM 2 Sub Task 4 Final Technical Report</i> . ACWS Technical Report No. 8 prepared for the Adelaide Coastal Waters Study Steering Committee. Centre for Water Research, University of Western Australia, Nedlands WA 6907, July 2005.
ACWS TR 9	Westphalen, G., Oloughlin, E., Collings, G., Tanner, J., Elington, Y. and Bryars, S. (2005). <i>Responses to reduced salinities of the meadow forming seagrasses Amphibolis and Posidonia for the Adelaide metropolitan coast</i> . ACWS Technical Report No. 9 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic sciences) Publication No. RD01/02814, Adelaide.
ACWS TR 10	Wilkinson, J. (2005). <i>Reconstruction of historical stormwater flows in the Adelaide metropolitan area</i> . ACWS Technical Report No. 10 prepared for the Adelaide Coastal Waters Study Steering Committee, September 2005. Department of Environmental Health, Flinders University of SA.

- ACWS TR 11** Collings, G., Bryars, S., Nayar, S., Miller, D., Lill, J. and O'Loughlin, E. (2006). *Elevated nutrient responses of the meadow forming seagrasses, Amphibolis and Posidonia, from the Adelaide metropolitan coastline*. ACWS Technical Report No. 11 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/0208-16, Adelaide.
- ACWS TR 12** Collings, G., Miller, D., O'Loughlin, E., Cheshire, A. and Bryars, S. (2006). *Turbidity and reduced light responses of the meadow forming seagrasses Amphibolis and Posidonia, from the Adelaide metropolitan coastline*. ACWS Technical Report No. 12 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/0208-17, Adelaide.
- ACWS TR 13** Nayar, S., Collings, G., Miller, D. and Bryars, S. (2006). *Nutrient fluxes in the meadow forming seagrasses Posidonia and Amphibolis from the Adelaide metropolitan coast*. ACWS Technical Report No. 13 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/0208-18, Adelaide.
- ACWS TR 14** Bryars, S., Miller, D., Collings, G., Fernandes, M., Mount, G. and Wear, R. (2006). *Field surveys 2003-2005: Assessment of the quality of Adelaide's coastal waters, sediments and seagrasses*. ACWS Technical Report No. 14 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/0208-15, Adelaide.
- ACWS TR 15** Bryars, S., Collings, G., Nayar, S., Westphalen, G., Miller, D., O'Loughlin, E., Fernandes, M., Mount, G., Tanner, J., Wear, R., Eglinton, Y. and Cheshire, A. (2006). *Assessment of the effects of inputs to the Adelaide coastal waters on the meadow forming seagrasses, Amphibolis and Posidonia. Task EP 1 Final Technical Report*. ACWS Technical Report No. 15 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/0208-19, Adelaide.
- ACWS TR 16** Bone, Y., Deer, L., Edwards, S. A. and Campbell, E. (2006). *Adelaide Coastal Waters Study - Sediment Budget*. ACWS Technical Report No. 16 prepared for the Adelaide Coastal Waters Study Steering Committee, August 2006. School of Earth and Environmental Science, Discipline of Geology, The University of Adelaide.
- ACWS TR 17** Wilkinson, J., Bestland, E., Smyth, L. and White, N. (2006). *The loads of particulate matter and atmospheric nitrogen deposited from wet and dryfall to Adelaide metropolitan coastal waters*. ACWS Technical Report No. 17 prepared for the Adelaide Coastal Waters Study Steering Committee, March 2006. Flinders University of South Australia.
- ACWS TR 18** Wilkinson J., White, N., Smythe, L., Hutson, J., Bestland, E., Simmons, C., Lamontagne, S. and Fallowfield, H. (2005). *Volumes of inputs, their concentrations and loads received by Adelaide metropolitan coastal waters*. ACWS Technical Report No. 18 prepared for the Adelaide Coastal Waters Study Steering Committee, September 2005. Flinders Centre for Coastal and Catchment Environments, Flinders University of SA.
- ACWS TR 19** Henderson, B., Dobbie, M. and Harch, B. (2006). *An integrated environmental monitoring program for Adelaide's Coastal Waters*. ACWS Technical Report No. 19 prepared for the Adelaide Coastal Waters Study Steering Committee. CSIRO Mathematical and Information Sciences Technical Report No. 05/154, Canberra.
- ACWS TR 20** Pattiaratchi, C., Newgard, J. and Hollings, B. (2006). *Physical oceanographic studies of Adelaide coastal waters using high resolution modelling, in-situ observations and satellite techniques - Sub Task 2 Final Technical Report*. ACWS Technical Report No. 20 prepared for the Adelaide Coastal Waters Study Steering Committee. School of Environmental Systems Engineering, University of Western Australia.

We are thankful to the following organisations that provided background data:

- SA Water
- Climate Services Section of the Australian Bureau of Meteorology
- Department of Water, Land and Biodiversity Conservation
- Department for Environment and Heritage.

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EXECUTIVE SUMMARY AND KEY RECOMMENDATIONS

Over the years, there has been growing concern about the effects of coastal and catchment development on the marine environment near Adelaide. Nutrients and other pollutants are introduced to near-shore waters from urban and rural runoff (particularly in the southern streams), sewage treatment plants, and some industrial sources.

Environment management agencies, including the South Australian EPA and the Coastal Protection Branch of the Department for Environment and Heritage, have undertaken monitoring activities to quantify seagrass loss and identify impacts on biological and physical coastal processes (including sand movement). Other stakeholders and coastal communities have also expressed concern about algal blooms, water quality for aesthetic values and recreational contact, environmental health, the status of marine habitats, and biodiversity.

However, our understanding of the processes involved and the interrelationships among them has hitherto been inadequate to underpin a comprehensive management response. In 2001 the South Australian government initiated the Adelaide Coastal Waters Study (ACWS) to redress these knowledge deficiencies and to develop an integrated understanding of the system so as to guide future management actions.

An integrated view of the ecosystem will allow the community and managers to assess ecological priorities in the light of practical, economic, and social objectives; it will help gauge suitable trade-offs while minimising the risk of unintended or irreversible (and possibly costly) damage to other parts of the ecosystem.

Other similar large-scale studies have demonstrated the value in this approach. Examples include the Port Phillip Bay Environmental Study in Victoria, the Perth Coastal Waters Study and the Southern Metropolitan Waters Study in Western Australia, and the Brisbane River and Moreton Bay Wastewater Management Study in Queensland. The ACWS is based on the broad principles of adaptive management, a procedure that seeks to reduce the risk of adverse environmental outcomes by continually refining models, processes, and understanding as new data and evidence is gathered.

This report is one of two volumes and it summarises the main findings and outcomes arising from the 4-year study. The companion Volume 2 provides considerably more detail from each of the six research tasks that comprised the ACWS; further detailed results and discussion can be found in the series of technical reports available for download from www.clw.csiro.au/acws.

ACWS had three focus points: water quality, seagrasses, and sediments. Other ecosystem components such as reefs, mangroves, and fish were outside the terms of reference for this study, as were considerations of impacts on human health and on recreational and aesthetic values. This is not to diminish the importance of these aspects of overall coastal marine health and functioning, but simply reflects the limits of available resources and the need to concentrate on assets at greatest risk.

The ACWS research teams were fortunate in being able to draw upon a significant body of existing data and previous research outcomes on Adelaide's coastal waters, findings that had been acquired over many decades. The primary task, therefore, was to fill gaps in our understanding rather than to start with a blank sheet.

In terms of findings, the ACWS has delivered on its main objectives and in the process it has considerably enhanced our understanding of key processes, stressors, and responses associated with the delicate balance between water quality, seagrass loss, and sediment stability. Consistent with the findings of other similar large-scale studies around Australia's coastline (Port Phillip Bay Environmental Study, Brisbane River and Moreton Bay Study, and Perth Coastal Waters Study), Adelaide's coastal marine environment has undergone significant modification and degradation as a result of many years of near-continuous inputs of nutrient-rich, turbid, and coloured water and wastewater. While these constituents have long been implicated in the loss of seagrasses off Adelaide's metropolitan coast, until now the precise mechanism was poorly understood.

All the evidence points to a key role of nitrogen loads in causing nutrient enrichment of coastal waters, growth of epiphytes, and (perhaps) direct effects on the seagrasses. There is no evidence from this study to show that toxicants or other nutrients play a key role in the ecosystem dynamics. This is totally consistent with the findings of other studies of coastal waters in Australia.

This study has generated a unique historical record of nitrogen (and other) loads to coastal waters, coupled with a long series of observations of seagrass cover in Adelaide coastal waters. Analysis of this historical loading trend (coupled with the realisation there are long time lags in this system between loading increases and seagrass losses) shows that seagrass losses were widespread after the loads increased to about half the present levels.

Sediment movement inshore of the seagrass beds is presently sufficient to prevent regrowth of seagrasses. *Amphibolis* has been shown to recruit to patches of sacking and other rough materials anchored to the bottom - in this way a recruitment source is available to support future recovery if conditions are conducive to recruitment and subsequent growth. Even so, recovery is expected to be slow. In other parts of the world it has taken up to 20 years for seagrasses to regrow once suitable conditions were re-established, and for both *Posidonia* and *Amphibolis*-dominated systems this timeframe may exceed 100 years. Large-scale recovery of seagrass meadows should not be expected unless dramatic and lasting reductions in coastal inputs are made. Even then, sediment instability and nutrient recycling may inhibit progress towards this objective. While evidence of modest (unassisted) recovery in the vicinity of decommissioned sludge outfalls has been noted, it is more likely that that large-scale recovery of seagrass meadows along Adelaide's coast will require intervention, either in the form of provision of appropriate settlement substrate for seedlings, transplanting of mature stock, or the harvesting and planting of germinated seedlings.

In the pages of this report (and the companion technical reports) are detailed the results of years of research, modelling, investigations, and analysis by a dedicated group of scientists. I am confident that their results and understandings will provide an invaluable resource for current managers and future generations of researchers.



Prof. David Fox
Director, Adelaide Coastal Waters Study
November 2007

RECOMMENDATIONS

Recommendation #1

As a matter of priority, steps must be taken to reduce the volumes of wastewater, stormwater, and industrial inputs into Adelaide's coastal environment. This should be done within the context of an overarching strategy designed to remediate and protect the metropolitan coastal ecosystem.

Recommendation #2

The total load of nitrogen discharged to the marine environment should be reduced to around 600 tonnes (representing a 75% reduction from the 2003 value of 2400 tonnes).

Recommendation #3

Commensurate with efforts to reduce the nitrogen load, steps should be taken to progressively reduce the load of particulate matter discharged to the marine environment. A 50% load reduction (from 2003 levels) would be sufficient to maintain adequate light levels above seagrass beds for most of the time. The reduced sediment load will also contribute to improved water quality and aesthetics.

Recommendation #4

To assist in the improvement of the optical qualities of Adelaide's coastal waters, steps should be taken to reduce the amount of CDOM (coloured dissolved organic matter) in waters discharged by rivers, creeks, and stormwater drains.

Recommendation #5

While the available data suggests that toxicant levels in Adelaide's coastal waters pose no significant environmental risk, loads from point sources such as the Port River, WWTPs, and drains should continue to be reduced. Routine monitoring of toxicant loads and concentrations should be undertaken every 3-5 years.

Recommendation #6

Develop and implement a comprehensive and integrated environmental monitoring program that will enable natural resource managers and all Stakeholders to evaluate changes in the coastal marine environment over time and at various spatial scales.

Recommendation #7

Maintain and develop the comprehensive data base of historical inputs generated by this study. It is suggested that a single entity be created to oversee the administrative functions associated with data collection, storage/retrieval, analysis, and reporting. This entity should also assume responsibility for the on-going maintenance and application of the various models produced by the ACWS so as to ensure that they

remain both relevant and accessible. Consideration should also be given to the establishment of a research/monitoring coordination body. A primary function of this body would be to prioritise on-going and future research activities and to seek and allocate funding in accordance with those priorities.

Recommendation #8

Implement a long-term monitoring program to assess seagrass quality (or 'health') at sites adjacent to land-based discharges and at suitable reference sites.

Recommendation #9

Implement a long-term monitoring program of the outer depth margin of Posidonia meadows in Holdfast Bay.

Recommendation #10

Implement a long-term monitoring program of seagrass meadow fragmentation at a range of sites in Holdfast Bay.

Recommendation #11

Undertake detailed mapping of the distribution of Amphibolis across the Adelaide metropolitan area, determine the lower depth limit of seagrasses in Holdfast Bay, and map seagrasses in the southern metropolitan area between Seacliff and Sellicks Beach.

Recommendation #12

Undertake a spatially intensive nitrogen stable isotope survey to determine the offshore and northern extents of nitrogen influence from WWTP and industrial outfalls along the Adelaide metropolitan coastline, and also characterise nitrogen stable isotope signatures of potential nitrogen sources.

Recommendation #13

Undertake an audit of key environmental assets in the southern metropolitan coastal region; identify risks to those assets and develop an integrated management plan to mitigate the risks. The applicability of management actions developed in response to the findings of this study to halt and reverse ecosystem degradation in the northern regions should be investigated with a view to adopting it (possibly with modification) in the southern region.

Recommendation #14

Adelaide's coastal marine environment must be managed as a component of a system that integrates catchment management, urban and rural land use, demographics, urban and industrial development, climate change/climate variability, and water re-use.

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1 BACKGROUND AND CONTEXT

Over the years, there has been growing concern about the effects of coastal and catchment development on the marine environment near Adelaide. Nutrients and other pollutants are introduced to near-shore waters from urban and rural runoff (particularly in the southern streams), sewage treatment plants, and some industrial sources. The historical situation is well known. The retreat of the 'blue line', which marks the near-shore edge of the seagrass beds appears to have commenced in the period between 1935 and 1949 in Holdfast Bay, stimulated perhaps by the first sewage discharges from Glenelg in 1943. The Penrice soda-ash plant at Osborne in the Port River also started operating in 1940. Further losses in the north were associated with the discharge of wastewaters from Bolivar in the late 1960s. The retreat was largely complete by the 1980s. Sludge outfalls which operated between the 1960s and 1993 caused the loss of seagrasses offshore. The greatest rate of loss of seagrasses occurred in the early 1970s, about 8 years after the maximum rate of population growth in the metropolitan region. In recent years the rate of seagrass loss appears to have slowed, with some re-colonisation occurring in the areas of loss around the old sludge outfalls. There has, however, been no re-colonisation inside the 'blue line' along the beaches and fragmentation of the seagrass meadows in central and southern Holdfast Bay continues.

1.1 Historical Context of Adelaide's Coastal Environment

Prior to European settlement, Adelaide's coastal waters were pristine. The pattern of catchment outflows in the Adelaide region was dominated by winter runoff, which was largely assimilated by the swamps and marshes behind the coastal dunes. Outflows from the Port Adelaide River (hereafter referred to as the Port River) would have been infrequent. Loads of nutrients and turbidity to coastal waters would have been small as a result and, because they would have been dominated by runoff from native bush, the flows would have been characteristically high in coloured organic material and low in turbidity and available nutrients. The impact of these loads on coastal waters would have been small and intermittent, leaving largely intact marine ecosystems abutting the land. Water quality in the near-shore zone would have been similar to that found in the rest of the Gulf. Seagrasses (most notably *Amphibolis* and *Posidonia*) were presumably abundant in shallow waters along the coast, and these not only stabilised the sediments but were a source of new, calcareous material (from decaying marine organisms found within the seagrass meadows).

Coastal swamps were drained and filled in the mid 1950s and an efficient network of storm drains established. The completion of the concrete lining of the suburban Sturt River channel effectively replaced an efficient stormwater detention and settlement system (that discharged at a low and steady rate) with a rapid-transit system delivering large 'parcels' of turbid freshwater to the coastal zone after each significant rainfall event. In addition to the Sturt River and Brownhill and Keswick Creeks, the Patawalonga system includes the airport drain. Until recently the Patawalonga system drained through the Patawalonga flood gates. The Patawalonga Lake acted as a settling pond for stormwaters – it has been estimated that the Lake removed around 43% of suspended solids. In the early 1970s recreational activity in the lake was banned due to faecal contamination and the lake bed was dredged and the contaminated material land-filled on the airport site.

In 2001, the Barcoo Outlet was constructed. This is a siphonic system that, starting at the upstream end of the lake, diverts flow underneath the beach to a discharge point a few tens of metres off shore. Flow into the Patawalonga Lake is

controlled by sluices which release water into the lake when the capacity of the Barcoo Outlet to drain is exceeded. This system bypasses the Patawalonga Lake, effectively short-circuiting contaminated storm flow from the Sturt River, Brownhill Creek, and the airport drain directly to the coastal zone without the beneficial settlement afforded by Patawalonga Lake.

The cumulative impacts of over 60 years of continuous and episodic land-based inputs have resulted in a significantly degraded coastal environment. The loss of over 5000 ha of seagrass is of particular concern, given the scale and significance of both direct and indirect effects. Direct effects include loss of biological diversity and changes to the biological, chemical, and physical benthic habitat. In Adelaide, a secondary effect of seagrass loss has been the increased instability of the seafloor, resulting in the mobilisation and transport of sediments along the coast. Large deposits of fine-grained sand, previously trapped within seagrass meadows, now accumulate in sandbars close to shore.

2 MANAGEMENT ISSUES AND STUDY OBJECTIVES

Over the years, there has been growing concern about the effects of coastal and catchment development on Adelaide's marine environment. Nutrients and other pollutants are introduced to near-shore waters from urban and rural runoff (particularly in the southern streams), sewage treatment plants, and some industrial sources. At the same time, environment management agencies, including the South Australian EPA and the Coastal Protection Branch of DEH, have undertaken monitoring activities to quantify seagrass loss and identify impacts on biological and physical coastal processes (including sand movement). In 2000, the Department for Environment and Heritage initiated a review of the management of Adelaide's metropolitan beaches. The outcome of this review was the development of a 20-year management strategy for Adelaide's beaches. The cornerstone of this strategy was a combination of approaches, including sand recycling, engineering structures, and importing coarse sand from external sources. Dredging and sand bypassing are also undertaken along the metropolitan coast to maintain channel depths and enable sand to continue to drift northward. More recently, however, the effectiveness and social impacts of these management strategies has been questioned, and new techniques for beach replenishment – such as pumping sand through pipes – have recently been trialled.

Other stakeholders and coastal communities have expressed concern about a variety of other issues such as algal blooms, water quality for aesthetic values and recreational contact, environmental health, and the status of marine habitats and biodiversity. However, until now our understanding of the processes involved and the interrelationships among them has been inadequate to underpin a comprehensive management response.

2.1 *Management Issues*

There is a long list of issues that have acted as drivers for the ACWS, and although many of these were obvious candidates (e.g. the impact of high sediment and nutrient loads), other, more subtle, issues (e.g. the role of epiphytes on seagrass decline) required more careful elicitation. Stage 1 of ACWS was devoted to the identification and documentation of an extensive, although not necessarily exhaustive, list of stakeholder issues and concerns.

Figure 1: The Edwards Street Drain in Brighton discharging turbid storm runoff in (a) 1974 and (b) a more coloured foaming discharge in 2004. (Note: foaming commonly results from the breakdown of organic matter such as leaf debris.)
Photo a: from Lewis S. A. (1975); Photo b: J. Wilkinson



a



b

2.2 Generic Stakeholder Issues

The complete list of stakeholder issues can be found in Volume 2 of this report or the consolidated research plans¹. The generic issues are captured by the following questions:

- What is the fate of nutrients (N and P) and what are their respective impacts on the receiving marine environment and ecosystem functions?
- What are the relative contributions of all contaminant inputs?
- Are there any other parameters of concern in the coastal waters in addition to or instead of nutrients?
- What is the pollution load entering the coastal zone from all sources?
- Is it pollution load or concentration that is important in water quality management?
- What impact do low-salinity discharges have on seagrass communities and different species within communities?
- What is the cumulative impact on seagrass health of low-salinity and high-turbidity discharges from the various coastal stormwater outlets?
- Why have we lost and continue to lose the near-shore seagrass?
- Is seagrass loss due to freshwater inputs, nutrients, increased turbidity, other pollutants and other effects including coastal processes - or a combination of all of these?

¹ Available at http://www.clw.csiro.au/acws/documents/Final_ACWS_Consolidated_Research_Plan_Aug04.pdf

- Is seagrass loss progressive or episodic (e.g. driven by storm events or high stormwater discharge)?
- Are there other indicators of marine environment disturbance in addition to seagrass decline?

The predominant themes to emerge from the generic issues are discussed in the following sections.

2.2.1 Discharges of wastewater and stormwater

Coastal degradation caused by wastewater and stormwater discharges became apparent from the late 1940s. During the 1970s, a peak period of degradation occurred that mirrored significant increases in development, population, and discharges. Prior to the 1930s, there were relatively few inputs to the coastal zone. However engineering projects - such as the diversion of the Torrens River, the construction of numerous stormwater drains, the lining of Sturt River, and the Barcoo outlet - significantly increased the volume of turbid, highly coloured, nutrient-enriched waters delivered to coastal waters. During the same period, new wastewater treatment plants (WWTPs) were commissioned and these added to the loads of sediments, nutrients, 'fresh' water, and other contaminants into the marine environment. In addition, between 1961 and 1993, sludge material from the Glenelg and Port Adelaide facilities was piped off-shore and allowed to disperse and settle under the action of currents, tides, and other physical processes. There is also anecdotal evidence to suggest that occasionally the sludge pipes ruptured fairly close to shore, although the frequency and duration of such events is not documented.



Figure 2: Major discharge of stormwater from the Torrens River into Adelaide's coastal waters on 25 October 2005. Dark region is increased turbidity. *Photo: S. Bryars*

2.2.2 Water quality: contaminants and toxicants

In addition to increased sediment and nutrient loads, there are many other indicators of general water quality. Physical parameters such as temperature, salinity, light, and dissolved oxygen are usually most relevant to biotic functioning and integrity, while anthropogenic contaminants such as heavy metals, pesticides, herbicides, organochlorines, and hydrocarbons can pose significant risks to human and marine life. Other similar studies around the Australian coast have detected the presence of such contaminants, although generally at levels that pose no significantly increased risk. Previous studies of pollution levels in the Port River identified moderate to high turbidity; high levels of PCBs, lead, zinc, and copper; and high ammonia and chlorophyll-a concentrations. There have been a limited number of studies of similar scope and intensity in the near-shore coastal region.

2.2.3 On-going seagrass decline and low levels of re-establishment

The loss of large tracts of (*Posidonia*) seagrass is one of the most visible and significant impacts on Adelaide's coastal environment. Seagrasses provide a natural habitat for many species of marine life and they stabilise the underlying sediments. Any loss will clearly negatively impact on these functions and may also increase the risk of colonisation by exotic marine pests.

Migrating sand patches within seagrass meadows, coupled with anecdotal evidence supported by aerial photos taken in the 1930s, suggest that the 'blue line' (i.e. the inner edge of seagrass meadows) was within 200 m from the shore in Holdfast Bay in the middle of last century, but by 1968 it had regressed hundreds of metres further offshore. During the period 1949 to 1995, some 4000 ha of seagrass was lost between Aldinga and Largs Bay. While the rate of loss since the 1940s has been irregular, the average of 85 ha per year was marked by a substantial peak between 1971 and 1977. During this short period approximately 50% of the total seagrass meadows between Glenelg North and West Beach (using 1949 as a baseline) was lost.

In terms of species, there has been a noticeable trend away from mixed *Posidonia* and *Amphibolis* seagrass communities, with the latter lost in many areas. Minimal re-establishment has been detected in the vicinity of the decommissioned Port Adelaide sludge pipe. The environment improvement plans (EIPs) of the last 10 years have had a pronounced beneficial impact on coastal water quality; however this alone is unlikely to result in successful re-establishment of lost seagrass communities since other, non-nutrient-related factors also contribute to the lack of recolonisation. The role of 'blowouts' (episodic loss of small patches of seagrass) in explaining larger spatial and temporal trends in seagrass loss is not well understood. A particular concern is that Adelaide's seagrass beds may have been fragmented by the expansion of blowouts to such an extent that remnant patches are now vulnerable to lower-intensity (more frequently occurring) storms than would be the case for larger seagrass patches.

2.2.4 Sediment instability and dynamics

As was noted in the previous section, the loss of seagrass has implications for the stability of the underlying sediments. Adelaide's beach replenishment program is tangible evidence that sediment-transport rates are out of equilibrium, with an accumulation to the north and depletion in the south. The South Australian DEH, Coastal Protection Branch, has estimated that sand supply to the active beach zone

has been increased by approximately 100,000 m³/y due to seagrass losses. This loss of seagrass creates a cycle of further loss through negative effects of increased turbidity and through accession to erosive forces associated with blow outs. Seagrass losses have also modified the bathymetry profiles, with depth increases further impacting on coastal erosion processes.

2.2.5 Threats to habitats and ecological processes

Seagrass loss equates to a loss of local biodiversity. An approximate 40-fold difference exists between biodiversity in seagrass and bare-sand communities. Effluent discharges and increasing sedimentation rates threaten the abundance and diversity of biota on reefs (e.g. the loss of large brown algae on northern reefs). In Barker Inlet, *Ulva* (cabbage weed) growth is smothering mangrove seedlings and its decomposition reduces oxygen availability. The exposure of the clay or calcrete base material (due to seagrass loss and sediment removal) increases the risk of colonisation by exotic pests and the exclusion of native species.

2.3 Study Objectives

The Adelaide coastal ecosystem is unique because of potential large-scale interactions between seagrasses, beach and near-shore morphology, benthic biota, nutrients and toxicants, and water quality. In 2001, the SA government initiated the Adelaide Coastal Waters Study (ACWS) to redress knowledge deficiencies and develop an integrated understanding of the coastal system from which to guide future management actions. An integrated view of the ecosystem will allow the community and managers to assess ecological priorities in the light of practical, economic, and social objectives; it will help gauge suitable trade-offs while minimising the risk of unintended or irreversible (and possibly costly) damage to another part of the ecosystem.

Other similar large-scale studies have demonstrated the value in this approach. Examples include the Port Phillip Bay Environmental Study (PPBES) in Victoria (Harris et al. 1996), the Perth Coastal Waters Study in Western Australia (Lord and Hillman 1995), and the Brisbane River and Moreton Bay Wastewater Management Study in Queensland (Dennison and Abal 1999). The ACWS was based on the broad principles of adaptive management, a procedure that seeks to reduce the risk of adverse environmental outcomes by continually refining models, processes, and understanding as new data and evidence is gathered.

As with any environmental study, there is a need to clearly define the scope so that limited resources are appropriately allocated to addressing the most important issues. After extensive consultation with stakeholders, it was agreed that the Adelaide Coastal Waters Study would focus on:

- seagrass loss
- seabed instability
- water quality degradation.

There are of course numerous other important environmental issues associated with the sustainable management and use of Adelaide's coastal waters (such as mangroves, recreational and commercial fisheries, recreational water quality, beach aesthetics, and so on). That they have not been specifically studied as part of the ACWS is not to diminish their importance but is simply a matter of focus, resources, and risk management.

The main research themes and stakeholder issues which were specifically investigated by the ACWS are identified below.

2.3.1 Nutrients

- Fate of nutrients (nitrogen and phosphorus) and their respective impacts on the receiving marine environment and ecosystem functions;
- Relative contributions (volumes and loads) of contaminant inputs from all sources and the significance of impacts on water quality and the marine ecosystem;
- Target loads for receiving waters.

2.3.2 Other contaminants

- identification of contaminants (other than nitrogen and phosphorus) that are implicated in seagrass loss;
- quantify contaminant loads (other than nitrogen and phosphorus) entering the study region;
- toxicity of contaminants to seagrasses;
- relative impact of Port River inputs.

2.3.3 Stormwater and wastewater inputs

- composition of stormwater;
- fate of stormwater and wastewater contaminants;
- loads of wastewater and stormwater contaminants;
- spatial distribution of stormwater outfalls and association with seagrass loss;
- significance of stormwater/wastewater colour and turbidity for coastal ecosystems;
- effectiveness of government and industry environment improvement plans.

2.3.4 Seagrass ecology

- mechanism for seagrass loss (both initial triggers and on-going decline);
- role of freshwater inputs, nutrients, increased turbidity, and other pollutants, and other effects including coastal processes or a combination of these;
- dynamics of seagrass loss (episodic, continual, blowouts, etc.);
- tolerance of seagrasses to altered conditions (turbidity, light, nutrients, toxicants);
- impact of low salinity levels on seagrass communities (and different species within communities);
- prospects of seagrass recolonisation and conditions which would be conducive to this;
- implications for other coastal and ecological processes if widespread seagrass recovery was attained;
- nutrient sources for seagrass epiphytes.

2.3.5 Physical processes and sediments

- identify and understand the physical processes (winds, tides, currents, temperature, density effects, etc.) that operate on Gulf-wide and local scales;
- sources and sinks for coastal sediments – sedimentary ‘budget’;
- defining the interplay between sediment transport and seagrass loss;
- defining physical processes that determine fate of sediments and loss of seagrass (e.g. ‘scouring’, wave attenuation);
- characterising the effect of the Port River system on the Gulf and near-shore coastal waters.



Figure 3. Adelaide Coastal Waters Study region.

2.4 Study Region

The ACWS study area extends along the eastern side of Gulf St Vincent from Port Gawler at the discharge of the Gawler River, to Sellicks Beach in the south (Figure 3). The seaward boundary is nominally 20 km from the high water mark. No landward boundary was defined, but for the purpose of the study it encompasses the catchments of the contributing streams and rivers flowing to and discharging to the coastal waters. Although important, the Port River and associated estuary and wetlands were not a primary focus for the Adelaide Coastal Waters Study. However, the input of nutrients and other contaminants from the Port River to the coastal strip have been quantified and factored into model development and calibration.

As the study progressed it became evident that resolution of most management issues required increasing focus in the near-shore zone (typically out to about a depth of 10 m or 5 km off-shore). Accordingly, four near-shore zones and two off-shore zones were identified based on considerations of land use, physical properties, inflows, and historical developments (Figure 4). A description of the six zones is given in Table 1.

Table 1. ACWS zonation according to terrestrial inputs

Zone	Features
1 (Northern)	Gawler River, Bolivar WWTP, Smith Creek, and all terrestrial discharges physically within the mouth of the Barker Inlet. Seagrass loss associated with the combined impacts of Bolivar and the Barker Inlet discharges.
2 (Central)	All major discharges from Largs Bay to Merino. Near-shore seagrass loss.
3 & 3A (Southern)	All remaining discharges from Marino to Sellicks Creek. Relatively steep shelving with minimal impact.
4 (Central offshore)	Off-shore meadow fragmentation.
5	Port Adelaide sludge outfall zone.

2.5 Study Design

The study was designed around the key components: (i) quantification of inputs (type and load); (ii) a physical model that ‘moves’ the inputs around in a manner that honours the real system; and (iii) ecological model(s) to predict the response of key ecosystem components (e.g. seagrass) to their immediate environment. The development and constant refinement of a conceptual model informed the study design and assisted in the interpretation of results (Figure 5).

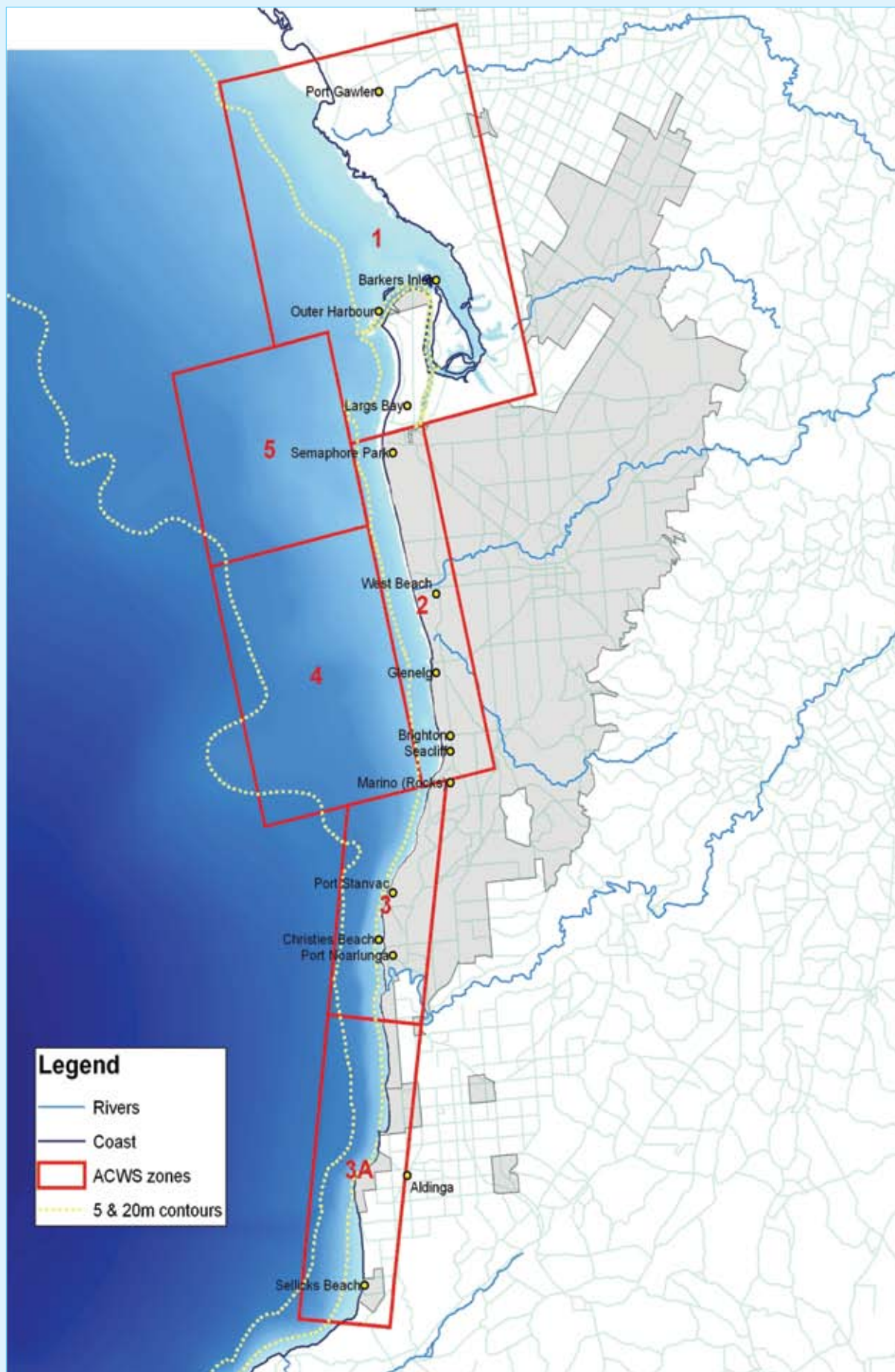
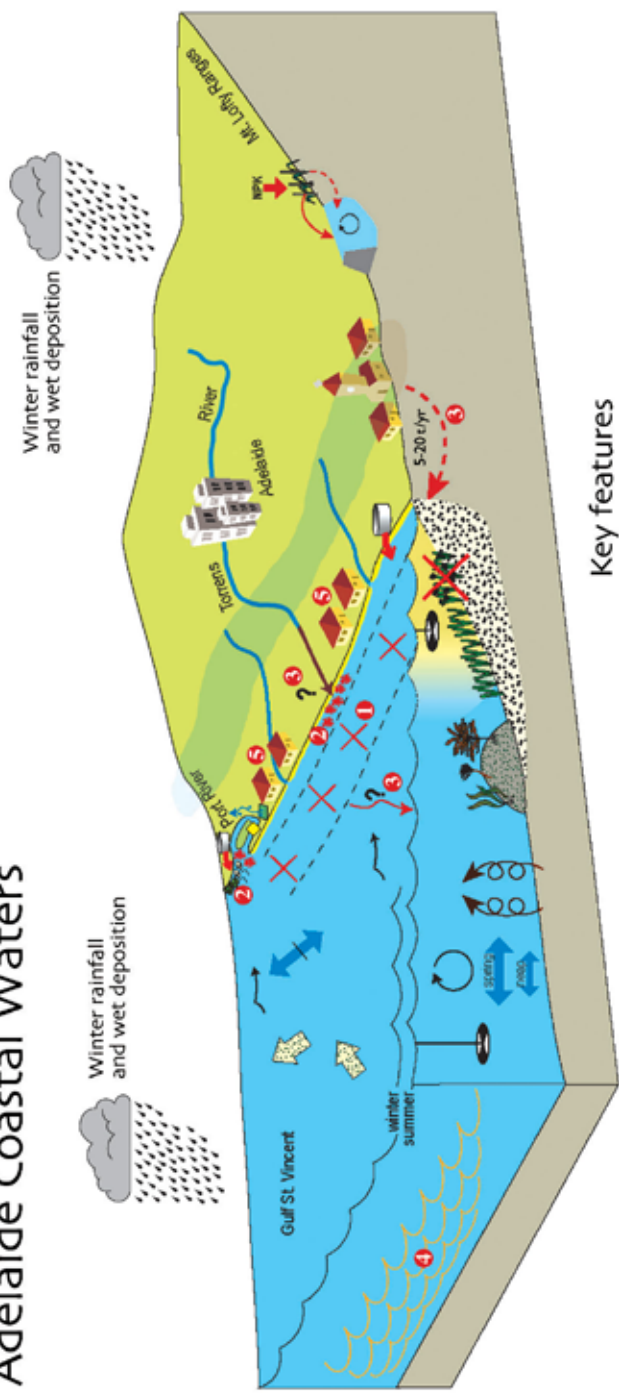


Figure 4. Zones within the Adelaide Coastal Waters Study region.

2.6 *Research Tasks*

The ACWS research tasks were grouped according to the three main components (i, ii, and iii) mentioned in the previous section. A listing of these tasks and a brief description is given in Table 2. The models in (ii) and (iii) were ‘uncoupled’ in the sense that the physical (hydrodynamic) model employed by the ACWS did not have an embedded model to simultaneously describe (in space and time) ecological processes. While coupled models are attractive, they can be difficult to calibrate, can be computationally expensive, and have no guarantee of superior performance over less complex approaches. It was for these reasons, together with the fact that the ACWS was focussed on ‘macro’ issues (for which detailed modelling of biological processes such as epiphyte grazing and plant respiration was not required), that a simpler, uncoupled modelling approach was adopted.

Adelaide Coastal Waters



Major environmental issues

- 1 Seagrass loss in Adelaide coastal waters
- 2 Eutrophication resulting in *Ulva*, red tides *Gyrodinium aureolum* and seagrass epiphytes
- 3 Unquantified nutrient inputs from atmospheric groundwater sources and stormwater and sediments
- 4 Physical seafloor processes and bedforms
- 5 Coastal dunes and development
- Discharge from waste water treatment plant
- High turbidity levels

Key features

- Offshore reefs with fan worms and kelp
- Subtidal seagrass meadows dominated by *Posidonia* spp
- Runoff from fertilized crops captured by dams
- Ephemeral lens of runoff pulses with high turbidity and reduced light penetration

Environmental setup

- windmixing
- seasonal sea level variability
- fortnightly spring/neap tides
- Strong longshore drift of water and sediment
- resuspension
- net sand movement $150-180 \times 10^3 \text{ m}^3/\text{yr}$
- net sand movement $80 \times 10^3 \text{ m}^3/\text{yr}$
- Strong longshore drift of water and sediment
- clay / calcareous sediments
- toxicants
- Mediterranean climate

Figure 5. The 2006 ACWS conceptual model

Table 2. Research tasks for the Adelaide Coastal Waters Study

Task code	Research/activity title
Stage 2 Research tasks	
Input studies - quantity and quality	
IS1	Quantification of diffuse and point source terrestrial, groundwater, and atmospheric inputs to the coastal waters
IS 1-SP 1	Stormwater flows from major and minor catchments: audit and monitoring
IS 1-SP 2	Audit of the quality and quantity of effluent discharging from WWTPs to the marine environment
IS 1-SP 3	Groundwater discharge to the coastal environment: flow quality and quantity assessment
IS 1-SP 4	Wetfall and dryfall input directly into the coastal zone
Ecological processes	
EP 1	Assessment of the effects of inputs to the Adelaide coastal waters on seagrass ecosystems and key biota
Environmental information systems	
RS 1	Remote sensing study of marine and coastal features and interpretation of changes in relation to natural and anthropogenic processes
Physical processes and modelling	
PPM 1	Coastal sediment budget
PPM 2	Physical oceanographic studies in the Adelaide coastal waters, using high resolution modelling, field observations, and satellite techniques.
Environmental monitoring program	
EMP 1	Spatial/temporal design; statistical analysis; quality assurance and control
Stage 3 Synthesis and reporting tasks	
DST MM 1	Development of a coarse-resolution management model of the Adelaide coastal waters

3 RESEARCH OUTCOMES – KEY UNDERSTANDINGS

The study has adopted three levels of reporting: 1) a high-level overview and summary of main results (this document, Final Study report Volume 1); 2) a detailed findings (Final Study report Volume 2); and 3) highly specific task results (Task reports 1-20 listed on page vivii). All reports are available for download from www.clw.csiro.au/acws.

A summary of the main study findings is given in Table 3 and these are expanded upon in the following subsections.

Table 3. Summary of main findings

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Water quality	Pollutants from stormwater (rivers, creeks, drains)	<ul style="list-style-type: none"> Nutrient and sediment loads - quantify and develop meaningful targets 	<ul style="list-style-type: none"> Historically, very small contribution; now contributes about 30% of total volume. Engineering works (diversion of Torrens River; proliferation of drains; dune modification) and urban development responsible for dramatic increase in loads. Significant quantities of 'freshwater' being exported to coastal marine environment each year (approx. 115 GL from stormwater). Seasonal patterns in flow mean that summer-winter discharge is in ratio 7:93. The Torrens River typically contributes about 20 GL/y; approx. 15 GL/y for each of the Onkaparinga, Patawalonga, and Gawler rivers. Barker Inlet delivers about 30 GL/y. Stormwater now carries high annual loads of suspended sediments, dissolved organic material, and nutrients: approx. 153 tonnes nitrogen; 20 t phosphorus; 1.3 t copper; 1.5 t lead; 7000 t sediment. Stormwater-derived sediments largely responsible for turbidity in coastal zone (peaking between August to November). Concentrations of copper, lead, and zinc exceed national 'trigger' values (typical values in creeks: copper 0.016 mg/L; lead 0.07 mg/L; zinc 0.09 mg/L). Highest lead loads May through September. Pesticides have been detected in stormwaters (most notably the Torrens River). Water quality severely compromised during storm events (turbid plumes). NB: <i>human health impacts were not investigated by this study.</i> Nutrient concentrations tend to be higher in summer than winter. Nutrient concentrations higher near shore (<5 m depth).
		<ul style="list-style-type: none"> Other chemicals of concern - identify, quantify, and assess risk 	

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Water quality	Pollutants from wastewater treatment plants (including sludge outfalls)	<ul style="list-style-type: none"> Nutrient and sediment loads - quantify and develop meaningful targets; 	<ul style="list-style-type: none"> Approx. 43% (approx. 75 GL/y) of water discharged to marine environment is from WWTPs. Distribution of inputs: 47% Bolivar; 23% Glenelg; 18% Port Adelaide[#]; 12% Christies Beach. Seasonal patterns in flow mean that summer-winter discharge is in ratio 35:65. Typical analysis: 1000 tonnes nitrogen/y; 2000 t particulates/y; 340 t phosphorus/y; 3 t copper/y; <0.5 t lead/y. Nitrogen sources: 38% Bolivar; 38% Christies Beach; 24% Glenelg. Phosphorus sources: 38% Bolivar; 43% Glenelg; 19% Christies Beach. Phosphorus concentrations are not predicted to change between 2004 and 2020 except north of Port River where an increase is predicted.
		<ul style="list-style-type: none"> Other chemicals of concern - identify, quantify, and assess risk 	<ul style="list-style-type: none"> Particulate sources: 85% Bolivar; 11% Glenelg; 4% Christies Beach. Copper: 2 tonne/y (Bolivar), 0.8 t/y (Glenelg), 0.25 t/y (Christies Beach). Lead: 0.15 tonne/y (Bolivar), 0.05 t/y (Glenelg), 0.01 t/y (Christies Beach). Zinc: 1.8 tonne/y (Bolivar), 1.5 t/y (Glenelg), 0.5 t/y (Christies Beach).
	Pollutants from Industry	<ul style="list-style-type: none"> Other chemicals of concern - identify, quantify, and assess risk 	<ul style="list-style-type: none"> A range of organic contaminants has been detected in treated wastewater including phenols, phthalate esters, chlorinated hydrocarbons, organochlorine pesticides, and phenoxy acid herbicides. These are detected only sporadically and generally at low concentrations. These organics not thought to be implicated in any seagrass loss.

Water quality

- Penrice Soda responsible nearly 1/2 of total nitrogen entering coastal zone (approx. 1000 tonne/y at time of study, most recent estimate is 850 t/y).
- Overall, nitrogen concentrations decreased between 1965 and 2004 (most notable in the north from more recent decreases in Penrice Soda nitrogen load).
- Nitrogen concentrations not expected to change between 2004 and 2020 except in north of Port River where an increase is predicted.

**Non-land based
pollutants
(atmosphere, rain,
groundwater)**

- Relative contribution from these sources
- Nearly 20% of the particulate matter delivered to the coastal waters is from the atmosphere.
- Rainfall to the coastal waters contributes approx. 33 tonne/y nitrogen and 5 t/y phosphorus.
- Approx. 45% (1.3 tonne/y) of lead is delivered to the coastal waters comes from the atmosphere as well as about 1/4 t/y of copper.
- The only nutrient in appreciable quantities delivered by groundwater is nitrogen (50 tonne/y).

**Toxicants
(all sources)**

- Identify, quantify, and assess risk
- Very little concentration data available with toxicants being detected sporadically (some exceptions are high nickel concentrations at Glenelg, Brighton, Port Noarlunga) and high zinc along metro coastline.
- Previous reports suggest high metal concentrations may be harmful to ecosystem health (although not considered a threat to seagrasses).
- Glyphosate was detected after significant rainfall events.

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Water quality	Biological activity	<ul style="list-style-type: none"> Identify, quantify, and assess risks 	<ul style="list-style-type: none"> Increased nutrient loads increase risk of algal blooms in near-shore waters (<5 m) - particularly in and around the Torrens River and Barker Inlet. This risk is increased under conditions of: high nutrient loads, 'dodge' tide, calm winds, and high solar radiation. Ambient nutrient levels off-shore are generally low (waters are classified as oligotrophic). Stable nitrogen isotope work undertaken as part of this study has confirmed that WWTP-derived nitrogen is being transported well off shore causing exceedence of ANZECC/ARMCANZ trigger values on occasions. Nitrogen from WWTPs and Penrice is being taken up in significant quantities by seagrasses close to, and distant from, these sources. Maximum levels of chlorophyll-a, faecal coliforms, and dissolved organic carbon detected in vicinity of Barker Inlet. Summer inflows from Barker Inlet/Port River system can become trapped in this region, increasing the risk of algal blooms and contamination.
	Reduced salinity	<ul style="list-style-type: none"> Determine volume of freshwater discharged to marine environment Dispersion characteristics Assess ecosystem impacts 	<ul style="list-style-type: none"> Freshwater volumes noted above. For Gulf St Vincent, evaporation exceeds rainfall, so waters tend to be hyper-saline. Metro waters have salinity of 37 psu which increases slightly (+1 psu) over summer. Waters are warmest in late summer (> 25°C) and coldest in late winter (~12°C). This temperature difference controls overall density of Gulf waters. Metropolitan coastal salinity and temperature strongly influenced by Gulf-wide circulation patterns.

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Water quality		<ul style="list-style-type: none"> Reduce discharge to sea 	<ul style="list-style-type: none"> Average salinity decreased along entire coast between 1965 and 2004 except Barker Inlet/Port River system which increased. Average salinity between 2004 and 2020 is predicted to remain unchanged, except Barker Inlet/Port River system which is predicted to decrease.

Suspended sediments/particulates	<ul style="list-style-type: none"> Suspended sediment loads - quantify and develop meaningful targets Evaluate and assess environmental risk 	<ul style="list-style-type: none"> Sediment/particulate loads noted above. Near-shore waters (<5 m) typically well mixed but can be highly turbid after significant rainfall events and this can persist for extended periods (> 10 days). Within the study region, suspended material is mainly phytoplankton to the west and a mixture of CDOM, tripton, and phytoplankton near the coast. Concentrations of suspended matter are about three times higher in the northern regions (particularly near Barker Inlet) than southern regions. Suspended sediment concentrations generally decreased between 1965 and 2004 although increases around Bolivar were evident. Suspended sediment concentrations not predicted to change between 2004 and 2020 except in Port River system and Bolivar region which is expected to reduce.
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Dissolved organic matter	<ul style="list-style-type: none"> Identify sources, spatial and temporal distribution Assess risk and identify actions to mitigate 	<ul style="list-style-type: none"> Major constituents in the water column are phytoplankton, tripton, and CDOM (by-products from decomposition of seaweed and other plant material). Light absorption in water column mostly due to CDOM component. CDOM levels in near-shore zone thought to be influenced by seasonal variation in freshwater inputs.
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Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Sediments			
	Transport	<ul style="list-style-type: none"> - Develop understanding of physical processes and how these affect and are influenced by other processes - Develop sediment budget - source, sinks, and fate 	<ul style="list-style-type: none"> - Sediments come from both marine and terrestrial sources. - Transport rates out of equilibrium; net drift and accumulation to north. - approx. additional 100,000 m³/y of sediment* being delivered to coastal zone.
	Remobilisation of pollutants	<ul style="list-style-type: none"> - Assess potential for nutrients and other contaminants to be released from sediments - Assess risk and identify actions to mitigate 	<ul style="list-style-type: none"> - Very little data on sediment contaminants although: <ul style="list-style-type: none"> - Previous work has revealed high concentrations of some metals in Port River estuary but low elsewhere. - Chromium and zinc were detected over broad area of the coast. - Copper detected only around Bolivar. - Relatively high concentrations of chromium and zinc in deeper waters of southern portion of study region. - Limited sampling suggests: below detection levels for organochlorine/organophosphate pesticides; triazine herbicides; glyphosphate; polycyclicaromatic hydrocarbons; petroleum hydrocarbons. - Within seagrass meadows of Holdfast bay, sediment nutrient levels (particularly ammonia) were higher than water column concentrations.

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Sediments			
	Stability	<ul style="list-style-type: none"> Interaction between seagrass loss and sediment stability 	<ul style="list-style-type: none"> Seagrass loss exposes underlying sediments which subjects them to greater erosive forces and hence increased mobilisation. Actual rates of movement/loss dependent on a number of factors including depth and particle size. Currents near sea-floor range from 0.2 to 0.8 m/s. Results suggest that wave-induced currents in the near shore region are capable of mobilising fine to medium sized sands almost continuously.
Seagrasses			
	Initial loss	<ul style="list-style-type: none"> Identify probable causes for historical loss of seagrass Reconstruct initial species composition and distributions 	<ul style="list-style-type: none"> Approx. 4000 ha loss between 1949 and 1995; most recent estimate is 5200 ha⁺. Much of this loss occurred in the mid 1970s - about 8 years after the peak in Adelaide's rate of population increase although loss has been continuous and episodic. Pattern of loss is unusual in that it commenced close to shore and progressed off-shore. The 'blue line' is now about 1 km off-shore. Seagrasses mostly comprised of <i>Amphibolis</i> and <i>Posidonia</i>; <i>Amphibolis</i> appears to be particularly susceptible to land-based discharges. Significant early losses around Port Adelaide sludge outfall with minimal re-establishment. Spatial patterns: significant losses in northern regions (vicinity of Bolivar WWTP and Barker Inlet); losses in central region (Holdfast Bay) commenced in 1940s; little documented evidence of declines of seagrass in southern regions although this cannot be ruled out. Initial losses have been linked to stormwater drains, sludge outfalls, wastewater discharges, coastal development, diversion of Torrens River. Primary causative agent of seagrass loss is most likely high nutrients (nitrogen); more complex and subtle interactions between nutrients, light, turbidity, and colour also thought to be involved.

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Seagrass		<p>Continuing loss</p> <ul style="list-style-type: none"> ▪ Identify probable causes for continuing loss of seagrass ▪ Identify possible causal mechanisms for lack of recruitment and on-going decline ▪ Predict future losses under variety of scenarios 	<ul style="list-style-type: none"> ▪ Continuing loss (and/or lack of re-establishment) is thought to be a nutrient-related issue although other factors may come into play once seagrasses have been lost e.g. greater shear stresses on seafloor, lack of suitable substrate for seed propagation, increased frequency and severity of 'blowouts'. ▪ Preliminary benthic chamber experiments suggest that about 31% of the total ammonium and <1% of the total nitrate that is discharged into the coastal system is used by seagrass complexes (seagrass and epiphytes). However, these estimates may not be indicative of long-term uptake and further work is required to more accurately describe nitrogen cycling within sediments - including rates of remineralisation, nitrification, and denitrification. ▪ Degraded light climate (see below) in near shore zone compromises photosynthesis and may offer a partial explanation for lack of re-colonisation in this region.
		<p>Epiphytes</p> <ul style="list-style-type: none"> ▪ Develop understanding of interaction between nutrient loads, epiphyte growth, and seagrass vitality 	<ul style="list-style-type: none"> ▪ nitrogen uptake by epiphytes on <i>Amphibolis</i> is higher than uptake rates for epiphytes on <i>Posidonia</i>. ▪ There is strong evidence to suggest an epiphyte-mediated seagrass decline.
		<p>Light climate</p> <ul style="list-style-type: none"> ▪ Develop understanding of spatial-temporal relationships between water quality and light climate 	<ul style="list-style-type: none"> ▪ Seagrasses have a high light requirement: typically between 5% to 30% of surface irradiance although <i>Posidonia</i> was observed at 18 m depth where the annual average was 4% of surface irradiance. ▪ Light climate in near-shore zone critically dependent on prevailing conditions in terms of: quality/quantity of discharges; weather conditions; physical transport; re-suspension. ▪ Optical properties of the metropolitan waters can be severely degraded during storm events. Outflows from the Torrens River and Barcoo Outlet play a significant role during these periods.

Environmental asset or process	Stressor or threat	Management issues / knowledge gaps	Finding(s)
Seagrass			<ul style="list-style-type: none"> - Restoration of 'normal' light conditions after a significant storm event can take up to two weeks. - Light availability at 3 m depth during storm events can be much less than at deeper sites (> 10 m).
	Water quality	<ul style="list-style-type: none"> - Develop understanding of interaction between water quality and seagrass vitality 	<ul style="list-style-type: none"> - Major constituents in the water column are phytoplankton, tripton, and CDOM (see under Dissolved Organic Matter above). - Seagrass vitality is compromised by high nutrient levels (nitrogen). - Reduced salinity unlikely to be cause of seagrass loss. - High turbidity levels reduce the light reaching the seabed. Light reductions below the minimum required (see 'light climate' above) compromise seagrass vitality. This study has not been able to quantify the impact on seagrasses due to the <i>combined</i> effects of high nutrient and turbidity levels. - Direct toxicant effects unlikely to be responsible for seagrass loss. - A detailed model that links these factors and allows 'what if' scenarios to be explored is being developed as part of Stage 3 of the study.

* As of January 2005, Port Adelaide discharge diverted to Bolivar high salinity treatment plant

DEH, Coastal Protection Branch

+ The two estimates are not directly comparable since they have different geographical extents



3.1 Physical Processes

Within the study region, tidal currents dominate the circulation pattern, with wind having a secondary effect through its influence on the mean circulation pattern, particularly at the surface. Current patterns align parallel to the coastline. The seasonally varying wind climate produces a reversal in the mean circulation pattern: in summer, the net movement of water is northwards, whereas during winter the direction is reversed towards the south; however, as the southerly and southwesterly winds are stronger and more prevalent, the annual movement of water is northward. In the near-shore zone, because of the dominance of wave-induced currents, the net flow is towards the north.

3.1.1 Nutrient transport

Because of the predominantly along-shore movement of water, land-based discharges are mainly transported in a north-south direction, parallel to the coastline, with minimal offshore dispersion. The near-shore waters, inshore of the 5-m depth contour, had higher residence times than those further offshore and varied between 1 and 10 days depending on weather conditions. During the summer, the mean residence times were lower (1-1.5 days), whereas during winter the mean residence times were slightly higher (up to 2.5 days).

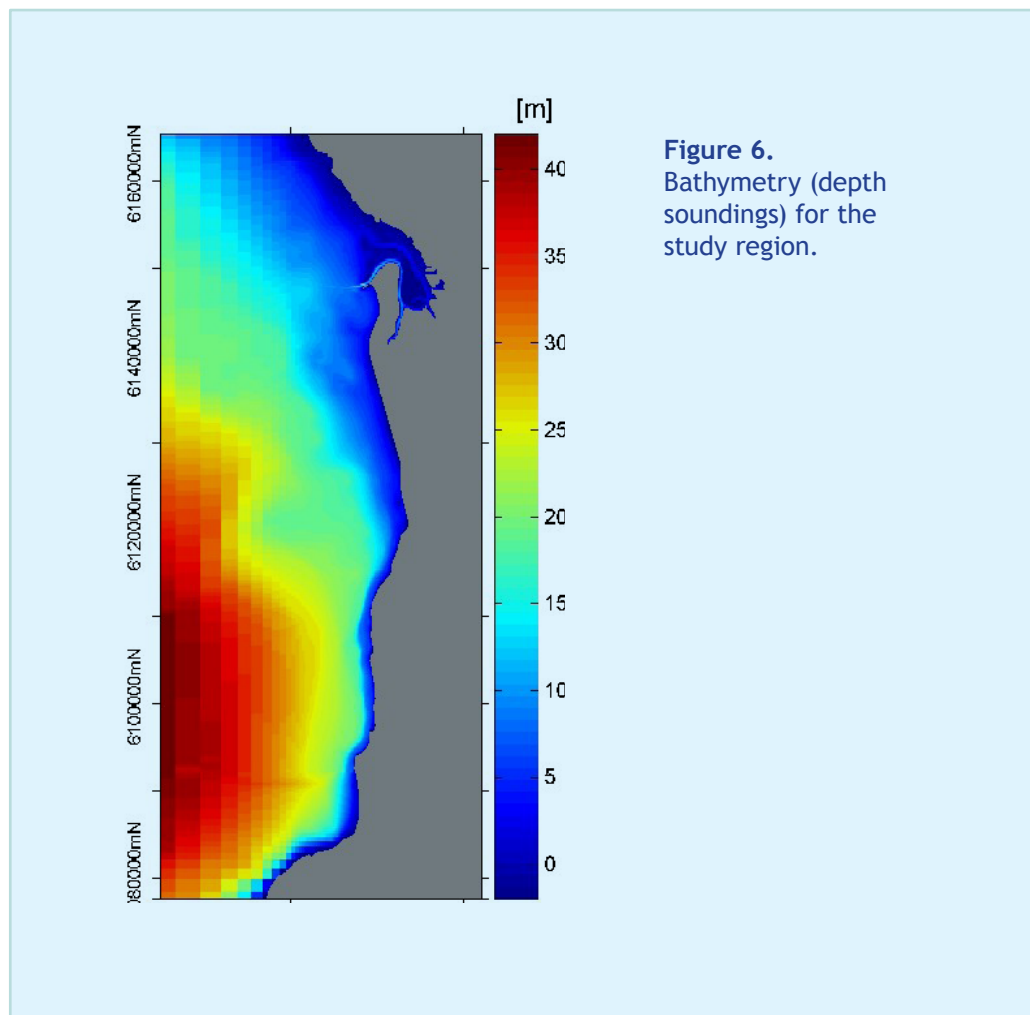
The Port River/Barker Inlet system has a major influence on nutrient and suspended sediment concentrations within the study region. This is through a combination of industrial (Penrice), wastewater, and stormwater discharges. In summer, the discharges were transported northwards from the Port River entrance, whereas during winter there was southerly transport with discernable impact along the Adelaide coastal strip. Discharges from the Bolivar outfall did not appear to have a direct influence on the Adelaide coastal strip. The relative importance of stormwater and wastewater discharges (industrial and municipal) depended on the particular nutrient (nitrogen or phosphorus) and also on season. During summer, discharges from wastewater outfalls (which included Penrice) had greater influence on the magnitude and extent of the suspended sediment concentrations, whereas in winter the stormwater discharges had a larger influence. For nitrogen concentrations, stormwater discharges resulted in higher concentrations during the summer, whereas wastewater discharges were dominant in winter. With respect to phosphorus concentrations, stormwater discharges were dominant along the metropolitan coastal strip during both summer and winter, whereas the wastewater discharge from Bolivar was dominant along the northern section.

3.1.2 Sediment transport

Sediment transport occurs along the Adelaide coastline due to the combined action of waves and tidal currents. Close to shore, it is the wave action that is important whereas outside the surf zone, as the depth increases, the influence of waves is generally diminished. The net northerly drift of sediments along Adelaide's coast is a consequence of wave- and current-induced shear stresses being exerted on the seabed. The rate at which sediment is transported is a function of the magnitude of this bottom shear stress, sediment grain size, and sediment density. Adelaide's coastal sediments are predominantly quartz and

carbonate species, with only a small fraction of clay minerals. The quartz fraction of sediments is higher in the inshore regions and the carbonate fraction is more prevalent in the offshore regions. It is these smaller, non-cohesive inorganic sediments that are readily mobilised along the metropolitan coastline.

The transport of sediments has important implications for seagrass recovery. In Adelaide, the most likely scenario is that once seagrass becomes lost from further offshore, the seabed becomes scoured, water depth increases, and higher energy wave action occurs closer to shore. *Amphibolis* is expected to recover first as it has been observed to grow in shallower sediments overlying a calcrete base. The recovery of *Amphibolis* would lead to the trapping of sediments, and this would facilitate the recovery of *Posidonia*. That this mechanism appears not to have occurred to any appreciable extent is most likely due to the fact that *Amphibolis* is more susceptible to eutrophication. Any long-term strategies for seagrass recovery will need to break this loop.





3.2 Inputs – Water Quality

Adelaide's coastal zone receives inputs from a variety of 'point' and 'diffuse' sources. Point sources include wastewater treatment plants (WWTPs), rivers, streams, creeks, and drains, while diffuse sources are groundwater and atmospheric deposition. The major inputs and chemical constituents within a 10-km-wide strip along the coast from the Gawler River to Sellicks Beach are summarised in Figure 7. About 391 GL of water enters this strip annually - approximately half as rainfall and half from WWTPs and stormwater. During the period April 2001 to April 2003, about 43% of the water discharged from land-based sources came from WWTPs. Since 1945, a total of approximately 2000 GL of wastewater has been discharged directly into the Adelaide coastal zone, with about a quarter of this coming from Bolivar in the last 20 years. Although significant in volume, the very low concentrations of nitrogen and other trace constituents in rainwater means this is an insignificant source when compared to land-based inputs. Of the estimated 2453 tonnes of nitrogen entering this zone annually, 90% is derived from WWTPs and Penrice Soda (49% and 41% respectively). The wetfall (or rain) input accounts for around 30 tonnes of nitrogen annually while dryfall (or dust) contributes less than 1% of total nitrogen. It is possible that further Environment Improvement Programs (EIPs), such as the one implemented by the SA EPA during the 1990s, may reduce the total nitrogen load to around 700 tonnes/y (see Recommendation #2).

Dryfall deposition contributes a significant component (18%) of the solids input to the coastal strip with an annual load of nearly 2000 tonnes from this source. Since particulates have higher levels of lead and copper, they have also contributed significantly to the total copper (5%) and total lead (44%). With the gradual phasing out of leaded petrol since the late 1980s, the concentration of lead in the air has declined dramatically. This has also reduced the indirect inputs of lead to the near-shore zone because stormwater now carries significantly less of this element. In the early 1990s the lead load to the immediate coastal zone was around 2 tonnes/y, whereas now it is near 0.4 tonnes/y (an 80% reduction).

Heavy metal concentrations are appreciably lower now than in the 1970s, and loads have been reduced dramatically since the early 1990s. Copper, lead, and zinc are the most prevalent metals found in metropolitan waters. Figure 8 shows the loads (kg) of copper, lead, and zinc from a number of creeks and rivers along the metropolitan coast between 1996 and 2004. In the case of copper and zinc, these are almost entirely from land-based discharges, while over 90% of lead comes in almost equal proportions from dust and stormwater.

Since load is the product of flow and concentration, part of the observed reduction is attributable to reduced flows due to drought. To reduce the effects of varying flow, the data have been re-expressed as mean annual concentrations (Figure 9). The most pronounced reductions occurred between 1996 and 1997 - particularly in the Sturt and Torrens Rivers where copper and zinc concentrations fell by about 50% and the lead concentration dropped by about 75%. This equates to load reductions of 4.2 tonnes for copper, 25.8 t for lead, and 35 t for zinc from these two sources between 1997 and 2004.

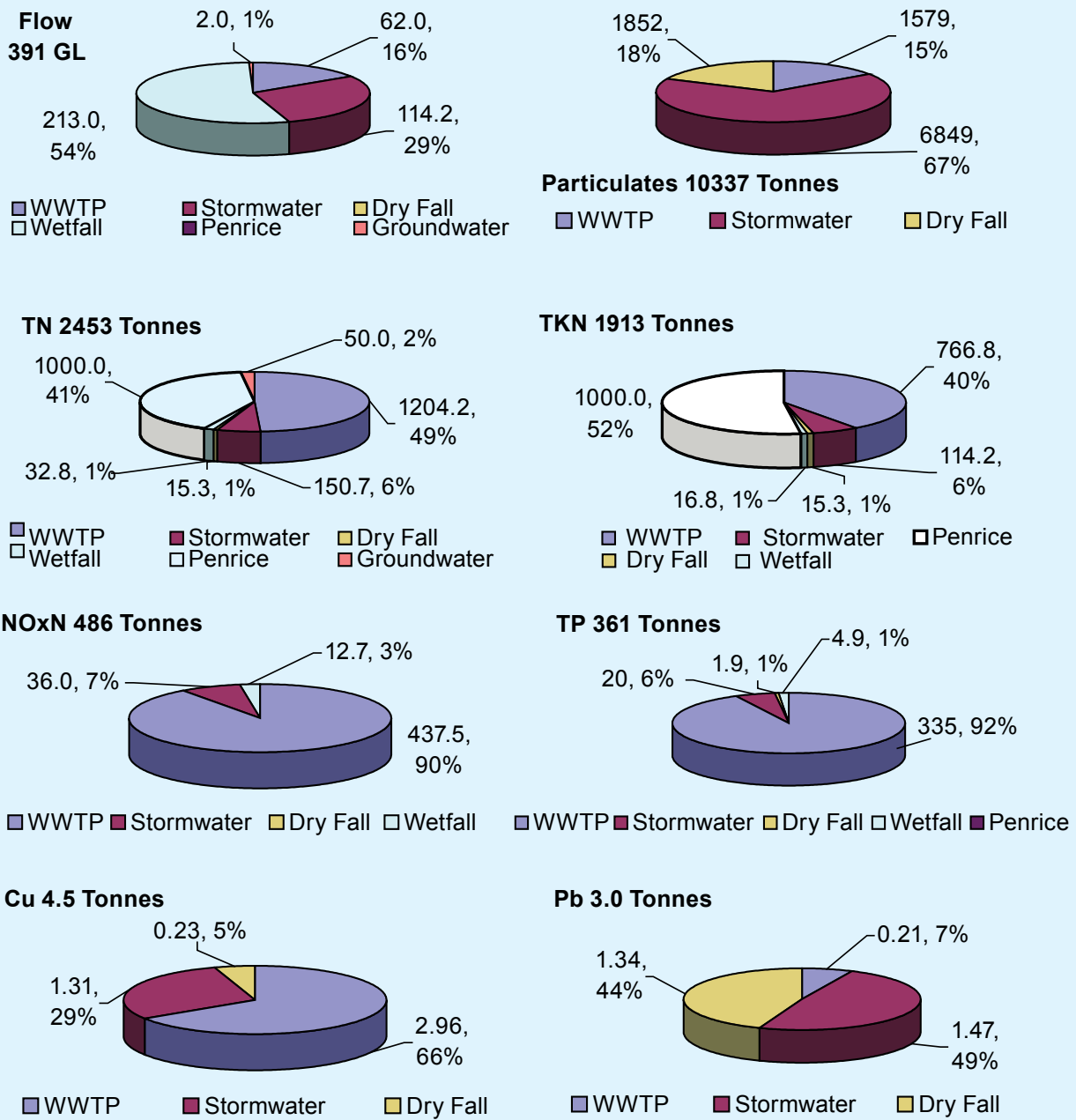


Figure 7. Summary diagram showing the annual contribution of wetfall and dryfall loads to the ACWS area (based on data collected between 2001 and 2003).

The average concentrations of copper, cobalt, zinc, and chromium from Bolivar, Glenelg, and Christies Beach WWTPs were all in excess of the ANZECC/ARMCANZ (2000) trigger levels for the protection of 95% of marine life. Of these metals, copper is between 20 and 43 times the trigger value and cobalt, zinc, and chromium are between two and four times the trigger value.

Organic contaminants such as pesticides, PCBs, PAHs, POPs, etc. have only been detected sporadically. This lack of detection suggests that these substances, if present at all, are present

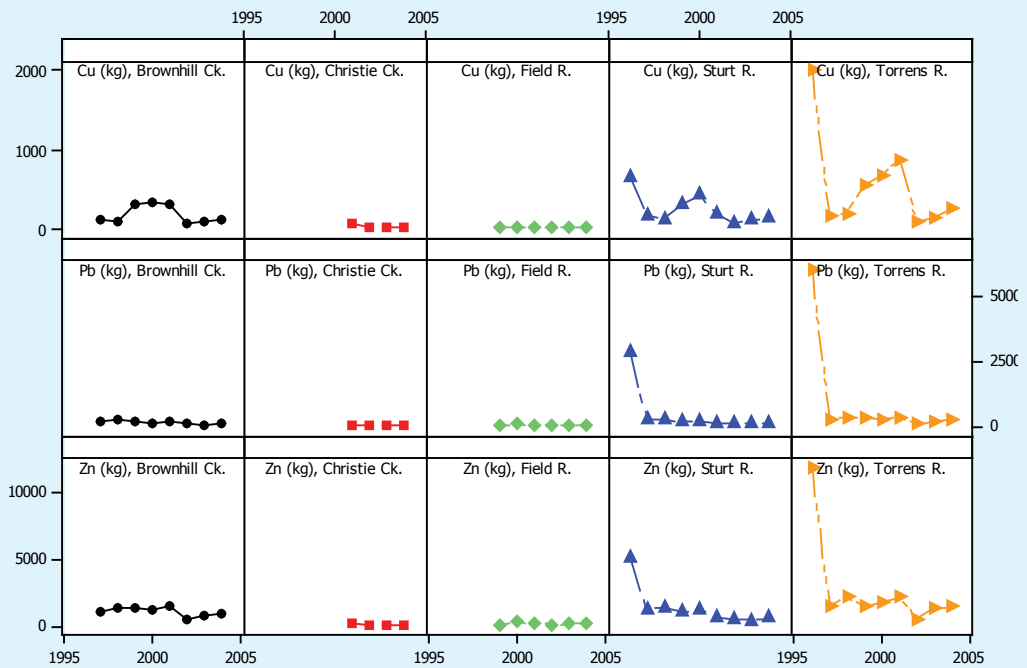


Figure 8. Loads (kg) of selected heavy metals from metropolitan creeks and rivers between 1996 and 2004.

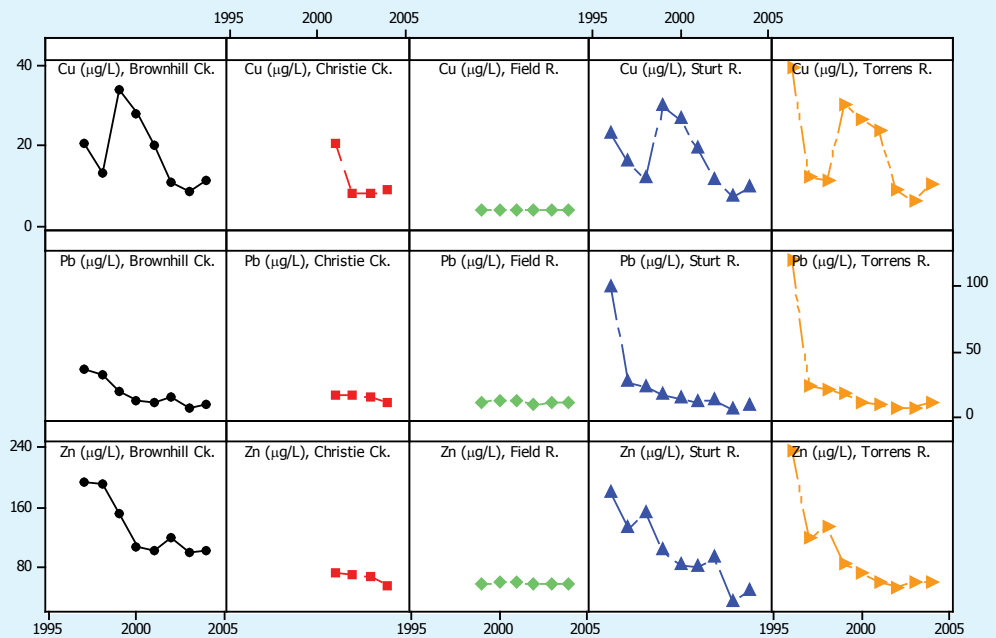


Figure 9. Mean annual concentrations (µg/L) of selected heavy metals for metropolitan creeks and rivers between 1996 and 2004.

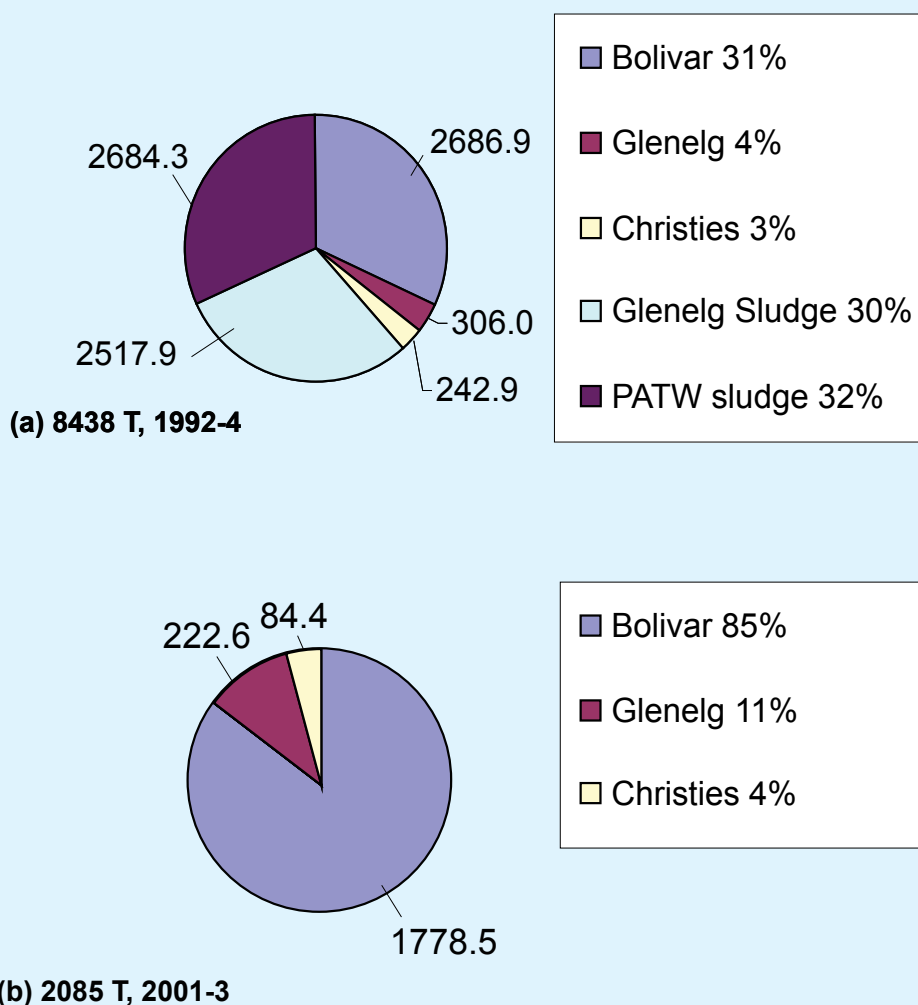


Figure 10. Suspended solids loads from the WWTPs in (a) the early 1990s and (b) after the cessation of digested sludge discharges and upgrading of Bolivar WWTP (2001/03).

at very low concentrations and are of low significance when set against the other bulk inputs of substances known to have a major impact on the system. Figure 10a illustrates the typical annual loadings of suspended solids from the WWTP effluents and sludge outfalls at the end of the period during which the sludge outfalls were still in operation. During the early 1990s the sludge outfalls accounted for around 62% of the annual solids load from WWTP sources, and Bolivar WWTP accounted for 31%. Glenelg and Christies Beach only contributed only 7% of the load. The cessation of sludge dumping in 1993 eliminated a major source of particulate matter to the Adelaide coastline. The WWTPs currently discharge around 2000 tonnes/y (Figure 10b) compared to 8400 tonnes in the early 1990s (the latter figure includes sludge discharges). This is a four-fold reduction in the overall WWTP derived load, with the treated wastewater (i.e. non-sludge) load falling to 64% of the load in the early 1990s.

A more detailed breakdown of flows and suspended sediment loads from land-based sources is shown in Figure 11, while Figure 12 shows the breakdown for nitrogen and phosphorus loads.

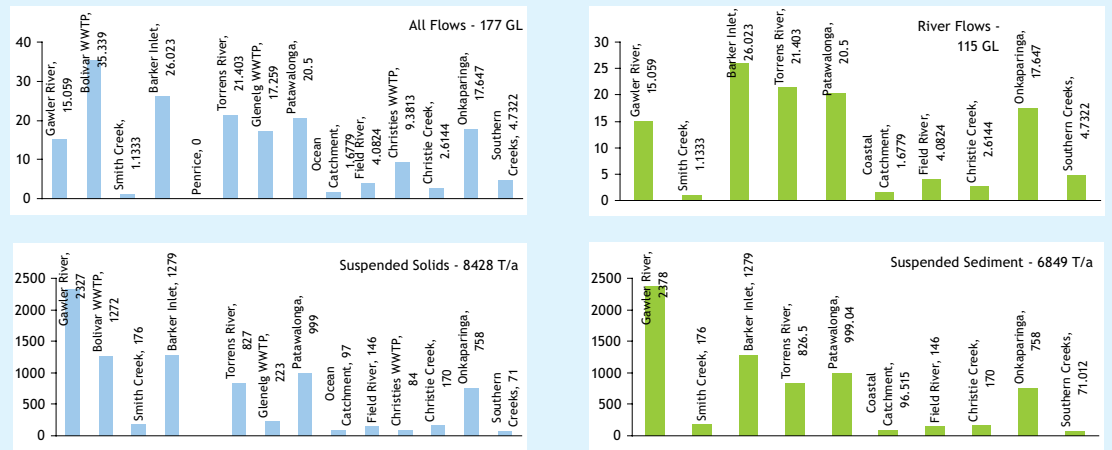


Figure 11. Breakdown of flow and solids for combined WWTP and stormwater (left panels), and stormwater only (right panels) based on data collected during 2001/03. Note: Gawler River load is an estimate only.

At Christies Beach the annual nitrogen load peaked at approximately 370 tonnes/y in 1996/97, a period when total nitrogen concentrations exceeded 35 mg/L. Ten years after the cessation of sludge disposal to sea, and following the upgrade of Bolivar to activated sludge, the nitrogen load dropped to 1000 tonnes/y. Treatment upgrades at Glenelg reduced the mean nitrogen concentration from around 30 mg/L to 20 mg/L, resulting in reduced nitrogen loads from this source. The nitrogen load from Christies Beach in 2002/03 was greater than in the 1986 to 1992 period (236.4 t/y of 213.4 t/y), partly as a consequence of the growth in connections and load into the plant. This load is net of the Willunga Basin Transfer which has reduced the annual discharge volume since 1999.

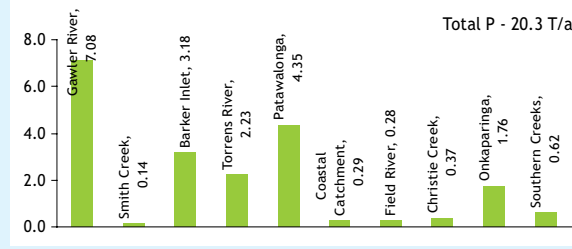
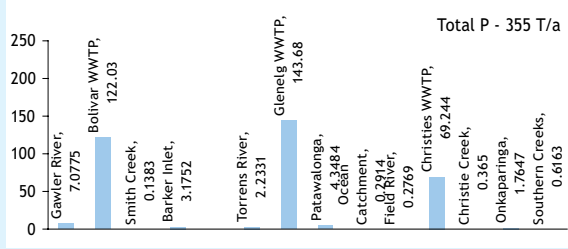
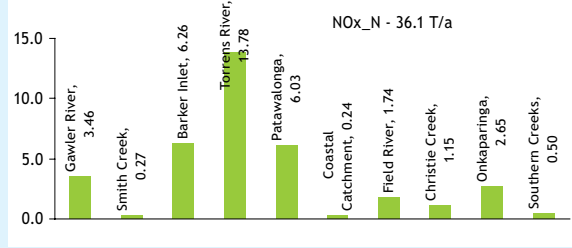
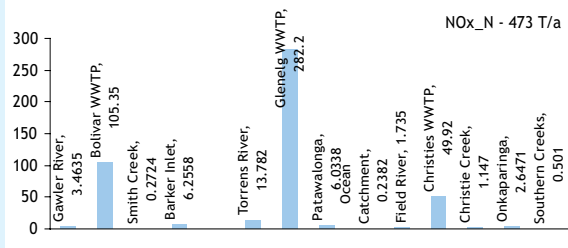
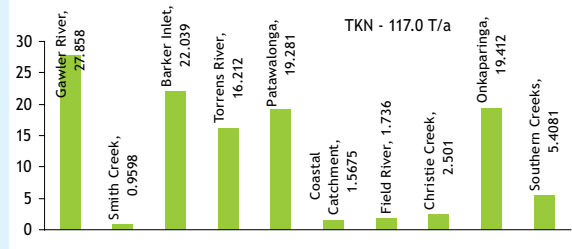
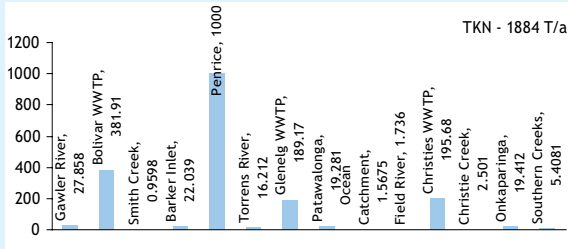
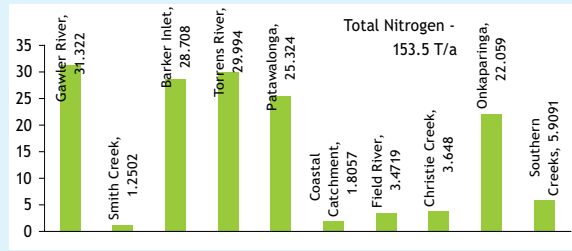
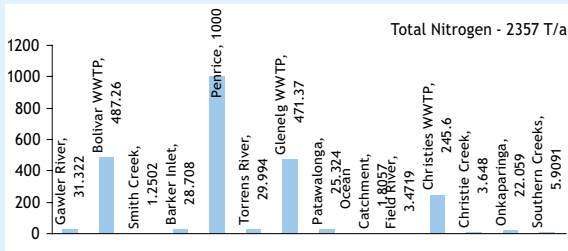


Figure 12. Breakdown of annual nitrogen and phosphorus loads for combined WWTP and stormwater (left panels), and stormwater only (right panels) based on data collected during 2001/03.

A detailed breakdown of selected heavy metal loads from the three main WWTPs and the old sludge outfalls is shown in Figure 13. The dramatic reduction in these loads since the early 1990s is clearly evident. The decommissioning of the sludge outfalls significantly reduced the loads of silver, copper, chromium, and zinc while treatment improvement processes at Bolivar and Glenside resulted in substantial reductions of cadmium, nickel, and lead.

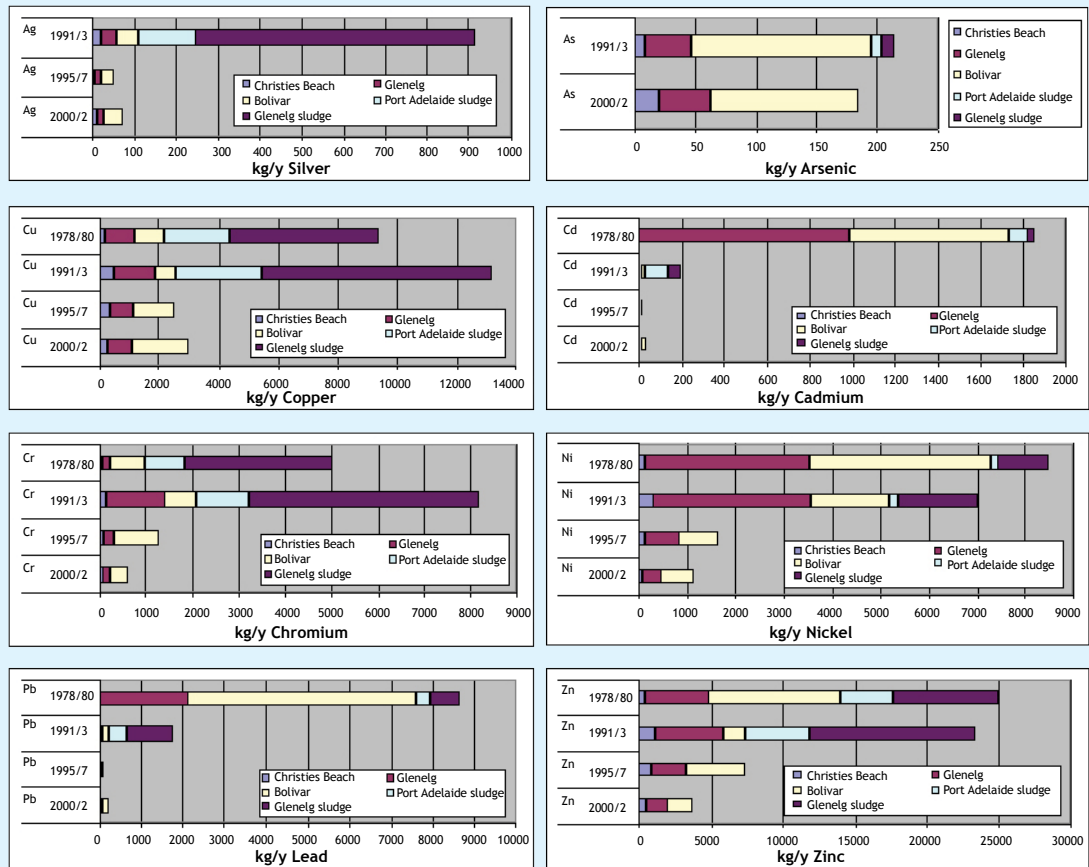


Figure 12. Loads for selected metals from Christies Beach, Glenelg, and Bolivar WWTPs as well as loads from decommissioned sludge outfalls at Port Adelaide and Glenelg.



3.3 Sediments

The renewable sediments in the study region are predominantly carbonate and quartz grains of varying size. The carbonate grains are produced by metabolic processes of marine flora and fauna within the region, while the quartz grains are generated by cliff erosion and scouring of catchments generally outside the region and transported by Gulf circulation processes. Relict grains represent a significant fraction of the sediment components, although this is not a renewable fraction. The numerous rivers, creeks, and drains along the study coastline periodically deposit large quantities of fine sediment to the inter-tidal area, resulting in highly turbid near-shore waters. Suspended sediments are also introduced to the coastal strip from waste-water treatment plants and industry (e.g. Penrice Soda). There is a marked decrease in the carbonate fraction in the sediment in the inter-tidal and beach zones in the study area, except in the northern region. This contrasts with other South Australian coastal areas that have extensive seagrass beds closer to shore. There is a correlation between mineralogical composition of the sediment grains and distance of the seagrass line from the shore.

Seagrass beds provide a favourable environment for biogenic carbonate production, and also supply an ideal substrate for calcareous epiphytes. Many of these are transported to the beach with the shedding of seagrass leaves, where they remain

as carbonate sand grains once the seagrass decays. This process represents a significant source of sediment grains. For example, each year a kilogram of seagrass produces about 1 kg of carbonate sediment at Semaphore and about 0.3 kg at Marino.

3.3.1 Coastal sediment quality

Relative to water quality, few data are available on coastal sediment quality for Adelaide's coastal waters. No data exist on nutrient levels in Adelaide's coastal sediments. The waters immediately off Holdfast Bay have been eutrophic for some decades now. It is possible that under conditions of high nutrient loads, nutrient-laden sediments and organic material accumulating on the substrate could result in increased levels of porewater nutrients. While sediment nutrient levels were not measured as part of the current study, results of benthic chamber work as part of Task EP 1 (Nayar et al. 2006) indicate that for seagrass environments in Holdfast Bay, sediment nutrient levels (particularly ammonia) are much higher than in the overlying water column. However, this is probably due to the naturally high organic content of sediments in seagrass meadows (Romero et al. 2006), and seagrasses seem to be more tolerant of higher levels of nutrients in sediments than in water (Ralph et al. 2006).

Based on a limited sampling of sediments, ACWS Task EP1 made the following observations:

- Concentrations of organochlorine and organophosphate pesticides, triazine herbicides, glyphosate, polycyclic aromatic hydrocarbons, and total petroleum hydrocarbons were all below detectable limits in the 12 sediment samples that were laboratory tested.
- The heavy metals chromium and zinc were detected at all 10 sites examined, while lead was detected at eight of the 10 sites.
- Copper was detected at only two sites.
- Concentrations of four heavy metals were low, with ranges of 0.6-11, 0.5-23, 0.96-4.3, and 0.73-0.85 mg/kg dry wt for chromium, zinc, lead, and copper, respectively. These levels are all well below the ANZECC/ARMCANZ (2000) recommended sediment quality guideline trigger values of 80, 200, 50, and 65 mg/kg dry wt, for chromium, zinc, lead, and copper, respectively.
- There were no clear spatial patterns related to depth, except in the southern part of the study region where levels of chromium, lead, and zinc were all markedly higher at depth.
- Sites in the vicinity of the Torrens River and Barcoo outlet had low levels of chromium, lead, and zinc compared to sites further offshore where those compounds were also detected.



3.4 Seagrasses

The ACWS has contributed fundamental insights into the mechanisms and factors controlling the loss, recruitment, and vitality of Adelaide's seagrasses. An innovative research program that coupled laboratory-based results with *in situ* observational and manipulative experiments has for the first time provided compelling evidence to support hypotheses of causal loss mechanisms. The major findings are summarised below.

Reduced salinity

It is unlikely that freshwater is implicated in the initial loss of seagrass off Adelaide's coastline although it may play a role in determining the capacity for natural regeneration/recovery at sites close to land-based inputs (rivers, creeks, drains, and WWTPs). Both species (*Amphibolis*

antarctica and *Posidonia sinuosa*) are highly tolerant to short-term (72 hours) reductions in salinity, with major salinity reductions required for prolonged periods (weeks) to kill adult plants. The reductions in salinity experienced along Adelaide's coast (particularly in the near-shore region where stormwater enters Adelaide's coastal waters and at locations adjacent to wastewater outfalls) are minor. However, short-term reductions in salinity can affect *A. antarctica* seedlings and *P. sinuosa* fruits. Thus, it is possible that reductions in salinity caused by stormwater and wastewater could influence recruitment processes on a very localised scale.

Toxicants

It is unlikely that toxicants (pesticides, organochlorines, hydrocarbons, herbicides, etc.) have been responsible for broad-scale historical seagrass losses. This is supported by the fact that toxicants have only been sporadically detected in very low concentrations in freshwater entering Adelaide's coastal water (which are then rapidly diluted) and that the concentrations required to affect seagrasses are relatively high. Sampling of the coastal waters following peak stormwater flows (when detection would be most likely to be undertaken) failed to detect any toxicants. Similarly, toxicant levels in sediments adjacent to stormwater outlets, as well as sites further off shore, found very low or undetectable toxicant levels. Finally, the historical levels detected in stormwater could never have reached levels capable of having an impact.

Turbidity

It is possible that increased turbidity from stormwater contributed to the broad-scale loss of near-shore seagrass.

Modelling results indicate that coastal inputs can become 'trapped' in the near-shore zone, resulting in a greatly diminished benthic light climate and that at times, light levels at 3 m depth can be so low as to cause the death of *Amphibolis* (but not at deeper depths). It is highly likely that near-shore light conditions were worse during the 1940s to 1960s (when much of the near-shore seagrass loss occurred) because discharges from the Torrens River then were significantly greater than at present. Experimental results from the Adelaide Coastal Waters Study have not been able to conclusively establish that a compromised light climate alone could have caused the loss of seagrass, although this remains a possibility.

Nutrients

It is most likely that nutrients from stormwater and wastewater were responsible for broad-scale historical seagrass losses. We now have multiple lines of evidence in support of this hypothesis, including laboratory and field-based experimental results. Historically, we know that the coastal waters have received almost continuous inputs of stormwater and wastewater for the last 70 years as well as industrial contaminants and sewerage sludge between the early 1960s and 1993. This served to increase the levels of water-column nutrients in Holdfast Bay and in the vicinity of wastewater outfalls. Perhaps the most significant initial activities (in terms of environmental impact) included the diversion of the Torrens River, waste disposal from the Glenelg WWTP, and the commencement of Penrice Soda discharges in 1940. This study has provided clear evidence that the existing offshore seagrasses from Port Gawler to Port Noarlunga continue to receive nitrogen sourced from WWTP and industrial outfalls (most notably Penrice Soda). Clearly, near-shore seagrasses (prior to their loss) would also have been exposed to those same nutrient sources.



Figure 14. The SARDI Aquatic Sciences tank farm where the mesocosm experiments were performed.

Results of the Adelaide Coastal Waters Study unambiguously prove that chronic, yet minor, increases in water column nutrients (as might be associated with WWTP and industrial inputs) could have caused the slow decline of *Amphibolis* and *Posidonia* in shallow, previously nutrient-poor, coastal waters. Mesocosm experiments have demonstrated that *Amphibolis* is more susceptible to nutrient enrichment than *Posidonia* – particularly in the presence of epiphytes and irrespective of depth. The existence of this effect on *Amphibolis* in the absence of epiphytes has not been unequivocally established. The present situation with respect to nitrogen input and biotic uptake in the receiving waters is depicted in Figure 15.

The findings of this study are consistent with observations in similar, nitrogen-limited marine environments which suggest that nitrogen, rather than phosphorus, plays a key role in the degradation of marine (and seagrass) systems. Inorganic forms of nitrogen (such as ammoniacal nitrogen and oxidised nitrogen) are generally of greater concern since they are biologically available. Further work would need to be undertaken to understand the effects of reducing nitrogen in Adelaide's coastal waters while leaving phosphorus loads unchanged.

In situ experiments used bags of slow-release fertiliser to provide long-term enrichment of nitrogen around pristine seagrass beds. Ammoniacal nitrogen concentrations in the treated plots were about 0.03 mg/L - about 3 times the ambient concentrations of SA coastal waters although close to (but generally less than) those now found on the Adelaide metropolitan coast (due to enrichment from wastewater and stormwater inputs). This enrichment resulted in rapid growth of epiphytes and a reduction, over a year, of the above-ground biomass. The experiments were the first manipulative studies to demonstrate that even these modest nutrient enrichments are sufficient to destroy pristine seagrass beds in a few years. A 'nutrient-epiphyte-seagrass decline model' has been developed which summarises our understanding of how increased nutrients affect seagrass (Figure 16). This model also supports previous correlative observations of seagrass loss at the Port Adelaide WWTP sludge outfall in offshore Holdfast Bay, the Bolivar WWTP outfall north of Outer Harbour, and the Glenelg WWTP outfall in near-shore Holdfast Bay.

While this model encapsulates the most contemporary understanding of the interplay between nutrients and seagrass loss, further research and development is required to definitively establish a *causal link* rather than a *correlation*.

It is possible, but unlikely, that the direct toxic effects of increased nutrients are responsible for the loss of seagrass. Ammonia is toxic to both *Posidonia* and *Amphibolis*, but only at concentrations that would be found directly adjacent to effluent discharges. Ammonia levels drop rapidly with increasing distance from the discharge point.

Finally, the effect of multiple stressors cannot be discounted. Thus, it is possible that a combination of increased nutrients and increased turbidity from stormwater and wastewater triggered the initial seaward regression of near-shore seagrasses in Holdfast Bay. Preliminary results from mesocosm experiments suggest that multiple effects are plausible. One such experiment simultaneously examined the effects of high nutrient levels, reduced light, and increased epiphyte load on *Amphibolis antarctica* and *Posidonia sinuosa*. Although an interesting interaction between ammonium concentration and light level was observed, extrapolation of these results to the field was not possible due to the unrealistically high nutrient concentrations and the short time-frame (4 weeks) used.

4 CONCLUSIONS

As Adelaide has grown, so too have the volumes and loads of nutrients, total suspended solids (turbid water), and dissolved organic carbon (coloured water) discharged to coastal waters. Furthermore, these loads of coloured stormwater are discharged directly to the Gulf, accompanied by municipal and industrial waste discharges rich in dissolved inorganic nitrogen and phosphorus. Wastewater discharges and the release of stormwater have changed the pattern of flows and loads. Urban runoff is 'flashier' than runoff from vegetated catchments, so that rainfall in urban catchments runs off quickly carrying nutrients and suspended solids from roofs, roads, and gardens. Since the rapid growth of the city in the 1960s, there has been both

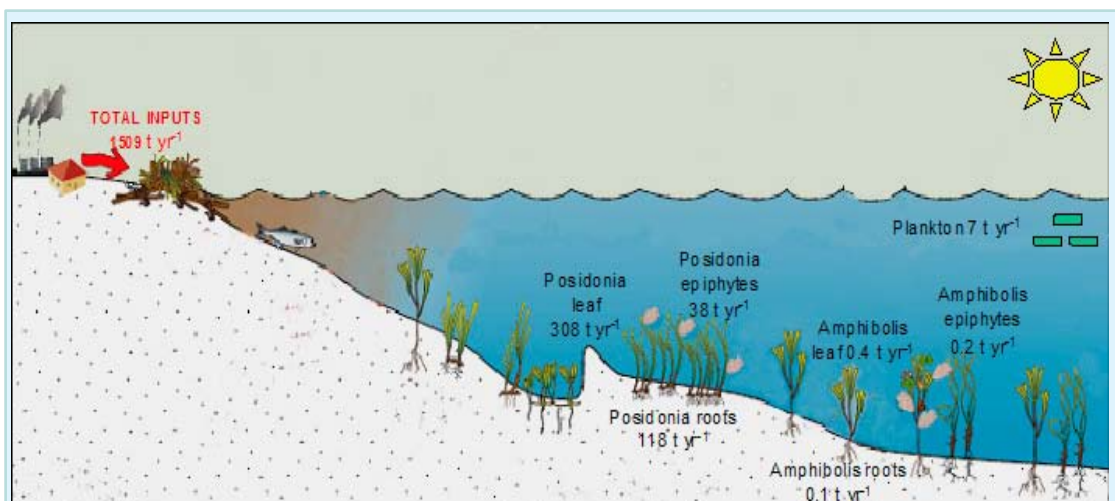


Figure 15. A simplified summary of the current annual ammonium biotic assimilation capacity in relation to the total anthropogenic inputs for the Adelaide coastal waters. Figures in tonnes of ammonium per year.

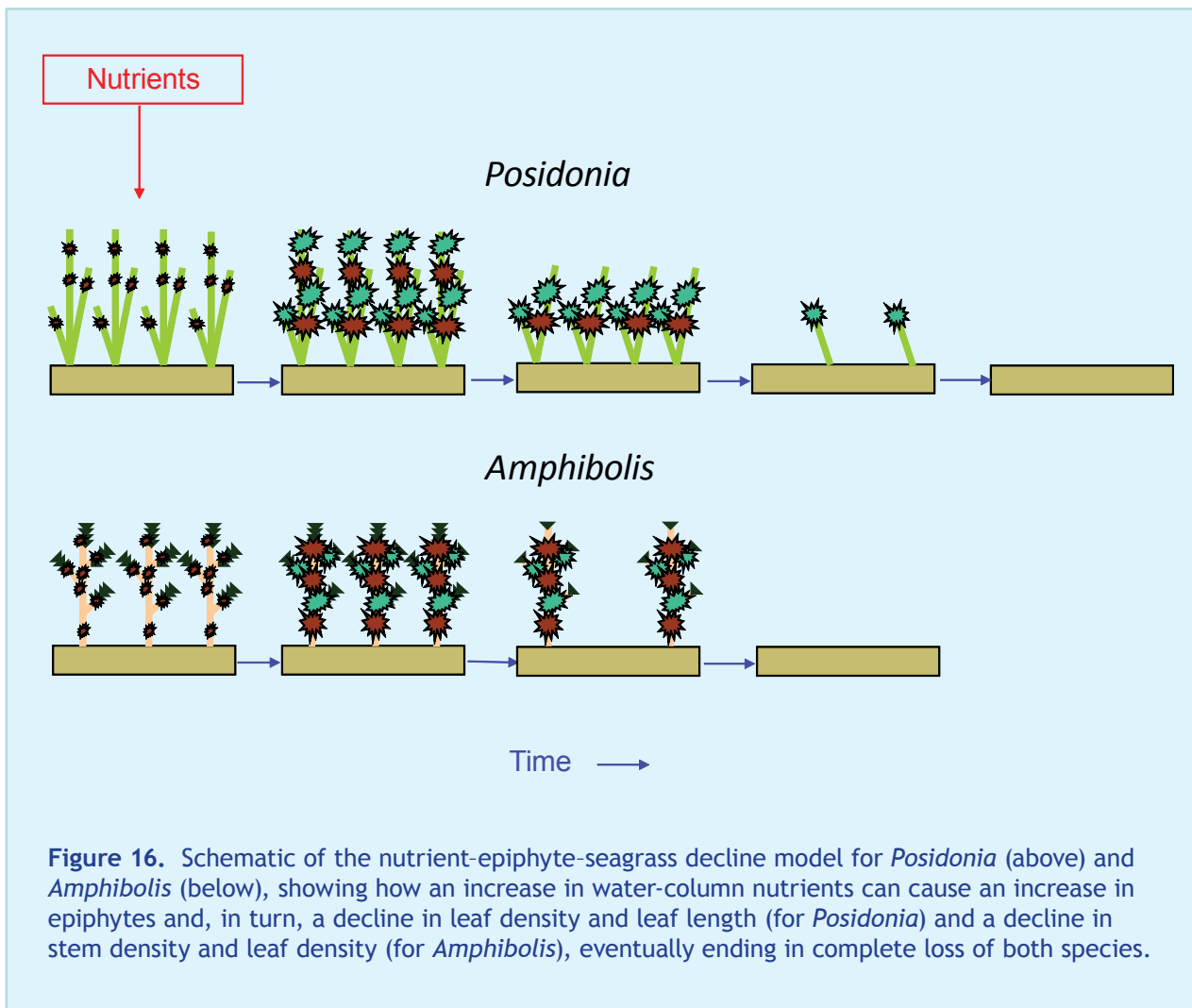


Figure 16. Schematic of the nutrient-epiphyte-seagrass decline model for *Posidonia* (above) and *Amphibolis* (below), showing how an increase in water-column nutrients can cause an increase in epiphytes and, in turn, a decline in leaf density and leaf length (for *Posidonia*) and a decline in stem density and leaf density (for *Amphibolis*), eventually ending in complete loss of both species.

a growth in the overall loads to coastal waters as well as a strong increase in summer flows. Summer flows – which would once have been practically zero – are now of the order of 5-8 GL/y. Winter catchment outflows are high in nitrate whereas summer catchment outflows are characterised by highly coloured water. So the overall load, its chemical nature, and its distribution in time have changed in the last 50 years.

All the evidence points to a key role of nitrogen loads in causing nutrient enrichment of coastal waters, growth of epiphytes, and (perhaps) direct effects on the seagrasses. There is no evidence from this study to show that toxicants or other chemical stressors play a key role in the ecosystem dynamics. This is totally consistent with the findings of other studies of coastal waters in Australia.

The major discharges of nitrogen now occur from the Bolivar WWTP, the Penrice plant, and from the Glenelg WWTP. Stormwater flows are a small fraction of the overall loads. The overall loads now amount to about 100-130 GL of water and a total nitrogen load of about 2350 tonnes per year made up by around 850 t N/y from Penrice, 1200 t N/y from municipal wastewaters, and 150 t N/y from stormwater flows. Before human impact the nitrogen loads would have been small - of the order of 50-80 t N/y – so that, overall, we have increased the nutrient loads to the Adelaide coastal waters by a factor of 30-50.

The Adelaide Coastal Waters Study has generated a unique historical record of nitrogen (and other) loads to coastal waters, coupled with a long series of observations of seagrass cover in Adelaide coastal waters. Analysis of these historical loading trends (coupled with the realisation that there are long time lags in this system between loading increases and seagrass losses) shows that seagrass losses were widespread after the loads increased to about half the present levels.

Nitrogen loads into the ACWS coastal zone (an area of about 100 km²) are presently estimated to be 27.5 tonne N/km². The residence time in this region is estimated to be of the order of 5-10 days (and as much as 30 days), making the effective nitrogen load 0.3 to 2.5 tonne N/km²/y. This brackets the known critical load for coastal ecosystems - derived from observations in many Australian coastal waters - of 1 t N/km²/y (Webster and Harris 2004). Certainly, seagrass loss is expected at loads around 3 t N/km²/y - as is observed here. Although seagrass loss appears to have stabilised over the last decade, our analysis suggests that an approximate 75% reduction (based on 2003 load estimates) in nitrogen load to coastal waters is required in order to encourage re-growth and re-colonisation.

It is evident that the highly turbid, nutrient-enriched, and coloured waters entering the coastal marine environment are directly associated with degraded water quality, loss of seagrasses, and (indirectly) alteration of sediment dynamics and other physical, chemical, and biological processes. While it is well known that seagrasses have a high light requirement, this study has not been able to demonstrate that turbidity alone is responsible for historical seagrass losses. Nevertheless, turbidity is a threat to seagrasses and the combined effect of high nutrient levels and increased turbidity may result in worse environmental outcomes than from either effect alone. For this reason we believe that, commensurate with efforts to reduce the nitrogen load, a targeted reduction of total suspended sediment load is required. Using a conservative target of 12% surface irradiance at 9 m depth would mean the overall sediment load (stormwater and WWTPs) discharged to the marine environment would need to be reduced by about 50% from its current value of about 8400 tonnes. Given the uncertainties about the role of sediments in seagrass loss, coupled with the fact that this calculation does not take into account the effects of re-suspension, we suggest that the numerical target be treated as 'aspirational' rather than a 'compliance' target. Further research is required to better understand the complex interactions between light availability, suspended sediment concentrations, nutrient enrichment, and seagrass/epiphyte response.

4.1 Physical Processes

The physics of the Adelaide metropolitan coastal waters have been investigated through moorings and ship-board surveys, as well as models. All the results indicate that the main features of the coastal circulation are closely tied to the impacts of the catchment and wastewater loads. Long-shore transport by wind and tide is about an order of magnitude larger than offshore transport, so the predominant fate of catchment loads is to be trapped close inshore and to be moved up and down the coast by the tide. The predominant water movement pattern - the residual flow - is northerly in summer and southerly in winter.

Because of the loss of seagrasses along the metropolitan beaches there is now more scouring and re-suspension of sediment than previously. There appears to be sufficient energy to re-suspend fine sediments throughout the near-shore zone. Analysis of sediment types along the coast has shown that, in addition to material

sourced from adjacent catchments, carbonaceous material produced biogenically within seagrass beds is an important component. The sources of 'new' sediments are controlled by the healthy state of the sea floor in the case of carbonates, particularly the important group of calcareous epiphytes on seagrasses, by reworking of coastal environments such as dunes and cliffs and the inputs from natural drainage systems.

The effects on the ecosystems in coastal waters has been investigated by a series of light meters moored in transects off Adelaide beaches. After rainfall events, the light intensity on the bottom at 3 m and 8 m depth is frequently less than that observed at 15 m because of discoloured and turbid stormwater trapped along the shore (this would be exacerbated by sediment re-suspension inside the 'blue line' after wind and rain events.) The seasonal pattern of rainfall in Adelaide (dry in the first half of the year, wetter in the second) means that there are frequent periods in the latter half of the year when it is quite dark on the sea floor close inshore.

Modelling of the coastal circulation has shown that at the same time as stormwater flows are trapped inside the 5 m contour in winter, there is also a turbid and nutrient-rich plume of water from Penrice, Bolivar, and the Port River which moves south along the 5-8 m contour. The model indicates that total nitrogen concentrations of 0.05-0.1 mg/L can be expected in coastal waters in winter - and these are confirmed by observations. Thus during winter there are frequent periods when near-shore environments are impacted by coloured, turbid, and nutrient-enriched waters. In summer, because of the predominantly northerly flow in coastal waters, inputs from Glenelg and other stormwater inputs from southern catchments similarly impact the metropolitan coastal strip. Inputs from Bolivar and the Port River are swept to the north. Thus the northern and southern inputs alternate seasonally in terms of their significance.

Water residence times along the shore are short because of tidal and wind-induced flushing. In the coastal strip 30-35 km long and about 2 km wide (inside the 'blue line') residence times are of the order of <2 days in summer and <4 days in winter. In the larger metropolitan coastal region the residence time is longer - about 10-30 days. These residence times may be much longer during periods of 'dodge tides' when water movement is slowed.

4.2 Response of the Seagrass-dominated Ecosystems in Coastal Waters

Results of the Adelaide Coastal Waters Study unambiguously prove that chronic, yet minor, increases in water-column nutrients (as might be associated with WWTP and industrial inputs) could cause the slow decline of *Amphibolis* and *Posidonia* in shallow, previously nutrient-poor coastal waters.

A combination of mesocosm experiments and *in situ* nutrient enrichment experiments demonstrated that *Amphibolis* is more susceptible to nutrient enrichment than *Posidonia* - particularly in the presence of epiphytes and irrespective of depth. The existence of this effect on *Amphibolis* in the absence of epiphytes has not been unequivocally established. The nutrient enrichment experiments at an unimpacted site on the western side of the Gulf resulted in rapid growth of epiphytes and a reduction of the above-ground biomass over a period of one year. The experiments are the first manipulative studies to demonstrate that even these modest nutrient enrichments are sufficient to destroy pristine seagrass beds in a few years.

The Adelaide Coastal Waters Study therefore shows that the seagrasses along the metropolitan coastline have been impacted substantially through nutrient enrichment and increases in turbidity and water colour. Together these serve to damage the seagrasses directly, increase epiphyte growth, and reduce light for photosynthesis. By increasing the frequency and magnitude of input events - through catchment clearing, urban development, and by-passing of

natural wetland filters (e.g. the creation of Breakout Creek) - as well as increasing the background nutrient concentrations through industrial and urban wastewater inflows, the tolerance limits of key species have been exceeded and seagrasses have been lost from city beaches.

Sediment movement inshore of the seagrass beds is presently sufficient to prevent re-growth of seagrasses. *Amphibolis* has been shown to recruit to patches of sacking and other rough materials anchored to the bottom - so a recruitment source is available to support future recovery if conditions were conducive to recruitment and subsequent growth. Even so, recovery is expected to be slow. In other parts of the world it has taken up to 20 years for seagrasses to re-grow once suitable conditions were re-established and for both *Posidonia* and *Amphibolis*-dominated systems this time-frame may exceed 100 years. Large-scale recovery of seagrass meadows should not be expected unless dramatic and lasting reductions in coastal inputs are made. Even then, sediment instability and nutrient recycling may inhibit progress towards this objective. While evidence of modest (unassisted) recovery in the vicinity of decommissioned sludge outfalls has been noted, it is more likely that large-scale recovery of seagrass meadows along Adelaide's coast will require intervention, either in the form of provision of appropriate settlement substrate for seedlings, transplanting of mature stock, or the harvesting and planting of germinated seedlings.

5 RECOMMENDATIONS

The ACWS has demonstrated that the key management actions required are those which will reduce inputs of nutrient, turbidity, and colour in stormwater and wastewater into metropolitan coastal waters. Present nutrient enrichment levels are clearly sufficient to cause seagrass loss. This is compounded by the increased inflows of turbid and coloured stormwater and catchment runoff. Calculation of nitrogen loads from the various sources, backed up by recent stable isotope studies, underscores the significant role to be played by SA Water, catchment water management boards, and Penrice Soda in working towards improved environmental outcomes.

The following recommendations have been made for the benefit of the Client and Stakeholders to assist with their assessment of various management options. Our recommendations are based upon and relate to specific investigations undertaken and knowledge gained during the course of this Study. A comprehensive response to the findings of this Study will integrate social, political, economic, and environmental values and involve considerations that are outside the terms of reference for this Study. Thus these recommendations should be seen as one component of the overall response-formulation process.

Recommendation #1

As a matter of priority, steps must be taken to reduce the volumes of wastewater, stormwater, and industrial inputs into Adelaide's coastal environment. This should be done within the context of an overarching strategy designed to remediate and protect the metropolitan coastal ecosystem.

Recommendation #2

The total load of nitrogen discharged to the marine environment should be reduced to around 600 tonnes (representing a 75% reduction from the 2003 value of 2400 tonnes).

Recommendation #3

Commensurate with efforts to reduce the nitrogen load, steps should be taken to progressively reduce the load of particulate matter discharged to the marine environment. A 50% load reduction (from 2003 levels) would be sufficient to maintain adequate light levels above seagrass beds for most of the time. The reduced sediment load will also contribute to improved water quality and aesthetics.

Recommendation #4

To assist in the improvement of the optical qualities of Adelaide's coastal waters, steps should be taken to reduce the amount of CDOM (coloured dissolved organic matter) in waters discharged by rivers, creeks, and stormwater drains.

Recommendation #5

While the available data suggests that toxicant levels in Adelaide's coastal waters pose no significant environmental risk, loads from point sources such as the Port River, WWTPs, and drains should continue to be reduced. Routine monitoring of toxicant loads and concentrations should be undertaken every 3-5 years.

Recommendation #6

Develop and implement a comprehensive and integrated environmental monitoring program that will enable natural resource managers and all stakeholders to evaluate changes in the coastal marine environment over time and at various spatial scales.

Recommendation #7

Maintain and develop the comprehensive data base of historical inputs generated by this study. It is suggested that a single entity be created to oversee the administrative functions associated with data collection, storage/retrieval, analysis, and reporting. This entity should also assume responsibility for the on-going maintenance and application of the various models produced by the ACWS so as to ensure that they remain both relevant and accessible. Consideration should also be given to the establishment of a research/monitoring coordination body. A primary function of this body would be to prioritise on-going and future research activities and to seek and allocate funding in accordance with those priorities.

Recommendation #8

Implement a long-term monitoring program to assess seagrass quality (or 'health') at sites adjacent to land-based discharges and at suitable reference sites.

Recommendation #9

Implement a long-term monitoring program of the outer depth margin of Posidonia meadows in Holdfast Bay.

Recommendation #10

Implement a long-term monitoring program of seagrass meadow fragmentation at a range of sites in Holdfast Bay.

Recommendation #11

Undertake detailed mapping of the distribution of Amphibolis across the Adelaide metropolitan area, determine the lower depth limit of seagrasses in Holdfast Bay, and map seagrasses in the southern metropolitan area between Seacliff and Sellicks Beach.

Recommendation #12

Undertake a spatially intensive nitrogen stable isotope survey to determine the offshore and northern extents of nitrogen influence from WWTP and industrial outfalls along the Adelaide metropolitan coastline, and also characterise nitrogen stable isotope signatures of potential nitrogen sources.

Recommendation #13

Undertake an audit of key environmental assets in the southern metropolitan coastal region, identify risks to those assets, and develop an integrated management plan to mitigate the risks. The applicability of management actions developed in response to the findings of this study to halt and reverse ecosystem degradation in the northern regions should be investigated with a view to adopting it (possibly with modification) in the southern region.

Recommendation #14

Adelaide's coastal marine environment must be managed as a component of a system that integrates catchment management, urban and rural land use, demographics, urban and industrial development, climate change/climate variability, and water re-use.

6 DIRECTIONS FOR FUTURE RESEARCH

While the ACWS has added considerably to our knowledge and understanding of the processes associated with coastal water quality, sediments, and seagrass, gaps inevitably remain. Areas for future research include:

- Experimentally test and model the combined effects of increased nutrients and turbidity on *Amphibolis* and *Posidonia*.
- Determine the photosynthetic parameters required for input to light-productivity models of *Amphibolis* and *Posidonia* off the coast of Adelaide.
- Conduct a spatially intensive $\delta^{15}\text{N}$ survey to determine the offshore and northern extents of nitrogen influence from WWTP and industrial outfalls in the ACWS region, and also characterise $\delta^{15}\text{N}$ signatures of potential nitrogen sources.
- Undertake further research on the basic biology of *Amphibolis*, which appears to be a crucial, yet sensitive, component of near-shore seagrass systems in Gulf St Vincent.
- Undertake further field research on the effects of increased nutrients in different locations/depths and in conjunction with decreased light (a proxy for increased turbidity).
- Undertake research on rates of meadow expansion and recolonisation in denuded and fragmented areas.
- Undertake research on sediment re-suspension and impacts on seagrass health.
- Undertake further research to refine nutrient budgets, determine denitrification processes, and develop a nutrient mass-balance model of Gulf St Vincent.
- Undertake more detailed research on the exchange between the Gulf and the adjacent Port River and Barker Inlet. This also requires a careful monitoring of water quality in this region during both summer and winter. The effects of reduced light levels on water quality and seagrass health associated with turbidity events in the near-shore zone need to be examined.
- Extend the investigation of physical processes that result in ‘blowouts’ in certain deeper water areas. This will require the determination of the physical sediment properties that can be used to define critical bed-shear stresses for mobilisation and transport and the use of models to provide spatial distribution maps of occurrences of bed-shear stresses resulting from the combined action of waves and currents (tide/wind).

7 MONITORING AND MANAGEMENT

Details of a suggested integrated monitoring program for Adelaide's coastal waters can be found in Technical Report 19 *An Integrated Environmental Monitoring Program for Adelaide's Coastal Waters*. A summary of the main components is provided in the following sections.

7.1 *Seagrass Monitoring*

The focus of seagrass monitoring is to determine the health, the distribution of species, and the extent of seagrass meadows. It is important that the protocols for monitoring seagrass are consistent with seagrass monitoring in other parts of South Australia to facilitate meaningful future comparisons.

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Fixed sites

Regular summer or autumn monitoring of health indicators in fixed quadrats should be undertaken at specifically chosen sites, which is a cost-effective way to assess seagrass health. Photographs of quadrats would provide a quick and useful record for future comparison.

Permanent markers

Permanent markers, such as brass rods, should be placed at the inner and outer edge of seagrass extent; subsequent measurement of the recession or growth from those markers is a simple and cost-effective method for assessing change to the seagrass extent.

Diver transect surveys

Transect surveys by divers are a valuable component of the seagrass monitoring program because they provide an assessment of the distribution and composition of the seagrass community over a wider area than quadrat sampling.

Video sampling

Video sampling is a cheap and inexpensive way of surveying relatively large tracts of seagrass meadows.

Aerial photography

Aerial photography is an effective way of assessing broad-scale changes to seagrass extent and distribution. It is also the best link to the past monitoring activity in the region (approximately 5-yearly aerial photographs have been taken since 1949, although not all are useful).

7.2 Sediment Stability

The SA DEH Coastal Protection Branch undertakes substantial monitoring of sediment stability in Adelaide's coastal waters. The proposed ongoing monitoring for sediment stability is an extension of the existing monitoring program. The only additions and modifications suggested is to review the location of the current profile/rod lines with a view to (i) extending some to coincide with key seagrass areas, and (ii) increasing the number of lines in the southern region.

7.3 Terrestrial Inputs

Impacts from land-based sources to the coast are most pronounced in Zones 1, 2, and 3 (Figure 4) and are generally well represented by existing monitoring of wastewater and stormwater.

It is recommended that water quality sampling of the receiving waters around the Bolivar outfall be monitored to capture any WWTP-related change. Similar sampling is already carried out in the receiving waters for the Glenelg and Christies Beach WWTP outfalls. It is also recommended that better estimates of stormwater loads be obtained for catchments that are presently not well quantified. This is particularly true of outlets away from the non-metropolitan area. For example, Field River does not have flow-proportional sampling. It is also suggested that dissolved organic carbon (colour) and turbidity of outputs from major stormwater outlets be regularly recorded given the potential effect these parameters might have on the light climate. Detailed monitoring of terrestrial inputs in the southern part of the study region is identified as important (given the likely population growth in that area and the objective of protecting existing seagrass). Atmospheric and groundwater inputs to Adelaide's coastal waters are a lower priority monitoring objective, since the contributions from these sources represents a small proportion of the total.

7.4 Coastal Water Quality

Water quality is a critical component of coastal health and is an essential component of any on-going monitoring program. The recommended monitoring of receiving waters of WWTPs, Port Adelaide River/Barker Inlet and the survey (Recommendation #12 of this report) have obvious implications for coastal water quality and should be considered simultaneously.

The existing SA EPA ambient water quality monitoring program is undertaken at 10 sites along the metropolitan coast (mostly jetties) and has a baseline monthly sampling intensity, which is increased to fortnightly during the summer months. This monitoring is necessary for compliance reasons and also informs decisions on the suitability of water quality for recreational activities. It also provides a valuable measure of the water quality after inputs to the coast are mixed and of how fine sediment is resuspended during windy weather. This gives an indication of the water quality that seagrasses in the near-shore zones are likely to experience. The parameters measured as part of the jetty sampling include turbidity, heavy metals, and bacterial counts. Nutrients are not measured since they are rapidly assimilated within the marine environment.

There is a need to regularly monitor water quality further offshore in the areas of existing seagrass meadows, and where seagrass re-colonisation is thought possible, because that constitutes a more direct measurement of the water quality which will ultimately determine the seagrass survival.

7.5 Physical Processes

Physical processes have an important effect on Adelaide's coastal waters. The hydrodynamics of the region affect the transport, mixing, and deposition of sediment and contaminants. Any changes to these processes may have implications for seagrass, sediments, and water quality; therefore monitoring of these processes is deemed necessary so that: (i) any shift to a new state (e.g. as a result of climate change/variability) is identified and the effects on coastal dynamics determined; and (ii) parameters of physical models be updated. It is recommended that the model developed as part of this study be updated annually.

It is essential to maintain access to wind, wave height, tide height, and storm records as these will help inform the processes of interest.

A regular broader refinement of the entire hydrodynamic model should be considered every 5-10 years in response to the collection of additional data and knowledge. This will ensure that the model continues to remain relevant and is providing information on appropriate spatial and temporal scales.

10 REFERENCES

- ANZECC/ARMCANZ (2000). Australian and New Zealand Guidelines for Fresh and Marine Waters. National Water Quality Management Strategy Paper No 4, Australian and New Zealand Environment and Conservation Council/ Agriculture Resource Management Council of Australia and New Zealand, Canberra.
- Dennison, W.C. and Abal, E.G. (1999). Moreton Bay Study: A Scientific Basis for the Healthy Waterways Campaign. South East Queensland Regional Water Quality Management Strategy, Brisbane, 246 p.
- 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 Australia.
- Lewis S.A. (1975) Gulf St. Vincent Water Pollution Studies 1972-1975. Report of the committee on the effects of land-based discharges from metropolitan Adelaide upon the marine environment of Gulf St Vincent. Engineering and Water Supply Department, South Australian Government. EWS 75/14.
- Lord, D.A. and Hillman, K. (1995). Perth Coastal Waters Study Summary Report. Water Corporation of Western Australia, Leederville, Western Australia.
- Nayar, S., Collings, G., Miller, D., and Bryars, S. (2006). Nutrient fluxes in the meadow forming seagrasses *Posidonia* and *Amphibolis* from the Adelaide metropolitan coast. ACWS Technical Report No. 13 prepared for the Adelaide Coastal Waters Study Steering Committee. South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/0208-18, Adelaide.
- Ralph, P.J., Tomasko, D., Moore, K., Seddon, S., and Macinnis-Ng, C.M.O. (2006). Human impacts on seagrasses: Eutrophication, sedimentation, and contamination. In: Larkum, A.W.D., Orth, R.J., and Duarte, C.M. (eds), *Seagrasses: Biology, Ecology and Conservation*, Springer, Dordrecht, Netherlands, pp. 567-593.
- Romero, J., Lee, K.S., Pérez, M., Mateo, M.A., Alcoverro, T. (2006). Nutrient dynamics in seagrass ecosystems. In: Larkum, A.W.D., Orth, R.J., and Duarte, C.M. (eds), *Seagrasses: Biology, Ecology and Conservation*, Springer, Dordrecht, Netherlands, pp. 227-254.
- Webster, I. and Harris, G.P. (2004). Anthropogenic impacts on the ecosystems of coastal lagoons: modelling fundamental biogeochemical processes and management implications. *Marine and Freshwater Research* 55, 67-78.

Glossary

Acute: Severe and short lived

Aerobic: Presence of free oxygen in a chemical process

Algae: Large group of non-flowering plants, many microscopic, generally containing chlorophyll. Most algae are aquatic

Algal bloom: Microalgae occurring in dense numbers in a water body, as a result of favourable conditions (i.e. nutrient enrichment)

Ambient: The prevailing environmental situation. Sometimes called 'background'

Ammonia: Compound consisting of a single nitrogen atom coupled with three hydrogen atoms. It is a nitrogen source for algae

Ammonium: The positively charged cation formed when ammonia is neutralised. It is a nitrogen source for algae.

Anaerobic: A process conducted in the absence of free oxygen

Anthropogenic: Changes resulting from human activities

Anoxic: Devoid of oxygen

ANZECC: Australian and New Zealand Environment and Conservation Council

Bathymetry: Depth characteristics of a water body

Benthic: Belonging to the sea floor

Benthos: Organisms living on or in association with the sea floor

Bioaccumulation: Concentration of substances (especially toxicants) in the tissues of plants and animals

Biochemical: Chemical reactions occurring in living organisms

Biodiversity: Measure of the number of species inhabiting a given area

Biomass: The living weight of animal or plant populations or communities

Biota: All living organisms of a region

BP: Before present

Catchment: The area of land from which runoff from rain enters a waterway

Chlorophyll: Green pigments of plants, which capture and use energy from the sun to drive the photosynthesis process

Chronic: Over a long portion of the organism's life span. Less severe and generally over a longer time span than 'acute'

Conductivity: Electrical conductivity - the capacity of water to conduct electrical current; used to measure level of salinity

Denitrification: Conversion of bound nitrogen to elemental (gaseous) form

Density current: Movement of lighter (less dense) water over denser water

Detection limit: Minimum level of quantification for a particular analytical method

Diffusivity: A measure of the rate at which properties mix or spread out in all three dimensions

Ecology: The relationship of living things to their environment

Ecosystem: A community of plants or animals or both

Eddy: A rotating or whirling movement of air or water

Effluent: An outflow, usually sewage or wastewater

Eutrophic: Having an unnaturally high content of algae due to excess nutrients

Eutrophication: leading to a eutrophic condition

Fauna: All kinds of animals

Flora: All kinds of plants

Flushing: The rate at which a lake or bay changes its water content

Flux: Flow of material

Geochemical: Relating to earth chemistry

Geology: The study of earth processes

Geomorphology: The study of land forms

Groundwater: That part of rainfall which seeps into the ground and moves slowly in a horizontal direction

Gyre: A large eddy

Guideline values: Values (often concentrations) thought to represent safe conditions and chosen as a result of available research

Habitat: The place where a plant or animal lives

Heavy metals: A general term for cadmium, chromium, copper, iron, mercury, nickel, manganese, lead, zinc, arsenic, and selenium

Hydrocarbons: Compounds of hydrogen and carbon such as petroleum

Hydrodynamic: Related to movement of water

Indicator species: Animals or plants which indicate an effect or impact. e.g. pollution or loss of habitat

Infauna: Fauna that lives within benthic sediment

Inputs: Substances entering a water-body

Macroalgae: Large algae, in this report used to describe kelps and larger seaweeds

Mesotrophic: Water body that has moderate nutrient and algal levels.

Meteorology: The study of climate and weather

Microalgae: Single-celled plants. Less than 1/10th millimetre in length or diameter

Model: Mathematical equation or series of equations that provides simplified description of system or situation devised to facilitate calculations or predictions. With use of a computer, can provide simulation of large-scale environmental processes, e.g. hydrodynamic model

Monitoring: Continuous measurement

Nitrate: The NO_3 anion

Nitrification: Formation of nitrate from reduced forms of nitrogen

Nitrite: The NO_2 anion

Nutrients: Substances (e.g. nitrogen and phosphorus in various forms) required for the growth of plants (like fertiliser)

Oceanography: The study of oceans

Oligotrophic: Water body that has low nutrient and algal levels

Organism: A living entity of any size, plant or animal

Organochlorines: Complex organic molecules with chlorine atoms attached (e.g. many pesticides)

Organophosphates: Group of pesticides chemicals containing phosphorus, which are intended to kill insects

Oxic: Having oxygen present

PAHs: Polycyclic aromatic hydrocarbons. A class of organic chemical compounds many of which are known or suspected carcinogens

PAR: Photosynthetically active radiation. The spectrum of light required by plants for photosynthesis

Particulates: Particles suspended in water

PCB: Polychlorinated biphenyls - a class of organic compounds used as cooling and insulating fluids. Banned in the 1970s due to high toxicity

pH: The negative logarithm of the hydrogen ion concentration; an index of acidity or alkalinity

Photosynthesis: Transformation of carbon dioxide and water to organic matter and oxygen by means of light energy

Phytoplankton: Microalgae that live in the water column

Plume: In oceanography a term applied to a recognisable outflow into a receiving water body (e.g. Torrens River plume)

Pollutant: A substance in excess or not belonging

POPs: Persistent organic pollutants. Toxic chemicals (e.g. PCBs) that persist in the environment and animals. POPs pose a risk of causing adverse effects to human health and the environment

Receiving waters: Waters that receive effluent from a particular source

Residence time: The nominal time spent by a substance in a water body subject to tidal exchange or river flushing

Salinity: The salt content of seawater

Seagrass: A group of flowering plants which live rooted in the sea floor

Sediment: Any solid material which sinks to the bottom

Sewage: Strictly speaking household waste but loosely applied to any waste sent to treatment plant

Stormwater: Runoff during storms

Stratification: Layering, usually due to temperature or salinity differences

Substrate: A surface on which organisms live or a substance serving a biochemical reaction

Suspended matter: See particulates

Suspended solids: See particulates

Terrestrial: Of the land

Tides: The movements of water in the ocean in response to gravitational pull of the moon and sun. As the earth turns the tides perform a daily cycle. Because the moon revolves around the earth the tides also undergo a lunar monthly cycle. The revolving of the earth around the sun imposes an annual cycle. All show up as high and low water levels

Topography: Mapping of land features

Toxic: Poisonous

Toxicant: A poison

Toxicity: Level or concentration of toxicant to create a toxic response

Turbidity: Cloudiness

Wastewater: Water that has been used and discarded. Not strictly the same as sewage

Wastewater Treatment Plant (WWTP): A place where human and industrial wastes are treated before disposal to land or water:

- **Primary treatment:** Screening the solids from the water and allowing organic matter and suspended solids to settle. This treatment typically removes one-third of the BOD and two-thirds of suspended solids

- **Secondary treatment:** Achieves stabilisation of biodegradable material through biological degradation. This treatment typically removes 85-90% of the BOD

- **Tertiary treatment:** Typically removes nutrients (nitrogen and phosphorus) and the remaining small volume of organic matter and organisms



The Adelaide Coastal Waters Study is an initiative of the South Australian Government and involved a number of Stakeholders from Government agencies, industry, and community groups. Its primary focus was on knowledge generation to improve our understanding of key coastal ecosystem processes to better inform sustainable management of Adelaide's coastal marine environment. The research phase of the study was undertaken between 2003 and 2006 and involved research teams and individuals from South Australia and other state universities, research organisations, and private consultants. The study was managed by CSIRO's Environmental Project Office.