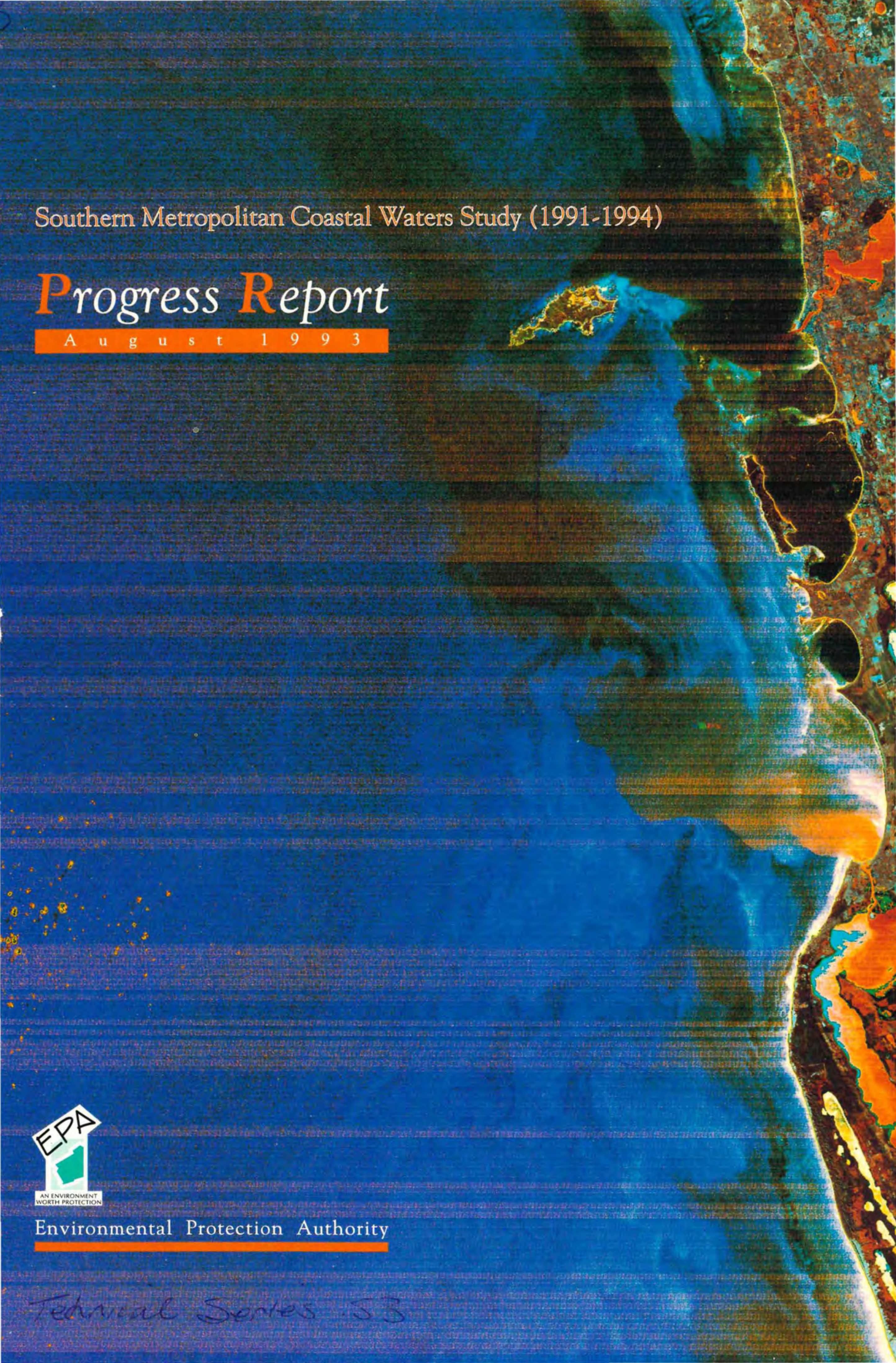

Southern Metropolitan Coastal Waters Study (1991-1994)

Progress Report

August 1993

Environmental Protection Authority

Technical Series 53

Southern Metropolitan Coastal Waters Study (1991-1994)

Progress Report
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C. J. Simpson, J. S. Burt, J. L. Cary, N. D'Adamo, R. J. Masini, D. A. Mills

Technical Series 53
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Front cover —
Landsat Thematic Mapper colour image of the waters off Perth recorded from an altitude of 720 km 0930, 14 August 1991 showing outflows of the Swan-Canning and Peel-Harvey estuaries.

Back cover —
Landsat Thematic Mapper pseudo colour image of the waters off Perth recorded from an altitude of 720 km 0930, 14 August 1991 showing the warm Leeuwin Current (pink) and the cooler inshore waters (blue-green).

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Errata

In the Table of Contents the title of the paper referenced to Page 15 should read:

Deeley, D.M.; Parsons, G.W. and Donohue, R.B. - Water quality monitoring in the Swan-Canning catchment: Interim Results.

In the same paper the data for Susannah Brook in Table 3.6 should be:

Discharge	NH_4-N	NO_3-N	TN	SRP	TP
2386	0.11	1.05	2.11	0.05	0.16

The attached Figures 1.1 and 1.2 were not supplied with the original document.

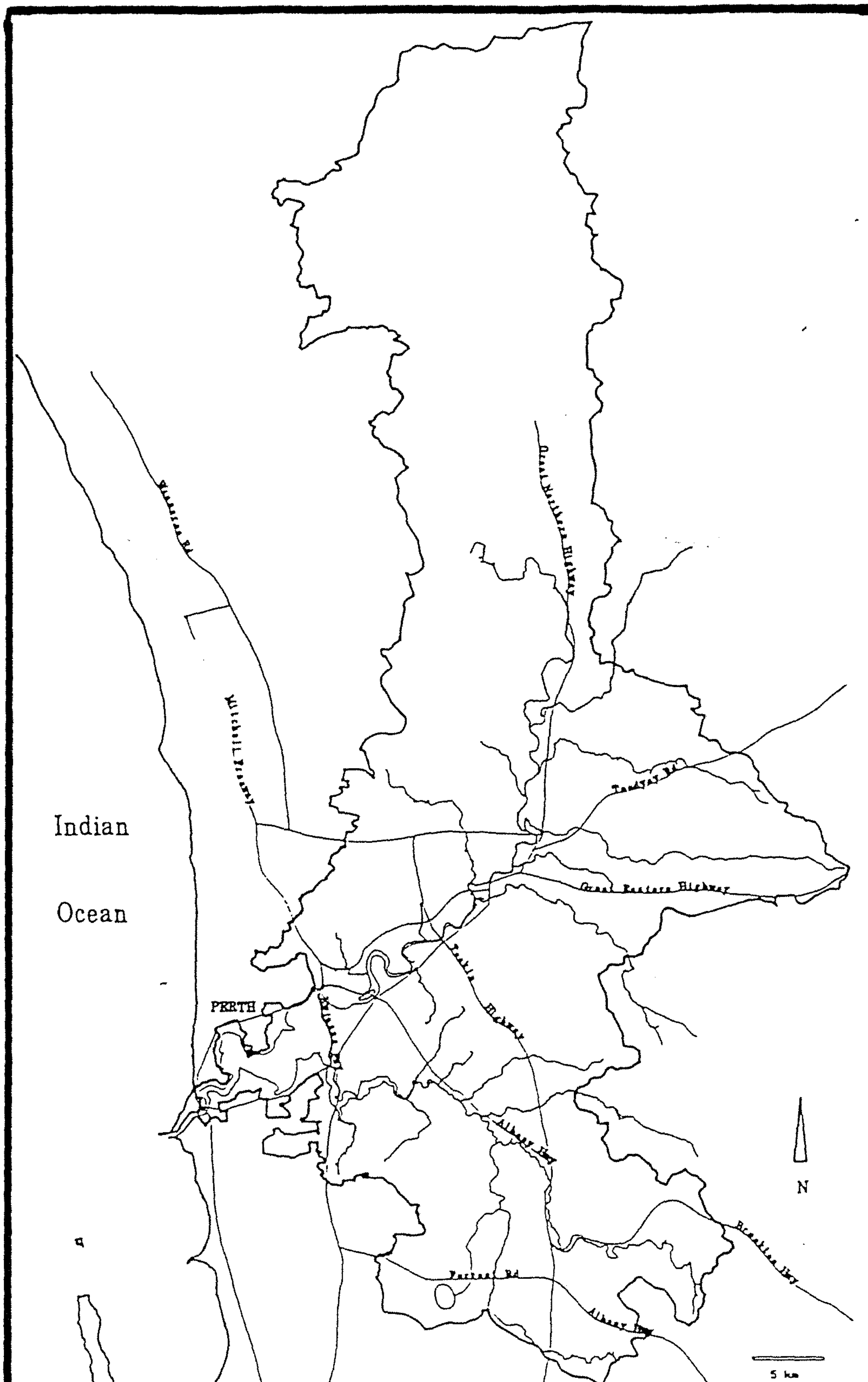

FIGURE 1.1: Location of the Swan-Canning catchment

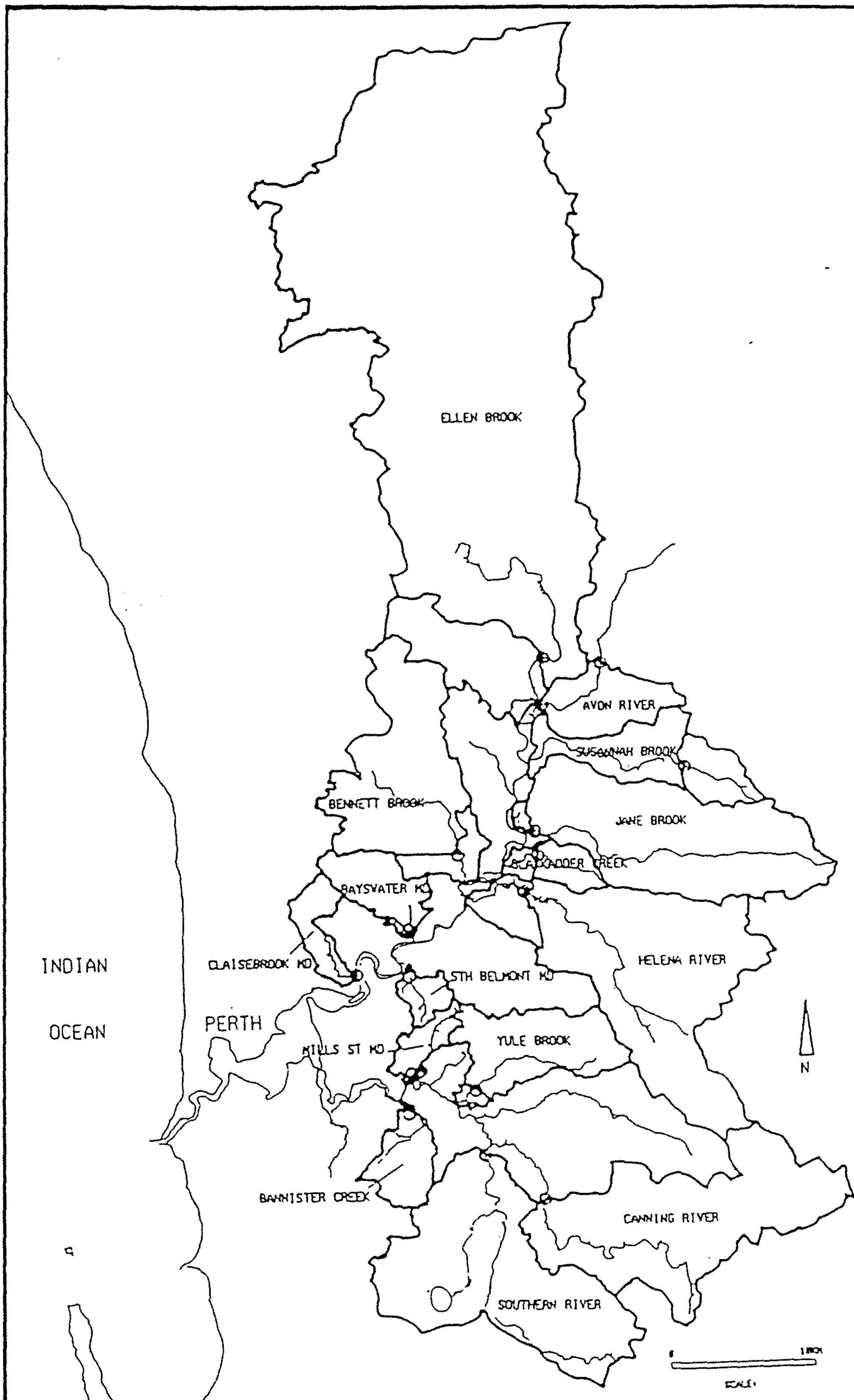

FIGURE 1.2: Location of the 15 monitored sub-catchments in the Swan-Canning system.

PREFACE

The Environmental Protection Authority of Western Australia (EPA) is responsible for protecting the environment of Western Australia. This is achieved, in part, by setting limits on industrial and domestic waste discharges to land, air and water. As industrial and urban expansion continues to the north and south of Perth, the total amount of waste generated will rise. If total cumulative loads of waste discharged to the environment increase unchecked, unacceptable environmental changes inevitably occur. Wastewaters are a significant proportion of the total waste produced and ultimately much of this enters the marine environment through either direct discharges, surface runoff, river outflow and inputs of contaminated groundwater.

The Southern Metropolitan Coastal Waters Study (SMCWS) is being undertaken by the EPA with the objective of developing a comprehensive environmental management strategy for these waters. A complementary study, in the northern and wider coastal waters off metropolitan Perth, is being co-ordinated by the Water Authority of Western Australia (WAWA) in collaboration with the EPA. Due for completion in December 1994, these studies will provide the information necessary to maintain the long-term health of these waters. This information, coupled with appropriate monitoring programmes, will help prevent a repetition of the problems that have occurred all too often in the marine environments of many of the major coastal cities of the world.

This document provides an outline of the objectives, rationale and progress to date of the Southern Metropolitan Coastal Waters Study.

ACKNOWLEDGEMENTS

The Environmental Protection Authority gratefully acknowledges the contribution of numerous State and Federal government agencies, tertiary institutions and private organisations that have provided, and continue to provide, resources in the form of staff, boats and equipment. The assistance of numerous individuals who volunteered their time and expertise is also gratefully acknowledged. Without this level of cooperation and assistance a study of this magnitude would not be possible. Special thanks to Mike Lapwood.

Contributors include —

- Australian Defence Force Academy (Department of Geography and Oceanography)
- Australian Surveying and Land Information Group
- Bureau of Meteorology
- Century Batteries
- Chemistry Centre of Western Australia (Environmental Chemistry Laboratory)
- CSIRO (Divisions of Fisheries, Oceanography and Advanced Analytical Chemistry)
- Curtin University of Technology (Departments of Biology and Chemistry)
- Department of Conservation and Land Management
- Department of Fisheries
- Department of Land Administration (Remote Sensing Applications Centre)
- Department of Marine and Harbours
- Department of Sport and Recreation
- Fremantle Port Authority
- Geological Survey of Western Australia (Hydrogeology Section)
- Kwinana Industries Council
- Melbourne Board of Works
- Murdoch University (Environmental Science, Nutrient Analysis Laboratory)
- Perth Radio
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- Swan River Trust
- The University of New South Wales (Departments of Mathematics and Water Engineering)
- The University of Western Australia (Departments of Botany, Zoology, Geography and the Centre for Water Research)
- Water Authority of Western Australia
- Waterways Commission
- Western Australian Museum (Division of Natural and Social Sciences)
- Western Australia Police Department (Water Police Branch)

CONTENTS

EXECUTIVE SUMMARY

Perth's population is predicted to increase from about one to two million people over the next 30 years. This increase will result in significant industrial and urban expansion in the metropolitan area with much of this development planned to occur along the coastal strip to the north and south of Perth. This growth inevitably will generate more waste which will require treatment and disposal. If current practices remain, much of this waste will ultimately enter the sensitive nearshore marine environment of Perth. At the same time, these waters will be the focus of increasing recreational activity and marine-based industries such as mussel farming. As the demand for the use of these waters increases, so too does the need to provide sound environmental management to prevent the problems that have occurred in the marine environment of many coastal cities around the world.

In April 1991, the Ministers for the Environment and Water Resources launched studies into the cumulative impacts of waste inputs to Perth's coastal waters. The Southern Metropolitan Coastal Waters Study (SMCWS) is currently being undertaken by the EPA with the objective of developing a comprehensive environmental management strategy for these waters. A complementary study, in the northern and wider coastal waters off metropolitan Perth, is being co-ordinated by the Water Authority of Western Australia, in collaboration with the EPA. Due for completion in December 1994, these studies will provide the information necessary to maintain the long-term health of Perth's metropolitan coastal waters. This document outlines the progress of the SMCWS.

Waste discharges to the marine environment are regulated under the Environmental Protection Act (1986), and the impact of waste inputs, in relation to the loss of key habitats and the effects of toxic materials on marine communities, is a central focus of the SMCWS. A modelling approach will help determine critical loads (with appropriate error terms) for nutrient inputs to these waters and, coupled with monitoring programmes, will be used to prevent loss of key habitats as a result of eutrophication. Inventory and baseline studies combined with water quality criteria, based on ecotoxicological testing, will be utilised in the SMCWS to minimise the effects of toxic materials on marine flora and fauna.

Inventory and baseline studies are being undertaken to provide a quantitative description of the physical, chemical and biological environment of the study area. The marine biological resources of the study area are being mapped and an accurate map of the main habitats is being constructed for modelling purposes. Information on recreational and commercial usage of these waters is being compiled. The last comprehensive survey of recreational usage of this area was in 1978. An inventory of past, present and future inputs of contaminants to these waters has been completed. The input of heavy metals and nutrients into Cockburn Sound has decreased markedly over the past decade. Discharge from industrial point sources has decreased significantly since the late 1970s, and groundwater inputs will contribute a significant proportion of the total contaminant load to Cockburn Sound in the future. Heavy metal and nutrient loads to Sepia Depression are projected to double over the next 30 years, if current domestic wastewater treatment and disposal methods continue.

Heavy metal and hydrocarbon contamination of sediments and mussels is considerably lower than during the late 1970s, reflecting the reductions in the discharge of these materials to the waters of Cockburn Sound and Owen Anchorage. Pesticide contamination of sediments and mussels was extremely low throughout the study area. In contrast, tributyl tin contamination was widespread and, considering the toxicity of this substance to some marine animals, is cause for concern.

Preliminary results from the physical oceanography programme indicate that the waters of Cockburn Sound are stratified for much of the time making density currents an important transport mechanism in these waters and highlighting the importance of including baroclinic processes in the hydrodynamic models. Net longshore transport in the offshore waters can be severely restricted under some conditions underlining the importance of understanding cross-shelf exchange processes. Satellite imagery and nutrient surveys over the study area indicate that the outflows from the Peel-Harvey and Swan-Canning estuaries have a significant widespread effect on the water quality of Perth's coastal waters in winter. Nitrate concentrations were 5-10 times higher in winter than summer as a result of these influences. During the winter of 1991, silicoflagellates dominated the phytoplankton populations in these waters. Species of this group are usually less than 10% of the total species present in marine phytoplankton populations.

A preliminary ecological model has been developed in collaboration with the WAWA. The model is being refined and studies are underway to provide the necessary information for the various relationships in the model.

INTRODUCTION

The protected coastal waters off the southern metropolitan coastline of Perth are utilised intensively for industrial, commercial and recreational purposes. Over the past 40 years, wastes have been routinely discharged into Cockburn Sound and, to a lesser extent, Owen Anchorage. During the 1960s and 1970s, extensive algal blooms occurred as a result of these discharges (DCE, 1979). These blooms, in turn, reduced light availability to the benthic plant communities resulting in a catastrophic loss of seagrasses in the Sound. The nutrients in these discharges, particularly nitrogen, were identified as the primary cause of the algal blooms. In addition, a range of heavy metals and other toxic substances in these discharges contaminated sediments and biota in some areas.

Following recommendations of the Cockburn Sound Environmental Study (DCE, 1979), the discharge of nutrients and toxic contaminants into these waters decreased substantially during the early to mid-1980s. Furthermore, a long-term monitoring programme was established to assess the ecosystem response to these management measures and included a 14-week survey of the water quality of Cockburn Sound and Owen Anchorage during summer every two to three years.

The first survey, in the summer of 1982/83, showed a significant improvement in water quality and a reduction in the rate of seagrass loss (Chiffings and McComb, 1983). The results of the next two surveys, in 1984/85 and 1986/87, indicated that this improvement had been maintained. During the 1989/90 survey, the water quality in Cockburn Sound was at levels approaching the late 1970s (Cary *et al.* 1991). This sharp decline coincided with a significant increase (over the previous survey) in nitrogen loading from the CSBP/KNC outfall, the major point source of nitrogen into these waters (Cary *et al.* 1991).

For these four surveys, a positive relationship was derived between mean nitrogen loading from this source and mean water quality (measured as chlorophyll *a*) in Cockburn Sound (Cary *et al.* 1991). This relationship suggests that, for mean chlorophyll *a* concentrations in summer to fall to the 1982/83 levels (i.e. 0.8 $\mu g\ l^{-1}$), total nitrogen loadings from this source should be less than about 600 kg d^{-1}, approximately the mean loading during the 1982/83 survey (Chiffings and McComb, 1983). It is, perhaps, significant that the best water quality recorded in Cockburn Sound since the mid-1970s, followed a year when nitrogen loading from this source was the lowest measured, and averaged about 250 kg d^{-1} (Martinick *et al.* 1993).

Nitrogen loading into Cockburn Sound from the CSBP/KNC outfall is now significantly lower than in 1989/90 (Martinick *et al.* 1993). Surveys by CSBP Pty Ltd in 1990/91 and 1991/92 indicate that the interannual variation in water quality in Cockburn Sound is now greater than in the past (S. Fitzpatrick, personal communication) suggesting that other factors are becoming more important as nutrient loads from industrial point sources decrease.

The results of the monitoring programmes, and the 'sudden' loss of seagrass meadows on east Parmelia Bank in the early 1980s, demonstrate the inherent biological instability of marine ecosystems that have a history of environmental disturbance and underline the importance of gaining a better understanding of the cumulative environmental impacts of waste (particularly nutrients) inputs into the shallow, temperate coastal waters of Western Australia. In recognition of this situation, the Department of Conservation and Environment (now the EPA) provided funding to the University of Western Australia between 1986 and 1989 for a post-graduate study of the nutrient dynamics of Perth's coastal waters (Paling, 1991). This study provides a good basis for the studies now being undertaken in the metropolitan coastal waters by the EPA and the WAWA.

With the projected doubling of Perth's population, from about one to two million, over the next 30 years, and with over 95% of domestic wastewaters currently being discharged into the coastal marine environment of Perth, the need for a better understanding has never been more urgent. Furthermore, with new industrial and urban developments planned for this area, waste inputs to these waters may increase.

The sheltered waters of Cockburn Sound and Warnbro Sound are the focus of recreational activities in this area and with the rapid spread of urban development in the southern metropolitan area, these activities are likely to increase. These waters are also being used increasingly for commercial activities such as mussel farming. As the demand for use of these waters increases, so also does the need for sound environmental management.

The outcomes of the Southern Metropolitan Coastal Waters Study (1991-1994) will provide the basis for an integrated approach to the long-term management of these waters.

1.1 Study objectives

The overall goal of the *The Southern Metropolitan Coastal Waters Study (1991-1994)* is to develop an understanding of the environmental consequences of the cumulative impacts of waste discharges to these waters and to use this information to develop a comprehensive environmental management strategy consistent with maintaining the long-term health of the marine environment of the southern metropolitan coastal waters of Perth.

The broad objectives of the SMCWS are —

- quantify current and predicted future contaminant inputs;
- determine the current status of the environment;
- establish a baseline for the detection of future environmental changes;

- predict the movement of water-borne contaminants;
- develop computer-based ecosystem simulation models to predict the environmental consequences of future nutrient input scenarios; and
- develop ecological environmental quality objectives for these waters.

Scope

The study area includes the waters of Cockburn Sound, Shoalwater Bay, Warnbro Sound, Owen Anchorage, Gage Roads and Sepia Depression. Some aspects of the study will include the waters of Rottnest Island and Comet Bay, between Warnbro Sound and Mandurah (Figure 1).

Duration

The SMCWS was launched on 18 April 1991 with the final report scheduled to be presented to the Environmental Protection Authority by 31 December 1994.

Co-ordination

The SMCWS is being co-ordinated by the Marine Impacts Branch of the Environmental Protection Authority.

1.2 Study approach

Marine ecosystems are affected by human activities as a result of the impacts associated with development (e.g. marinas), exploitation of natural resources (e.g. fishing, mining) and waste inputs (e.g. eutrophication, toxicity). In Western Australia, direct impacts such as marina development and mining are managed through the environmental impact assessment process under the Environmental Protection (EP) Act (1986). Fish and marine wildlife are managed under other statutes and, as such, are not considered in the SMCWS. Waste discharges to the marine environment are regulated under the EP Act, and the impact of waste inputs, in relation to the loss of key habitats and the effects of toxic substances on marine communities, is a central focus of the SMCWS. This emphasis, therefore, complements existing sectional marine management frameworks in the metropolitan coastal waters of Perth.

A modelling approach will determine critical loads (with appropriate error terms) for nutrient inputs to these waters and, coupled with monitoring programmes, will be used to prevent loss of key habitats as a result of eutrophication. Inventory and baseline studies coupled with water quality criteria, based on ecotoxicological testing, will be utilised in the SMCWS to minimise the effects of toxic materials on local flora and fauna.

In relation to managing waste discharges to the environment of Western Australia, the EPA has adopted the philosophical position that the environment has some capacity, albeit limited, to 'assimilate' some types and amounts of waste without unacceptable changes occurring in the long-term (EPA, 1989; Masini *et al.* 1991). This approach acknowledges that, even with the best recycling and reuse programmes, some waste will inevitably be produced and require disposal. It also acknowledges that the receiving environment does not absorb waste without change, but that some changes will occur no matter how small the input. Consequently this approach is centred around determining the environmental quality objectives (EQOs), both ecological and cultural, and establishing the linkages between human activity and changes to these objectives.

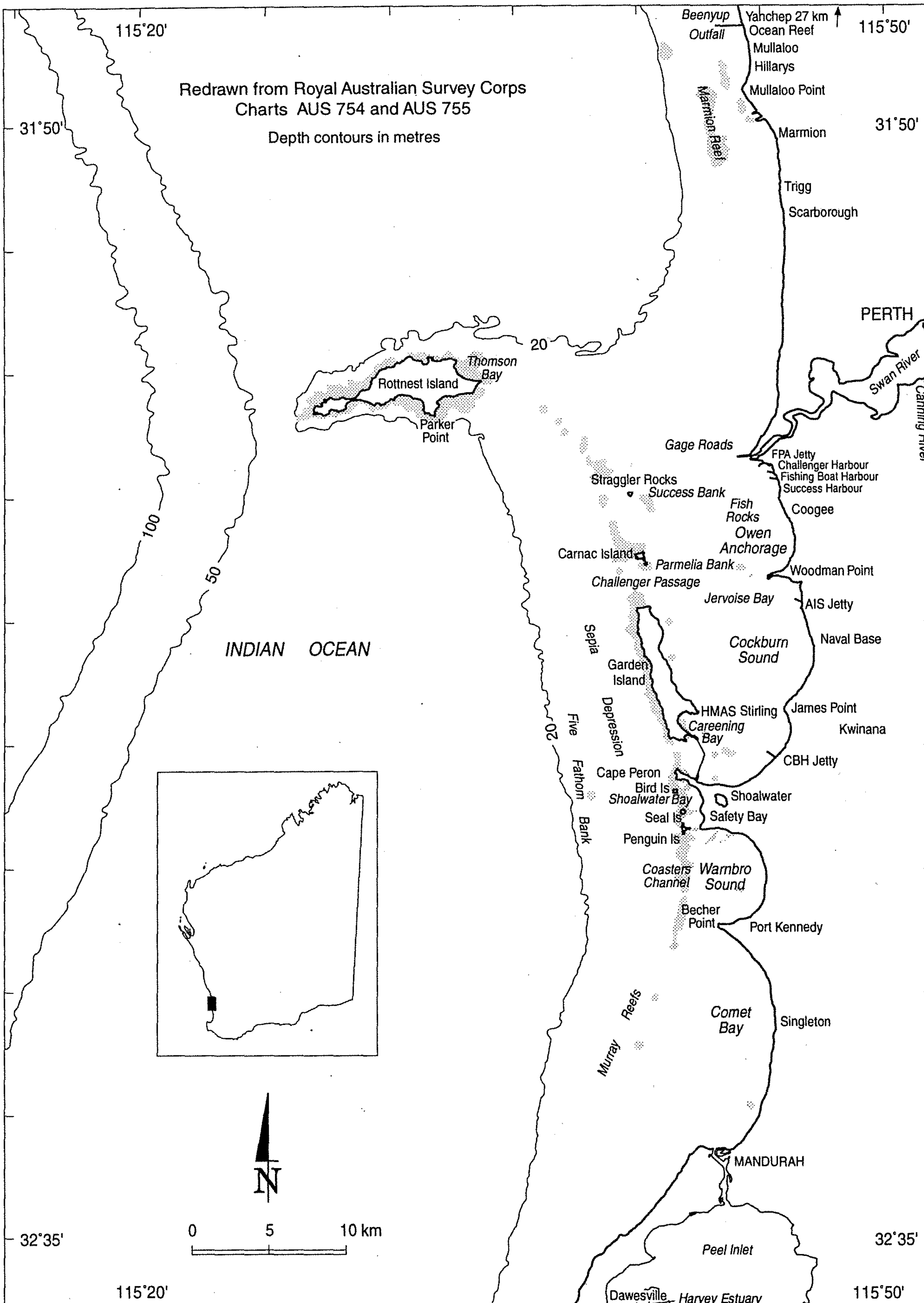
The 'ecological' EQOs must conform to the principles of *ecological sustainability* (i.e. maintenance of biodiversity and ecosystem structure and function) and, as such, are 'non-negotiable' and scientifically determined. Similarly, the 'cultural' EQOs must conform to the principles of *cultural sustainability* (i.e. maintenance of community aspirations) and, by definition, are 'negotiable' and culturally determined. Cultural EQOs are derived from a balance of existing and future community uses and are confined to the range between 'the natural state' (or zero impacts) and the point just before the principles of ecological sustainability start to be affected. Specific environmental quality criteria will provide the technical expressions of these objectives.

The main contaminants entering Perth's coastal waters, now and in the future, can be separated into two broad groups: toxic materials and nutrients. The inherent difficulties in achieving reliable results from analysing trace toxic contaminants in seawater, coupled with the fact that their concentrations are transient, both temporally and spatially, and the generally high cost of trace analyses severely limit the use of seawater for monitoring contaminant trends. On the other hand, sediments and some organisms (particularly filter feeders such as mussels), are generally good integrators of contaminant concentrations in water, and are easier to analyse for trace levels. The latter approach has been adopted in this study for all contaminants other than nutrients.

Using the concentrations of nutrients in water to establish trends can be misleading. For example, discharges of nutrients may be quickly taken up by plankton or macroalgae, and thus seen as increased biological production, not as higher concentrations in water. To assess the long-term impacts of future nutrient loadings to these waters a modelling approach has been adopted. The modelling will simulate the key physical and biological processes that are relevant to determining the effects of nutrient enrichment on these ecosystems. This approach will provide the predictive capacity necessary for long-term planning and, coupled with appropriate monitoring programmes, will protect key habitats from the effects of eutrophication.

Any model which attempts to accurately describe the functioning of an entire ecosystem will be extremely complex. The most ecologically important components of the system susceptible to nutrient enrichment, must be identified in order to simplify the

Figure 1 —
Location map of the study area

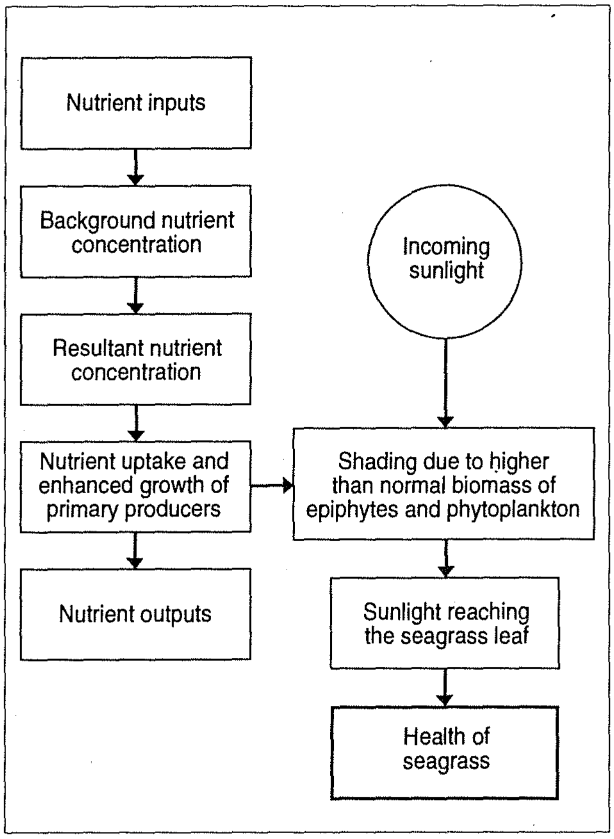


model and provide appropriate indicators of ecosystem response. The pathways of cause and effect must be identified so that investigations can 'target' the relevant processes which, in most cases, are likely to be ecosystem or even habitat specific.

Posidonia seagrass communities are the dominant primary producer in the more protected waters of the temperate coastal ecosystems of Western Australia. These meadows provide food, habitat and nursery areas for many marine animals and stabilise sediments against wave action. As such, these communities are ecologically important. The historical environmental problems in Cockburn Sound in the 1970s, and the Albany Harbours in the 1980s (Simpson & Masini, 1990), indicate that *Posidonia* seagrass communities are highly susceptible to the effects of nutrient enrichment. In both areas, widespread loss of seagrass meadows occurred as a result of prolonged light shading caused by excessive algal growth stimulated by high nutrient inputs. Furthermore, the loss of *Posidonia* seagrass meadows is now considered to be essentially 'irreversible' (Kirkman, 1989). Thus, seagrass communities have been identified as the key component of the coastal ecosystems off Perth due to their ecological importance, high susceptibility to the effects of nutrient enrichment and the 'irreversible' nature of these effects.

The general pathways of cause (i.e. nutrient loading) and effect (i.e. seagrass death) is outlined in Figure 2. These linkages are the focus of the ecological modelling of the SMCWS.

Figure 2 —
Simple conceptual nutrient effects ecological model for temperate seagrass-based ecosystems



1.3 Relationship to WAWA study

In 1990, the EPA assessed a proposal from the Water Authority of Western Australia (WAWA) to construct and operate a second wastewater ocean outlet into the waters of Marmion Marine Park (EPA, 1990). The environmental impact assessment concluded that the proposal was environmentally acceptable provided the nutrient loadings from both outfalls did not exceed the maximum loads set for the original single outfall. This decision was based on the conclusion that the short and long-term impacts of increased nutrient loading to these waters could not be predicted with adequate certainty. The EPA also indicated that in the event of the WAWA submitting further proposals to increase nutrient loads to the coastal waters of Perth in the future, it would be necessary for the environmental impacts to be better understood.

As a result, the WAWA is currently undertaking a series of studies (*Perth Coastal Waters Study*) focussing on the environmental effects of municipal wastewater discharges to the marine environment. These studies will provide the information required to quantitatively assess short and long-term cumulative environmental impacts of existing and proposed wastewater outfalls into the coastal waters off Perth. Companion studies are considering alternatives to ocean discharge. Together these studies will determine the environmental and economic 'costs' of different disposal options, thereby providing the information base necessary for planning the disposal of Perth's domestic wastewater into the 21st century.

Specifically, these studies will examine the 'local' effects of the existing Beenyup outfalls at Ocean Reef on the biological communities of the Marmion Marine Park and adjacent waters and will involve determining the short and long-term effects of nutrient and toxic contaminant loadings. A second 'regional' study will determine the short and long-term effects of chronic wastewater discharges from all existing and proposed (to the year 2040) outfalls on the wider metropolitan coastal waters off Perth (nominally Mandurah to Yanchep).

The WAWA studies overlap with the SMCWS, both technically and geographically and, as a result, a high level of collaboration exists between the EPA and WAWA. The biological communities of the northern and southern metropolitan coastal waters are similar and, consequently, the biological component of the nutrient-effects ecological model is being developed jointly. Although the geographical separation and different geomorphology of the two local study areas require that the hydrodynamic components of the ecological model be developed independently, a significant level of collaboration exists in the shelf-scale oceanography programmes.

The integration of the EPA and WAWA studies, at their conclusion, will provide a comprehensive information base on which to plan the long-term management of Perth's metropolitan coastal waters.

REVIEWS

This section summarises various reviews of relevant information that were undertaken at the beginning of the study to ensure that the results of past studies were considered when planning further studies for the SMCWS.

2.1 Bibliography

A bibliography of environmental studies of the southern metropolitan coastal waters of Perth was compiled. The bibliography includes approximately 900 scientific papers and technical reports relevant to the SMCWS. The range of subjects include physical oceanography, coastal processes, marine biology and ecology, environmental impact assessments, management of the coastal strip and islands, socio-economic issues and the natural history of the area. The information in the bibliography has been stored electronically.

Source document —
Cary and Ryall (1991).

2.2 Community attitudes

An assessment of community attitudes was made to determine the level of community understanding of the environmental issues in the study area and to identify areas of public concern. Although this assessment was based on the results of two surveys that had been conducted several years before the beginning of the study, the results were considered to be broadly representative of community attitudes in 1991. The results determined, in part, the direction of the SMCWS's community awareness and environmental education programmes. A more recent attitudinal survey (Dames and Moore, 1993) was undertaken for the Kwinana Industries Coordinating Committee in February 1993. The results of this survey are not available. A brief summary of the two earlier surveys is outlined below.

A survey entitled *Public Attitudinal Survey - Perth Metropolitan Coastal Development* was undertaken in 1987 by the Centre for Urban Research at the University of Western Australia for the then State Planning Commission (Fenton and Syme, 1987). Although the study area extended from Yanchep in the north, to Singleton in the south, much of the information is extremely relevant to the objectives of this component of the SMCWS. A second survey entitled *The Kwinana Regional Strategy: Public Attitudinal Survey* was undertaken in 1988 by the CSIRO and funded by the Department of Resources Development and the Kwinana Industries Coordinating Committee (Syme and Nancarrow, 1988).

The *Public Attitudinal Survey - Perth Metropolitan Coastal Development* examined the attitudes of residents of the Perth metropolitan region to present and possible future coastal development. The metropolitan region was divided into three coastal areas: northern, central and southern, and an inland region. A total of 509 people were interviewed. The survey was structured to determine attitudes towards the entire metropolitan coast, towards specific coastal areas (e.g. Fremantle and Rockingham) and to identify criteria the public consider important in planning for specific types of coastal developments. Information of relevance to the southern metropolitan coastal region is presented below.

Fremantle was considered to be the most familiar coastal location in the metropolitan area. The two most common activities were swimming and sightseeing. Woodman Point was also considered a good location for fishing and boating. Rockingham was regarded as an attractive area whereas the coast between Coogee and Kwinana was regarded as the most unattractive locality, particularly the Naval Base/Kwinana area. Fremantle and Rockingham were identified as important places of interest for visitors. Ninety per cent of respondents believed that the remaining undeveloped coastal region of Perth should be preserved and protected, particularly the Rockingham area. Three quarters of those surveyed indicated that there should be no further industrial development along the coast, and if there was a need for industrial development then this should be located in close proximity to where it already exists, that is between Fremantle and Rockingham.

Fremantle area: Three-quarters of the people surveyed in this area indicated that the Fremantle node needed protection and preservation, with the majority also indicating a preference for no further industrial development.

Rockingham area: Most respondents were familiar with the Rockingham coastal region. The coast was seen as attractive and clearly in need of protection and preservation. A clear majority indicated a preference for no further industrial development in the region.

Control of pollution and the needs, views and requirements of people were the most important criteria respondents considered planners should take into account when developing industry on the coast.

The *Kwinana Regional Strategy: Public Attitudinal Survey* interviewed 454 people in the Cockburn, Kwinana and Rockingham areas. More than half of the respondents had lived in the region for more than 10 years and half the sample either worked or had a family member who worked in heavy industry. The questionnaire was developed to ensure that the 'positive' aspects of industrial development and community facilities in the region were considered as well as the 'negative' aspects.

Industry

Half those interviewed considered the relationship between industry and the community to be good and 82% rated industry's concern for the welfare of the community from moderate through to excellent. Employment was seen as the major advantage of industry in the region, both in the past and in the future, though less so in the future. Pollution was seen as the major disadvantage of industry, both past and future, though slightly more so in the future. The majority of the sample agreed with continued industrial development provided that the benefits continued to accrue. However this attitude was contingent on further development not causing pollution. Current pollution levels were seen as a moderately high risk to family well-being. Issues related to lifestyle were seen as the major benefits of living in the region. Current and future major industry based in the region were seen only as immediate benefits. The major hazards in the region were seen to be pollution and the transportation of fuel and toxic substances. The majority considered the benefits of living in Kwinana outweighed these risks.

HMAS Stirling Development
Respondents viewed this development as a moderate hazard. The docking of foreign military ships was seen as the fifth highest risk to human well-being in the area.

Cockburn Sound
The natural environment was considered to provide a significant recreational resource for the local residents with 64% being interested in the coast and Cockburn Sound. Ninety-five per cent rated the preservation of Cockburn Sound as important. The major activities along the coast were swimming (78%), fishing (67%), walking (50%), picnicking (46%), canoeing & boating (31%) and watersports (24%). Present levels of pollution in Cockburn Sound were considered to be the third major risk to human well-being in the area. Forty per cent of respondents considered that Cockburn Sound was not being well managed. When asked in what ways could it be better managed, 21% said to control waste discharges to the Sound, 17% said to stop the pollution and 62% didn't know.

Groundwater
Seventy-six per cent of respondents thought that urban or industrial development has a harmful effect on groundwater quality. Of those that believed that development was harmful, 60% did not think that the government was adequately controlling these impacts.

Comparisons between Kwinana, Rockingham and Cockburn
The perception of the area by people in the three municipalities had more similarities than differences. People from Kwinana acknowledged the benefits of industry more than people from Rockingham and Cockburn. This may be attributed to the fact that a higher proportion of respondents from Kwinana worked in the Kwinana industrial area. Respondents from all areas showed significant concern about issues relating to the risks of pollution to Cockburn Sound and to local groundwater resources.

2.3 Physical oceanography

At the beginning of the SMCWS, comprehensive reviews of past oceanographical and modelling studies of the coastal waters off southern metropolitan Perth were undertaken to identify gaps in existing knowledge (Hearn, 1991; D'Adamo, 1992). Further reviews have also been carried out by van Senden (1991) and Pattiaratchi & Imberger (1991) as part of the WAWA studies. A brief summary of existing knowledge of the shelf-scale and basin-scale oceanography pertinent to the SMCWS is presented below.

Shelf-scale

The continental margin off the coast of metropolitan Perth (Figure 1) has four major zones —

- a nearshore inner shelf zone of shallow (< 20 m) basins, lagoons and channels, partially enclosed by reefs and islands;
- a gently sloping mid-shelf, approximately 30 km wide, extending from the outer reefs to the 50 m isobath;
- a more inclined outer shelf, deepening from 50 m to 300 m over a distance of 30 km; and
- a continental slope.

Depth contours beyond the inner shelf are generally smooth and shore-parallel, except about Rottnest Island which extends across the mid-shelf, and a deep submarine canyon which cuts across the continental slope.

The Leeuwin Current is a poleward surface flow of warm, low salinity, tropical water which is driven along the edge of the western continental shelf of Australia by a regional gradient in sea level (e.g. Church *et al.* 1989, Smith *et al.* 1991). Significant interannual variations in the strength of the Leeuwin Current are thought to occur (Pearce and Phillips, 1988) in association with the Southern Oscillation, which is a major reversal of the atmospheric pressure fields in the Indian and Pacific oceans (Cane, 1983). Intra-annually, the Current deepens and intensifies in autumn and early winter when the opposing mean wind stress is least. Pearce and Church (1993) have shown that warm water from the Leeuwin Current is mixed shoreward across the shelf region off Perth, particularly during autumn, winter and spring. However, despite upwelling-favourable winds off Western Australia, upwelling of deep oceanic waters onto the continental shelf tends to be suppressed.

Satellite imagery (e.g. Pearce and Griffiths, 1991) and drifting buoy tracks (e.g. Cresswell and Golding, 1980) show the common occurrence of meso-scale undulations and meanders of the Leeuwin Current which become unstable and may grow offshore to amplitudes of order 200 km, before pinching off to form detached eddies. These warm-core meanders have strong anticyclonic circulation around their offshore frontal boundaries. A weaker northward recirculating flow, adjacent to the shelf, on the landward side of some meanders has also been documented (Pearce and Griffiths, 1991).

Perth has a Mediterranean climate with cool wet winters and hot dry summers, and the dynamics of the coastal waters show seasonal and interannual variations due to corresponding changes in wind and oceanic swell conditions, surface heating, rainfall, evaporation and buoyancy inputs from estuaries. In winter, weather systems passing over southwest Australia from the Indian Ocean consist of high pressure anticyclones, separated by cold fronts. Wind records from the study area show cycles, typically of 7-8 days, with episodic north-west to west winter gales associated with cold fronts, followed by longer periods of moderating and weak winds swinging through the south and the east with the passing of high pressure systems (Steedman and Craig, 1979; Breckling, 1989). In summer the belt of anticyclonic pressure cells has migrated south of the continent and produces an easterly airflow over the study area, normally modulated by a strong daily land/sea-breeze cycle; there are also occasional periods of many days in which the wind blows steadily from the east and northeast. Steedman and Craig (1979, 1983) conducted an analysis of seven years' wind data from Fremantle and classified the meso-scale and regional wind field patterns.

The nearshore currents (speeds of order 0.1 m s^{-1}) are primarily wind-driven, bathymetrically steered, and are subject to the effects of the earth's rotation. The long-shelf pressure gradient which drives the Leeuwin Current, also acts on shelf waters, its influence becoming more apparent under conditions of low wind stress or in deeper water. There has been very little information documented on the role of baroclinic processes on the shelf. In winter, nearshore current reversals occur typically at intervals of 3-4 days, in association with major wind shifts. The resultant monthly mean current vector magnitude, for the winter months, is of order of 0.01 m s^{-1} (Steedman and Associates, in Binnie and Partners, 1981). During periods of autumn calms, the flow is predominantly southward. In summer, with the onset of strong sea breezes from the south and southwest, the flow is predominantly northward.

The water level regime of south-western Australia has been summarised by Hearn (1991). The astronomical tides are mainly diurnal with an annual mean range of 0.5 m. Tidal currents are of order 0.01 m s^{-1}, and can only produce horizontal excursions of water of order 1 km. Low frequency oscillations in the coastal sea level are caused by barometric pressure, wind and oceanographic forcings. These factors together lead to water level changes up to 0.5 m over the spatial scale of the atmospheric pressure systems (1000 km) during time periods of order seven days. The corresponding scale of water movement along the shelf is estimated to be of order 10 km. Local forcings include the direct response of the sea level to barometric pressure variations and the forced water level adjustment to local wind stress (e.g. Harrison, 1983). Remote forcings, of meteorological or oceanographic origin, may involve the propagation of coastally-trapped waves, as suggested by Hamon (1966).

The major winter fluxes of freshwater to the area are derived from the Swan-Canning Estuary and the Peel-Harvey Estuary (Figure 1).

Basin-scale

The reviews of Hearn (1991) and D'Adamo (1992) identified the following factors to be fundamentally important to the general hydrodynamic behaviour of the nearshore basins —

- *Wind-stress* - the primary agent that mixes the water column vertically, sets up pressure gradients and drives currents within and between basins;
- *Vertical density stratification* - which stabilises the water column, provides resistance to vertical mixing by wind-stress or penetrative convection, and governs the level at which interchanging waters of differing density reside as they tend to gravitational equilibrium after horizontal density-driven exchange;
- *Horizontal density stratification* - which provides the background density field required for horizontal density-driven exchange;
- *Bathymetrical variation* - the water depth variations which lead to differential effects of heating, cooling and evaporation, and consequent horizontal density variation, both within basins and between the basins and adjacent waters; variable bathymetry also influences the distribution of downwind and return flows in wind-driven circulation;
- *Physical barriers* - such as islands, reefs and sills, which influence fetch lengths for winds, provide downstream barriers to currents driven by wind or other forcings, provide protection from regional currents and from the full force of oceanic sea and swell, and also lead to physical trapping of waters within semi-enclosed regions;
- *Regional forcings* - such as the long shelf pressure gradient which drives the Leeuwin Current and meteorologically forced low frequency oscillations of sea-level. These forcings can drive throughflows in the nearshore semi-enclosed regions, but the quantitative characteristics of their hydrodynamic effects required further investigation;
- *The earth's rotation* - most of the semi-enclosed basins are large enough and the coastal currents weak enough so that the influence of the earth's rotation (via the Coriolis force) will be significant; and
- *Tidal flows and wave pumping* - tidal flows are likely to have their greatest influence in bathymetric constrictions, such as over sills and through openings. Wave pumping can be important in constricted regions such as through channels, over sills and through gaps between islands and reefs, and could therefore be important to flushing of semi-enclosed lagoons and basins. These factors required further study.

The competing influence of hydrodynamic mechanisms controlled by either density stratification or wind stress was highlighted as a fundamental issue for the oceanographic studies of Cockburn Sound and surrounding waters. The presence of vertical and horizontal density stratification can significantly alter the manner in which wind drives vertical and horizontal transport in a semi-enclosed basin from that which would otherwise occur in a well-mixed system. Vertical density stratification, if strong enough, can shield bottom waters from the direct influence of the surface wind-stress or other vertical mixing mechanisms such as penetrative convection. The seabed can therefore be isolated from surface mixing influences by density interfaces and hence the exposure of benthic communities to pollutants will be influenced by the temporal and spatial characteristics of density stratification. This is of direct interest to the ecological questions being addressed in the SMCWS.

Past hydrodynamic models of Cockburn Sound (Commonwealth Department of Construction, 1977; Steedman and Craig, 1979) were two-dimensional and assumed that the basin was well-mixed and that its hydrodynamic behaviour was not influenced by density gradients. Steedman and Craig (1979) discussed the validity of this assumption and suggested that the system would be strongly influenced by density gradients when winds were less than about 5 m s^{-1}. A re-working of past data sets, and an analysis of more recent basin-scale salinity-temperature surveys, found that the deep basin in Cockburn Sound was appreciably stratified in density (vertically and horizontally) when winds were above 5 m s^{-1} (D'Adamo, 1992). The basin was found to be vertically well-mixed only when winds had been greater than about 10 m s^{-1} for more than about five hours, for example during strong sea-breezes in summer or storm events in winter. Winds above 10 m s^{-1} occur on average only about 10-15% of the time during the year (Steedman and Craig, 1979).

Data from surveys in the 1970s and 1980s (D'Adamo, 1992) suggest that horizontal stratification of salinity and temperature was common, with characteristic patches of isohaline or isothermal water having dimensions of order 1-5 km. However, the data resolution of those measurements was often insufficient to allow definitive interpretations relating to density structure (D'Adamo, 1992).

The most important stratifying influences were found to be freshwater fluxes from Swan River discharge events and vertical heating of the water column by solar radiation. Winds appeared to be the dominant mixing agent, with the influence of penetrative convection (due to surface cooling by heat loss to the atmosphere) not clearly quantifiable. Horizontal advection of surface waters driven by wind-stress was shown clearly by past studies to be a dominant exchange mechanism for the nearshore region. In addition, a detailed analysis of the three dimensional salinity and temperature data sets suggested that basin-scale density-driven adjustments of a horizontally stratified structure could lead to significant horizontal transport within the basin and between the basin and its adjacent waters (D'Adamo, 1992).

Estimates of water exchange from past studies of Cockburn Sound (with the Garden Island causeway in place) were based on the assumption that the system was continuously well-mixed. On that basis, estimates of replacement times of order of 30 days or less were calculated, in comparison to estimates of about 10 days or less before the causeway was built (Hearn, 1991; D'Adamo, 1992). However, the reviews concluded that the system is stratified both vertically and horizontally for a significant percentage of the time invalidating the assumption that the basin is typically well-mixed. Hence, it was concluded that further field and modelling work was necessary to quantify the influence of vertical and horizontal density stratification on the flushing of these waters.

Thus a major task of the oceanographic component of the SMCWS was to more accurately describe the seasonal characteristics of stratification as a function of environmental forcings such as wind stress, atmospheric heating and cooling, river discharge, and other factors such as regional currents, tidal forcings, and low frequency oscillations. In addition, it was concluded that the relative influence of baroclinic and barotropic transport mechanisms should be determined quantitatively, in order to assess the relative applicability of barotropic and baroclinic numerical models.

Modelling

The review of Hearn (1991) summarised the application of numerical hydrodynamic models to past studies of the shelf-scale and basin-scale oceanography of the Perth region. Modelling studies within the region have, until recently, been restricted to two-dimensional depth-integrated models. These models are useful for the study of water level fluctuations (e.g. due to tides) and unstratified barotropic flows with near uniform vertical current profiles. They are not ideally suited to studies of water exchange and contaminant flushing (particularly where the water body is density-stratified and wind-driven) but have been used in the past for this purpose when available computing power was more modest and when field data and data acquisition techniques were more limited.

The DHI model

This two-dimensional (depth-integrated) model was implemented at the Danish Hydraulic Institute (DHI) by the Commonwealth Department of Construction (1977) for the purpose of comparing water movements in Cockburn Sound before and after construction of the Garden Island Causeway. The model consisted of three nested grids with the sides of the cells reducing by one third (one ninth of the area) in moving down to the next (higher resolution) grid. The large scale (coarse) grid represented nearly the whole of the Perth metropolitan waters and extended from just south of Mandurah to north of Mullaloo, and offshore beyond Rottnest Island to a distance of 40 km from the coast. The basin-scale (medium resolution) model grid covered Cockburn Sound from just south of Cape Peron to north of Parmelia Bank, and offshore to a distance of 13 km from the mainland shore of Cockburn Sound. The sub-basin (fine resolution) model enclosed the Causeway and its western and eastern approaches. The model was wind driven with the options of including an alongshore ocean current and sea surface (tidal) variations, imposed as boundary conditions on the large scale model.

The DHI study suggested (Hearn, 1991) that the barotropic throughflow currents of Cockburn Sound were significantly reduced following construction of the causeway. The model results also suggest that there is active wind-driven circulation (represented as topographic gyres) within the Sound, with speeds much in excess of those associated with barotropic throughflow.

The Steedman and Craig model

This two-dimensional, depth-integrated barotropic model was developed during the Cockburn Sound Environmental Study and is detailed in Steedman and Craig (1979; 1983). A rigid-lid approximation was adopted (which excluded all seiching motion) in order that an implicit numerical scheme and a large model time step could be employed, thus allowing the model to be run for simulation periods of about 14 days corresponding to a complete weather cycle. The model area covered the whole of the Sound, extended offshore to beyond Sepia Depression and ran alongshore from Cape Peron to Fremantle, with a cell size of 1 km. The model was forced by a set of typical time-dependent wind stress scenarios and employed radiative boundary conditions at the seaward edges of the model grid.

The coastal boundary conditions specified in the model of Steedman and Craig represented Cockburn Sound with its southern entrance completely closed. This model therefore did not treat the throughflow flushing process. Rather, the model calculated depth-integrated results for wind-induced circulation within the Sound and water exchange across the northern opening. The model results suggested very little two-way exchange across the northern opening. Given the two-dimensional nature of the calculations, and that throughflows were not included in the model, it is difficult to estimate flushing rates for Cockburn Sound from these results. The modelled circulation patterns within the Sound formed essentially closed topographic gyres. Similar patterns of internal wind-driven circulation were previously obtained with the DHI model.

Correlation of current meter and wind records (Steedman and Craig, 1979, 1983) indicated that for wind speeds above about 5 m s^{-1}, a significant part of the circulation in Cockburn Sound, at scales of a few hundred metres, is wind-driven. However, at lower wind speeds the circulation appeared to be controlled by other factors.

The Hearn and Hunter models

Several two-dimensional modelling studies, at finer model grid scales, have been undertaken to predict various aspects of the internal flow in Cockburn Sound (e.g. Hearn, 1989; Hunter, 1990). These studies focussed on the shallow parts of Cockburn Sound at Kwinana, Jervoise Bay and Mangles Bay, for the purpose of evaluating specific engineering projects. The models were driven by various combinations of larger scale currents and wind-forcing.

Recent developments

In recent years computing power has increased rapidly, making three-dimensional modelling of coastal waters possible. Field measurements in the study area have highlighted the three dimensional nature of water circulation and mixing, particularly when forced by wind-stress, and in the presence of density stratification. The three-dimensional circulation and density stratification may significantly affect the contaminant flushing characteristics of coastal water bodies. For this reason, three-dimensional baroclinic circulation models are currently being implemented for the coastal waters off Perth (Pattiaratchi and Backhaus (1992), and Section 7.1).

Source documents —
Hearn, (1991); D'Adamo, (1992).

2.4 Biology

In October 1985, the Department of Conservation and Environment (now the EPA) provided funding to the University of Western Australia for a three year post-graduate study on the nutrient dynamics of Perth's coastal waters (Paling, 1991). The funding of this study was recognition of the need for a better understanding of the cumulative long-term environmental impacts of nutrient inputs to the temperate coastal waters of Western Australia. The study was a pre-cursor to the studies now being undertaken in Perth's coastal waters, by the EPA and the WAWA, and provides the basis for the brief review below.

Most coastal marine ecosystems rely primarily on inputs of organic matter created by marine plants using carbon dioxide, water and nutrients as the raw materials and sunlight for energy. For any given ecosystem the source of this organic matter is either internally produced within the system, or externally produced and advected into the system. The major primary producers involved include phytoplankton, algae and seagrasses.

The coastal ecosystems off Perth do not support an abundance of phytoplankton, rather, these systems are driven by attached macrophytes (seagrasses and macroalgae) and these are largely confined to inshore coastal waters less than 20 m deep. There are few natural external sources of nutrients to Perth's coastal waters. Nutrients are efficiently stored and recycled in these coastal environments and only small quantities are present in the water in forms that are readily available for plant growth. As a result, these waters are relatively clear and may be considered nutrient poor by world standards.

Seagrasses and macroalgae are the dominant marine macrophytes found along the Perth metropolitan coastline; they occupy substantial areas and produce large quantities of organic matter

(Table 1). In addition to producing organic matter, these macrophytes provide substrata for diverse assemblages of small plants and animals, habitat and nursery areas for fish and invertebrates, a means of trapping and binding sediments, and a medium for storing and recycling nutrients. The seagrass community is comprised of 18 species, however 90% of the total seagrass cover occurs in monospecific or mixed-species meadows comprised of only four species, two each from the genera *Posidonia* (*P. sinuosa* and *P. australis*) and *Amphibolis* (*A. antarctica* and *A. griffithii*). The macroalgal community is dominated by the kelp (*Ecklonia radiata*) which forms 95% of the algal biomass on reefs and by *Sargassum* which is seasonally important on the shallower reefs in the summer months.

The dominant macrophyte community, in different parts of the coastal waters of Perth, is largely dependent on the substratum. Seagrass meadows are only found on stable sediments whereas attached macroalgae are found on solid substrata such as limestone reefs and pavement. Areas of mobile sediment are inhabited by microscopic algae attached to sand grains or inhabiting the spaces between them, and are colonised from time to time by non-meadow forming seagrass species. Paling (1991) found that there is approximately 272 km^2 of substratum at depths of less than 20 m in the area bounded by Woodman Point to the north, Five Fathom Bank to the west and Becher Point to the south. Macroalgal assemblages occupy some 13% of that area and seagrasses about 8%, the remainder being bare sand and fine sediments. The requirement for sediment stability restricts seagrass meadow formation to relatively shallow areas afforded some protection from long-period wave energy. As a result, seagrass meadows are largely confined to the embayments of Warnbro Sound, Shoalwater Bay, Cockburn Sound and Owen Anchorage, all of which are protected to some degree by islands and shallow reefs (Figure 1).

Seagrass meadows are highly susceptible to the effects of nutrient enrichment, and when the dominant meadow forming species are lost, they are effectively lost forever due to the slow rates of rhizome spreading and an apparent inability to successfully re-colonise areas from seed (Kirkman, 1989). In broad terms, the link between nutrient input and seagrass death is well understood (e.g. Shepherd *et al.* 1989). Excessive nutrient inputs stimulate algal growth which, in turn, reduces light reaching the seagrasses to levels insufficient for long-term survival. In Princess Royal Harbour, near Albany, seagrass decline was attributed to a combination of shading due to excessive epiphyte loads on seagrass leaves and to smothering by unattached macroalgae (Simpson and Masini, 1990). In contrast, past studies of Cockburn Sound concluded that excessive growth of epiphytes and increased phytoplankton in the water were indirectly responsible for the observed seagrass losses (Cambridge *et al.* 1986).

Although the critical pathways have been identified (Figure 2), there is limited biological process information available for developing predictive nutrient-effects models for Western Australia's temperate waters. This information is currently being generated by the EPA and WAWA studies underway in the coastal waters of Perth. The preliminary results of some of these studies are presented in this report.

Source document —
Paling (1991).

Table 1 —
The relative areal coverage, production and nitrogen content of the two main benthic community types in waters less than 20 m deep, in the area bounded by Woodman Point to the north, Five Fathom Bank to the west and Becher Point to the south (after Paling, 1991)

Community type	Area (km^2)	Total dry weight (tonnes)	Production (tonnes y^{-1})	Nitrogen content (tonnes)
Seagrass	21.14	21 851	333.7	294.7
Macroalgae	35.85	60 290	1862.7	1066.0

COMMUNITY EDUCATION AND CONSULTATION

The major objective of the SMCWS is to develop an environmental management strategy for the southern metropolitan waters of Perth. The strategy will be centred around determining the environmental quality objectives (EQOs), both ecological and cultural, and establishing the linkages between human activity and changes to these objectives.

The 'ecological' EQOs must conform to the principles of *ecological sustainability* (i.e. maintenance of biodiversity and ecosystem structure and function) and, as such, are 'non-negotiable' and scientifically determined. Similarly, the 'cultural' EQOs must conform to the principles of *cultural sustainability* (i.e. maintenance of community aspirations) and, by definition, are 'negotiable' and culturally determined.

To achieve these objectives it is necessary to have both a scientific understanding of the linkage between human usage and environmental change, and a cultural appreciation of the current and future uses of these waterbodies. The ecological EQOs will be met by the various baseline and inventory studies, the development of an ecological nutrient-effects model and appropriate monitoring programmes. Cultural EQOs are derived from a balance of existing and future community uses and are confined to the range between 'the natural state' (or zero impacts) and the point just before the objectives of ecological sustainability start to be affected. As such, community consultation has a pivotal role to play in determining the cultural EQOs of the SMCWS.

For the community to be able to participate effectively, user groups need to be aware and understand the objectives, rationale and key ecological principles of the SMCWS and have an appreciation of the socio-economic benefits and the environmental implications of the various uses of these waters. A consultation programme was developed to provide this information and includes community education and consultative components. Apart from the general community, the target audience includes local politicians, relevant State and Federal government departments, local government, industry groups, conservation groups, schools, the marine scientific community and local community groups. A brief outline of the community education and consultation programme is presented below.

3.1 Community education

An assessment of community attitudes was undertaken at the beginning of the study to identify areas of concern and information deficiency (see Section 2.2). The results were used to help formulate the emphasis of this programme. Various activities have been undertaken to increase public awareness of the SMCWS and these are briefly outlined below.

Study launch

In April 1991, approximately 120 members of the local community were invited to the launch of the Southern and Northern Metropolitan Coastal Waters Studies at the Fremantle Port Authority by the Minister for the Environment, the Minister for Water Resources and the Chairman of the EPA. Representatives from all target audience groups were invited.

Educational literature

A booklet and fold-out brochure outlining the objectives, rationale and key ecological principles of the SMCWS, were published in 1991 (Cary and Simpson, 1991). Seven thousand booklets and 20 000 brochures were produced and most have been distributed.

Presentations

During 1991/92 approximately 60 presentations were given to target groups in the study area. A schedule for further presentations to these groups is currently being formulated for the second half of the study.

Media

In 1991, one hour of high quality video vision of various aspects (above and below water) of the SMCWS was produced. This has been used in television programmes (e.g. news, current affairs) on seven occasions to date. Numerous articles on the SMCWS have appeared in local newspapers and *The West Australian*. Local newspapers will be approached for further coverage during the second half of the study.

Display

A display has been constructed and used at schools and information days to promote the SMCWS. The display will be located at shopping centres in the study area during the second half of the study. An underwater photographic competition of the study area is currently being organised through Perth's underwater photographic clubs. The best of these photographs will form part of the display. The display has been used during Seaweek in 1991 and 1992. The EPA and the Scitech Discovery Centre are currently investigating the possibility of developing an interactive computer-operated display based on the SMCWS.

Video

A script has been written for an 8-minute educational video presenting the objectives, rationale and key ecological principles of the study. The video will be produced if funding is available.

Competitions

School projects and competitions are currently being organised through the Education Department to use the SMCWS as part of an educational programme.

3.2 Community consultation

Consultation programmes were undertaken for specific target groups and are outlined briefly below.

Politicians

In the first half of 1991, the Ministers for the Environment and Water Resources and the local Members of Parliament were briefed on the SMCWS. All relevant Ministers and local Members of Parliament will again be briefed during the second half of the study.

Local government authorities

The objectives and rationale of the SMCWS were outlined to the mayors and city managers from Perth's southern coastal local authorities at a briefing at the EPA in early 1991. They were given booklets and brochures to distribute to local residents in their constituencies. In the second half of 1991, various committees of the four local authorities in the study area were briefed and will be briefed again in the second half of 1993.

State and federal government departments

The Chief Executive Officers and senior staff of relevant State and Federal Government departments were invited to the launch of the SMCWS. In addition, some were given individual briefings during 1991.

Marine scientific community

The EPA conducted a seminar in the first half of 1991 for the West Australian marine scientific community to outline the objectives and rationale of the SMCWS and seek critical appraisal of the approach being taken. A presentation on the same subject was made in late 1991 to a special meeting of the WA branch of the Australian Marine Sciences Association. Since then, study members have presented more than 30 technical papers at national and state scientific conferences and workshops.

Industry

The Kwinana Industries Council Environmental Monitoring Committee (KIC) has been regularly briefed on the progress of the SMCWS since early 1992. The KIC committee distributed approximately 3000 of the study brochures to employees who worked for industries represented on the KIC committee.

Conservation groups

Representatives from conservation groups were invited to the launch. Representatives from the WA Conservation Council have been briefed on the SMCWS and brochures have been distributed to conservation groups in the study area. Further contact with conservation groups will be sought in the second half of the study.

Professional institutions

The Australian Marine Sciences Association (AMSA) has been briefed on the objectives and rationale for the study and regular updates on the SMCWS are included in the AMSA newsletter. The Institution of Engineers, Australia has also been briefed on the objectives and rationale of the study.

Community groups

Presentations have been given to numerous Rotary and Lions clubs and some senior citizen clubs in the wider study area. Lectures have also been given to the University of the Third Age.

Schools

Numerous talks have been given to primary and high schools throughout the first half of the Study. The EPA is in the process of producing educational material on the SMCWS for the Ministry of Education. The EPA is also currently involved in the training of science teachers on marine ecological principles using the SMCWS as a case study.

Universities

Lectures on the SMCWS have been given to environmental science, biology and engineering students at local universities. The SMCWS is currently being used as a case study in some courses.

General community

Except for the distribution of educational material to interested individuals, there has been little contact with the general community within the study area. During the second half of the study, the community consultation programme will be more active in the area of general community consultation.

3.3 Environmental quality objectives

Ecological EQOs will be determined in consultation with the marine scientific community. The cultural EQOs will be determined in consultation with the wider community, including all user groups, and will be derived from a balance between the various existing and future uses of these waters. A framework to determine the cultural EQOs will be proposed and undertaken as a separate consultative process outside the SMCWS.

Source document —
Cary and Simpson (1991).

INVENTORY AND BASELINE STUDIES

This section outlines the various inventory and baseline studies that are being undertaken as part of the SMCWS. Several of these studies are continuing (e.g. Section 4.1, 4.2) and others, such as the summary of recreational usage (i.e. Section 4.3), are based on a review of existing information. Brief summaries are presented below.

4.1 Marine biological resources

An inventory of the marine resources of the study area is being compiled as part of the characterisation phase of the SMCWS. This inventory will provide a detailed account of the non-commercial marine biological resources in these waters and a brief description is outlined below. In addition to the inventory, an accurate map of the major benthic habitats is being constructed, for the purposes of ecological modelling and as a reference for quantifying future habitat changes. This map will be based on a spatially rectified digital image that was recorded by airborne scanners during February 1993. An accurate (± 10 m) map of the coastline including islands, benthic habitats and water depth will be produced and overlaid with an AMG grid.

The principal physical feature of the nearshore marine environment of the southern metropolitan waters off Perth is the Garden Island Ridge, an extensive system of limestone reefs parallel to and within a few kilometres of the mainland. This system extends as a chain of islands, intertidal and subtidal reefs, from Mandurah to the Straggler Rocks, off Fremantle, and includes Penguin Island, Cape Peron and Garden Island (Figure 1). A similar ridge, Five Fathom Bank, occurs further offshore to the west of Sepia Depression, and extends from Cape Bouvard, 22 km south of Mandurah, to the west end of Rottnest Island. The islands and reefs form a barrier which protects the coastline from offshore swell, creating low energy coastal lagoons and embayments. In the lagoons, water depths are typically less than 10 m whereas in the central basins of Warnbro Sound and Cockburn Sound depths exceed 18 m.

The study area can be divided into five main habitats:

Limestone reefs

Most subtidal reefs occur offshore and are dominated by large brown algae such as the kelp, *Ecklonia radiata*, *Sargassum* spp. and a variety of red algae including crustose and articulate coralline species and non-calcareous foliose and filamentous species. The plant communities combined with the reef structure which includes caves, crevices and ledges, provides habitat for a variety of sessile invertebrates such as ascidians (e.g. colonial and solitary sea-squirts), sponges and soft corals. Mobile invertebrates include a wide variety of crustaceans, echinoderms, holothurians (e.g. sea cucumbers), molluscs and burrowing infauna (Gordon, 1986).

Intertidal reefs, forming platforms close to mean sea level, constitute a small proportion of the habitat in the study area. Although intertidal reefs occur onshore at Cape Peron, they are principally found offshore along the Garden Island Ridge system as fringing reefs adjacent to islands. Species dominance, diversity and abundance on reef platforms is determined principally by the frequency of tidal submergence giving rise to a zonation of community types. However the reef platform is generally dominated by brown algae, particularly *Ecklonia radiata* and *Sargassum* spp. The dominant animals include the commercially important abalone, *Haliotis roei*, the common whelk, *Thais orbita*, marine snails such as the chiton, *Rhyssoplax torriana* and the large turban shell, *Turbo torquata*.

Seagrass meadows

Seagrass meadows generally occur on the sandy seafloor of the protected waters inside the coastal reef chain. Small areas of seagrass are also found in sand pockets among subtidal reefs and in sand patches on the leeward side of reefs. Ten species of seagrass have been recorded in the study area and seagrasses occur to a depth of 18 m in Warnbro Sound and 12 m in Owen Anchorage. Meadows of greatest extent and density, however, occur in waters of less than 10 m, particularly on Parmelia and Success Banks. The dominant species are *Posidonia sinuosa*, *P. australis*, *Amphibolis antarctica* and *A. griffithii*. Seagrass meadows usually occur as a mixture of *P. sinuosa* and *Amphibolis* spp. Monospecific stands of *P. sinuosa* occur on the leeward side of Penguin Island. Currently only about 900 ha of seagrass meadows remain in Cockburn Sound, representing about 20% of the area originally covered by seagrasses.

Seagrasses are important primary producers and provide habitat for a diversity of animals, such as fish and invertebrates, and substrata for a wide range of attached plants (epiphytes). The sandy substratum beneath seagrass meadows also contains a diversity of animals and the meadows provide important nursery areas for many species of fish.

Mobile sand

Mobile sandy areas, in less than 20 m depth, occur in the protected waters on the eastern side of the Garden Island Ridge system and in Sepia Depression (Figure 1). Significant sediment movement occurs in these areas which is unfavourable for colonisation by plants. Consequently, the biota of these areas is dominated by fish and burrowing invertebrates, including molluscs and polychaete worms.

Deep basin sediments

The soft-substratum habitats that occur in the central deep basins (> 10 m depth) of Warnbro Sound and Cockburn Sound are unique on the central west coast of Western Australia

(Wilson *et al.* 1978). The plant communities of these deep basins are impoverished and restricted to some species of green and red algae. However, the epifaunal communities are diverse and abundant and include species of anemones, cerianthids, sponges and tunicates. Likewise the benthic infaunal communities have a wide variety of species including burrowing polychaetes, echinoderms, crustaceans and molluscs, particularly bivalves (Wells, 1978).

Marine mammals

Several colonies of the Australian sea lion (*Neophoca cinerea*) occur on islands along the metropolitan coast and, within the study area, include Carnac Island and Seal Island (Figure 1). These animals generally feed in offshore waters. The New Zealand fur seal (*Actocephalus torsteri*), the Sub-antarctic fur seal (*A. tropicalis*) and the leopard seal (*Hydrurga leptonyx*) are occasional visitors to Perth's coastal waters.

The Southern Right whale (*Balaena glacialis*) and Humpback whale (*Megaptera novaeangliae*) are common in the coastal waters off Perth, particularly during their migration period from July to November. The Minke whale (*Balaenoptera acutorostrata*) is also seen annually in coastal waters during the migration period, though in fewer numbers. The Pigmy Right whale (*Caperea marginata*) is an occasional visitor to these waters.

The bottlenose dolphins (*Tursiops truncatus*) occur in inshore waters sometimes forming 'resident' pods in particular areas. One such group occurs in Cockburn Sound and has become a popular tourist attraction. The striped dolphin (*Stenella caeruleoalba*) is an oceanic species occurring well offshore. This species has occasionally been found stranded on metropolitan beaches.

Marine reptiles

Loggerhead (*Caretta caretta*), leatherback (*Dermochelys coriacea*) and green (*Chelonia mydas*) turtles are occasionally sighted in the coastal waters off Perth.

Seabirds

The coastal islands and rock stacks in the study area, particularly in Shoalwater Bay, are important resting, breeding and nursery areas for a range of resident and migratory species. At least 56 species of seabird, including waders and divers, frequent the study area. The majority of waders are migratory and do not breed locally, visiting the area between September to April each year. Most of these birds are protected under international agreements. In contrast most of the divers are resident and use the offshore islands particularly in the Shoalwater Bay as nesting sites. A number of the migratory divers are also protected under international agreements.

Fairy Penguins (*Eudyptyla minor*) occur in waters south of Rottnest Island. The primary breeding area on the Western Australian coast is Penguin Island, in the Shoalwater Islands Marine Park. The most northern breeding site is Carnac Island. There are also roosting sites at Parker Point on Rottnest Island and on Seal and Bird Islands.

4.2 Recreational usage

With the rapid southward spread of urban development in Perth, the protected waters of Cockburn and Warnbro Sounds are becoming increasingly popular for recreational activities. As recreation usage increases so too does the potential for conflict with other users of these waters. Existing information on recreational usage is being compiled as part of the SMCWS and some of the results to date are outlined briefly below.

The last comprehensive survey of recreational usage of the southern metropolitan coastal waters was undertaken in 1978 as part of the Cockburn Sound Environmental Study (Fielman and Associates, 1978) and largely focussed on the recreational use of Cockburn Sound. At the time Cockburn Sound was considered to be at least equal to the Swan River in importance as a recreational resource. The peak day use of the beaches of Cockburn Sound and Owen Anchorage was estimated in 1978 to be 8300 people, with a further 1200 in the Shoalwater Bay-Warnbro Sound areas. Additionally, on a typical hot summer weekend some 620 boats used these waters.

Although no comprehensive studies of the recreational usage of Perth's southern metropolitan coastal waters have been conducted since 1978, there have been several surveys of recreational usage in specific areas and the main findings are summarised below.

Since the late 1970s, the population of the study area, including the Fremantle, Cockburn, Kwinana and Rockingham municipalities has increased by 60% to approximately 138 000 people (Figure 3). This increase, immediately adjacent to the southern metropolitan coastal waters, has also been accompanied by an increase in recreational activities and facilities. Some measure of this increase can be seen in higher recreational boat usage, the number of boat harbours and boat ramps and the increase in recreation and conservation reserves.

The number of registered recreational boats in Western Australia has increased from 40 000 in 1980 to 70 000 in 1990 (Figure 4). With approximately 70% of the WA's population living in Perth this equates to about 50 000 boats operating in the metropolitan area in 1990. The number of boat harbours and marinas has also increased. In the Fremantle area, the Fremantle Sailing Club was upgraded in 1979 and Challenge Harbour was built for the Americas Cup in 1986. Several marina developments have been proposed in recent years and include sites in Owen Anchorage, Mangles Bay, Warnbro Sound and Comet Bay.

Several conservation and recreation reserves have been created since the late 1970s, again reflecting the shifting emphasis to recreation pursuits. Existing reserves are shown in Figure 5. The A-Class reserve, M91, has been incorporated into the Beeliar Regional Park and has been set aside for passive recreation. The concept plan for the Woodman Point regional recreation/ conservation park was approved in 1981. The reserve, which is almost half the size of Kings Park, is the only major recreation/ conservation reserve between Fremantle and Rockingham and has been described as "the Kings Park beside the sea". In 1988,

Figure 3 —
Population growth of Fremantle, Cockburn, Kwinana and Rockingham

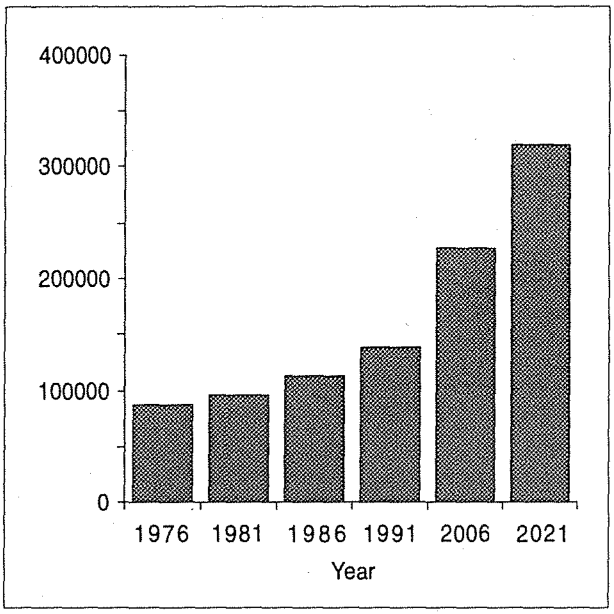


Figure 4 —
Increase in the number of recreational boats in Western Australia

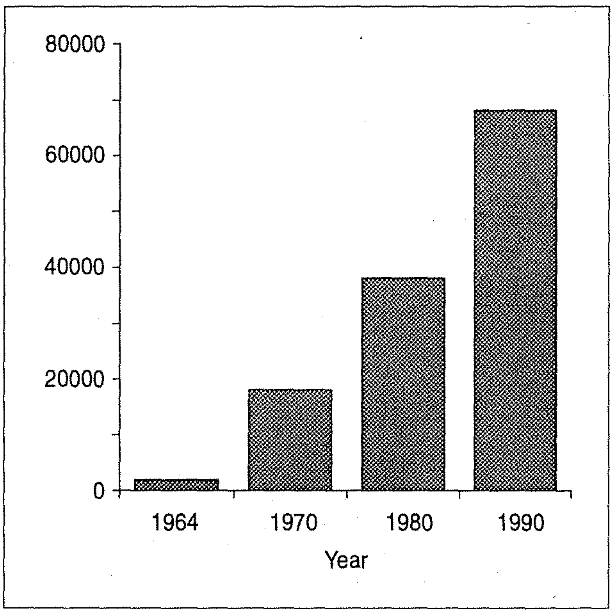
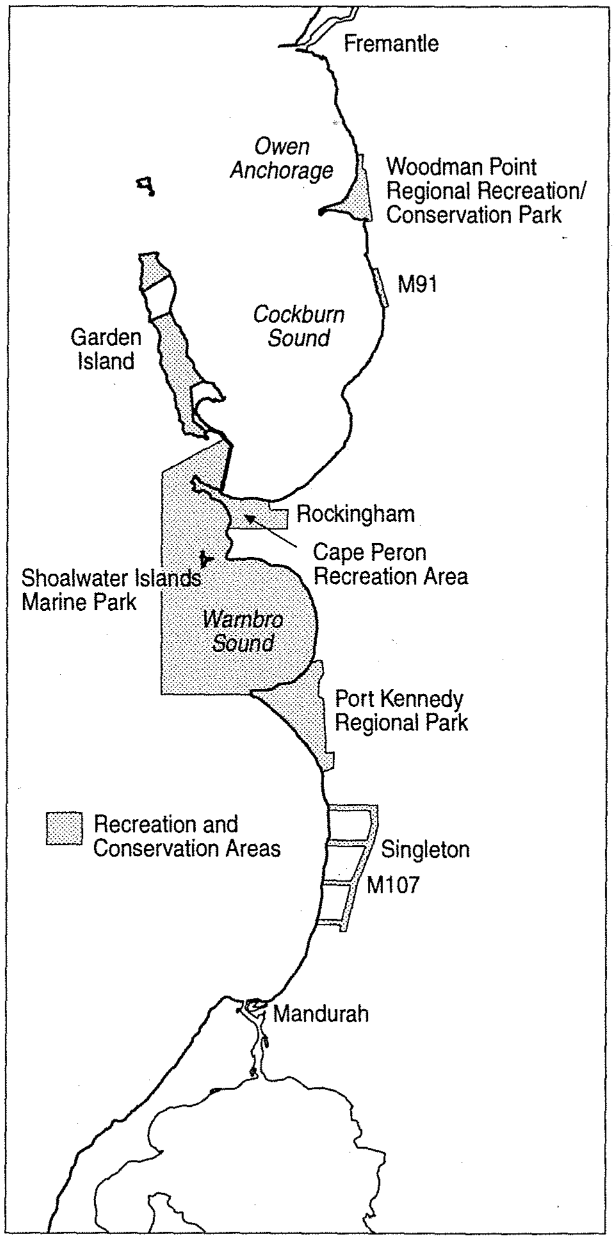


Figure 5 —
Recreation and conservation reserves in the study area



the Woodman Point Task Force received 70 submissions from the community on the future development of the park, with overwhelming support to retain Woodman Point for conservation and recreation with an emphasis to foster attractions for families (Woodman Point Community Task Force, 1988).

The Cape Peron area has been recommended for a combination of conservation and recreation activities, including a marina. These activities were recommended by the Cape Peron Study in 1988 (State Planning Commission, 1992). Garden Island has been developed as a Naval Base and a conservation and recreation reserve. A management plan has been developed for the conservation of the island and recreational facilities have been provided at designated areas. Recreational access to the island is only permitted by boat during the day.

The Shoalwater Islands Marine Park was gazetted in 1990 as a multi-purpose marine park. CALM has developed a management plan for the islands and the management plan for the marine area is currently being formulated. The Port Kennedy area is proposed to be developed as a regional park for recreation and conservation (EPA, 1989). Developments include a marina resort, two golf courses, some housing and an area set aside for conservation purposes.

Further work —
A survey of recreational usage of the study area is planned for the summer of 1993/94, but is dependent on funding being available.

4.3 Commercial usage

An inventory of major commercial uses of the southern coastal waters of Perth is being compiled as part of the characterisation phase of the SMCWS and a brief outline of these uses is presented below.

Commercial fisheries

Six commercial fisheries operate off the metropolitan coast of Perth. The largest and most important fishery is the Western Rock Lobster (*Panulirus cygnus*), and fishing grounds extend from the nearshore reefs to the shelf break. The coastal season presently extends from 15 November to 30 June and a significant proportion of the West Australian rock lobster fishing fleet is based at Fremantle.

The abalone, *Haliotis roei*, fishery extends from Cape Bouvard, south of Mandurah, to Moore River, 80 km north of Perth, and involves 12 licences. *H. roei* are found on intertidal reef platforms and subtidal reef slopes. The main fishing grounds are off the northern metropolitan area although large numbers can be found on offshore intertidal platforms along the entire metropolitan coastline.

The common mussel (*Mytilus edulis*) is farmed in six adjoining lease areas at the north eastern end of Garden Island and in three adjoining lease areas in the southern half of Warnbro Sound. These farms supply the domestic market of Perth and export markets are currently being developed. Mussel spat (juveniles) are collected from near the Cooperative Bulk Handling jetty on the eastern side of Cockburn Sound. The spat are transferred to the lease areas, attached to drop lines and suspended in the upper part of the water column until they reach marketable size.

The Southwest Trawl Fishery targets scallops (*Amusium spp*), western king prawn (*Penaeus latisulcatus*) and whiting (*Sillago* spp.). The prawn trawling grounds are principally in Comet Bay, south of Warnbro Sound, whereas the scallop grounds are approximately 25 km due west of Comet Bay.

There are presently 12 vessels with access to the West Coast Purse Seine (WCPS) fishery and nine vessels with access to the Metropolitan Beach Bait (MBB) Fishery, operating in metropolitan waters. The target species of the WCPS fishery include pilchard (*Sardinops neopilchardus*), scaly mackerel (*Amblygaster postera*) and occasionally anchovy (*Engraulis australis*). The MBB fishery target whitebait (*Hyperlophus vittatus*) and blue sprat (*Spratelloides robustus*).

A small wet-line and shark fishery involves approximately five vessels operating in offshore waters along the metropolitan coast.

A mixed species fishery targeting squid (*Sepioteuthis australis*), crabs (*Portunus pelagicus*), octopus (*Octopus tetricus*) and table fish involves about 20 boats operating primarily in the protected waters south of Fremantle.

Port and industrial operations

The Fremantle Harbour at the mouth of the Swan River is the Western Australia's principal port facility servicing coastal, national and international vessels. Further south, the protected deepwater basin of Cockburn Sound provides a natural harbour to service the Kwinana industrial area along the eastern shoreline. Industrial development in Kwinana began in 1952, with the establishment of an oil refinery, and since then, has expanded to be the most important industrial complex in the state, with an annual production of approximately $2 billion.

Shipping and related activities

The study area has the highest level of shipping activity in the state. In 1991/92, a total of 1 429 ships, at an average of 16 400 tonnes, used Fremantle Harbour and Cockburn Sound. The Jervoise Bay marina at the northeast corner of Cockburn Sound, is the site of a large ship maintenance and building industry. There are five marinas in Owen Anchorage and Cockburn Sound, providing facilities to smaller vessels such as trawlers, fishing boats and pleasure craft. HMAS Stirling in Careening Bay, at the southern end of Garden Island, has developed into a significant naval facility, accommodating Australia's western fleet.

Shellsand mining

Since 1972, Cockburn Cement Limited has mined shellsands on Parmelia and Success Banks, at the northern end of Cockburn Sound. Shellsand is used to manufacture cement and quicklime and this operation currently supplies approximately 70% of Western Australia's domestic requirements. The sands are mined by suction dredge, transferred to barges and shipped to a primary processing facility at Woodmans Point.

Oil exploration

Periodic seismic and exploratory drilling has been carried out in recent years in the offshore (25-30 km) metropolitan coastal waters, north and south of Rottnest Island. To date there have been no discoveries of commercial quantities of hydrocarbons.

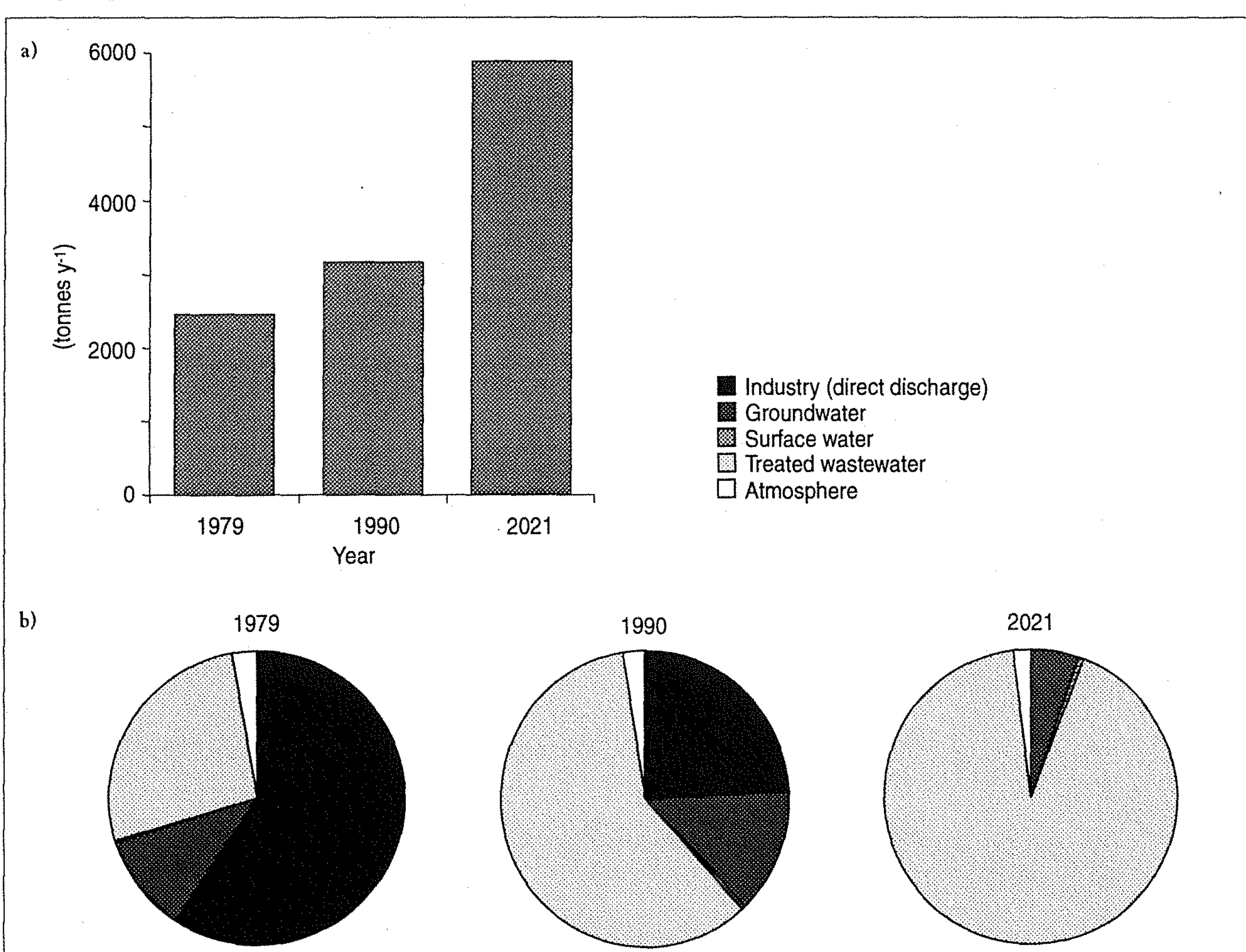
4.4 Contaminant inputs inventory

Contaminants, including heavy metals, pesticides, hydrocarbons and nutrients, enter Perth's coastal waters via a number of routes. Industrial and domestic wastewater outfalls, stormwater drains, groundwater inflow, deposition from atmospheric sources, exchange with offshore waters, and discharges from rivers and estuaries are the major types of inputs. Other sources of contaminants include the discharge of ballast waters from ships, leaching of toxic substances, such as organotin compounds (from antifouling paints used on boat hulls), and accidental spillages.

In 1991, the EPA commissioned the environmental consultants WG Martinick & Associates to compile an inventory of existing information on contaminant inputs to Perth's southern coastal waters (Martinick *et al.* 1993). The inventory includes estimates of historical loads of contaminants, estimates of current loads and estimates of loads which will enter these waters to the year 2021. The objectives of this study were to collate all existing information on contaminant inputs and to identify gaps in existing data so additional information could be gathered to redress any deficiencies. Information on more than 50 contaminants was compiled into an electronic database under the general headings of nutrients, oils & grease, biological oxygen demand, chemical oxygen demand, heavy metals, hydrocarbons, pesticides and bacteria.

Much of the recent and detailed data for the inventory were obtained from self-monitoring programmes associated with EPA licences applying to point source discharges into these waters. The historical data are more limited. Groundwater discharge rates to the ocean were estimated using data from a flow net analysis for the southern Perth area by Davidson (1984). Chemical data in groundwater are based on data provided by the WAWA and were obtained from 15 bores which penetrate the superficial formation along a 5 km wide coastal strip. Although the number of monitoring bores suggests a significant database, the quality and quantity of these data limit the accuracy of the pollutant load estimation for groundwater inflows. Contaminant loadings to the coastal waters from atmospheric deposition were estimated by examining comparable studies elsewhere, and applying appropriate modifications to climatic conditions and concentrations of airborne contaminants.

Figure 6 —
Nitrogen inputs to the southern metropolitan coastal waters: a) annual loads; b) sources



Two separate procedures were used for calculating annual contaminant loads from the Swan-Canning Estuary to the sea. The first used estimates of tidal volumes and average water column concentrations to calculate summer and winter loads while the second used estimates of contaminant loads entering the Swan-Canning Estuary taking into account the retention of contaminants in the estuary. Contaminant inputs in surface drainage were estimated using data from the urban catchments at Fremantle and Rockingham, both of which are managed by the WAWA and drain stormwater runoff directly into the ocean. Stormwater runoff data from Swan Canning Estuary catchments were also considered for comparative purposes.

A detailed account of the methodologies, data and results of this inventory can be found in Martinick *et al.* (1993). Some of these results are outlined briefly below.

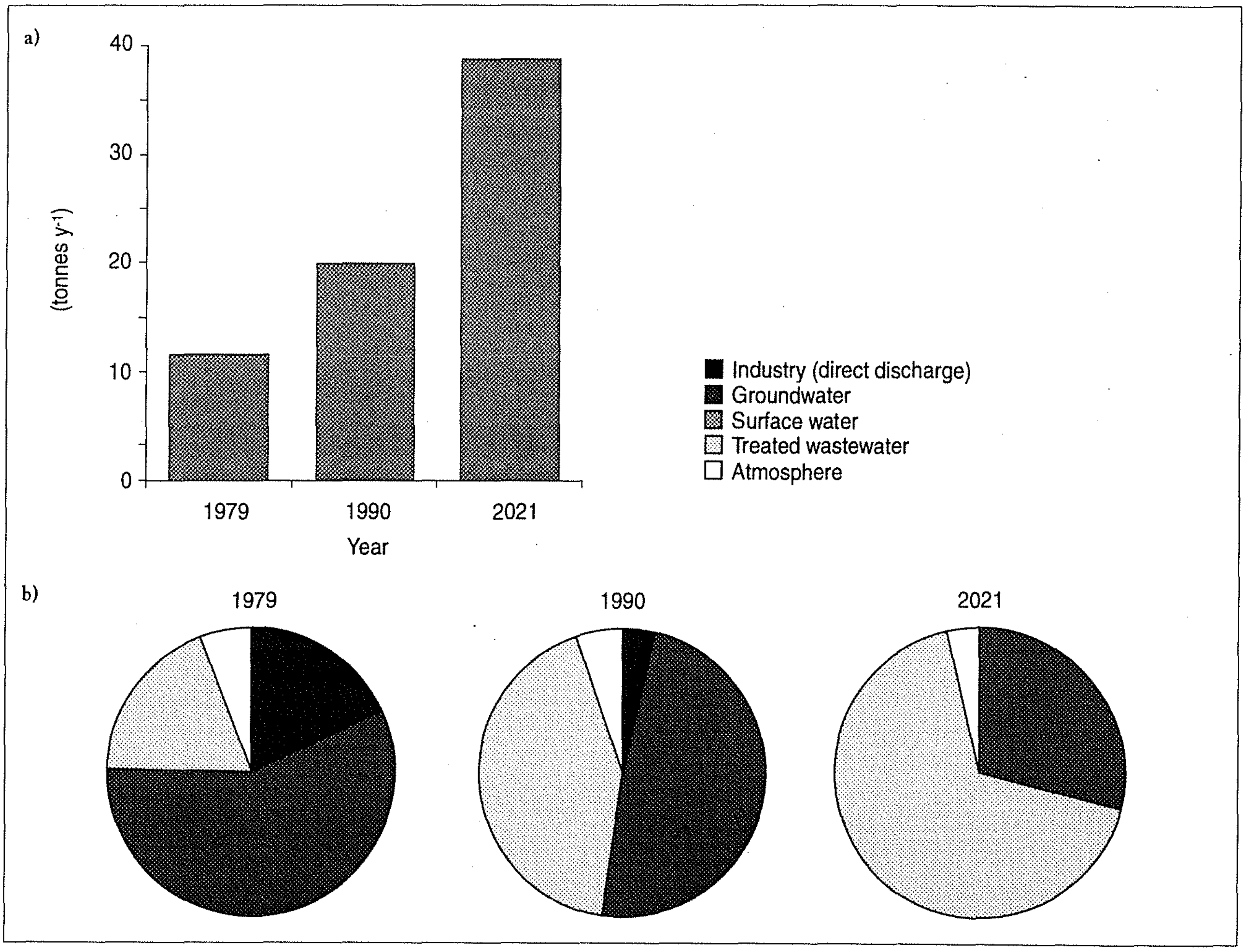
Inputs to the study area

Inputs of some contaminants to the southern metropolitan coastal waters of Perth are predicted to increase dramatically over the next 30 years. Trends for nitrogen and copper are broadly representative of the input trends for most of the other contaminants. Currently about 3000 tonnes of nitrogen per year are discharged to the southern coastal waters of Perth. By 2021, this will increase to 6000 tonnes per year if current treatment and disposal practices are continued (Figure 6a). The main source of nitrogen discharged to these waters has changed in recent times. In 1979, about 60% originated from direct industrial discharge. By 1990, industrial contributions to the total nitrogen loading was about 25% and by 2021, industrial discharges are projected to contribute less than 5% of the total. By contrast, domestic wastewater discharge contributed about 60% of the total in 1990, and will contribute over 90% of the total nitrogen load by 2021 (Figure 6b). Inputs of copper to these waters follow a similar trend; loads are projected to double between 1990 and 2021, with treated wastewater contributing about 70% of the total load by 2021 (Figure 7).

Cockburn Sound

Between 1979 and 1990, annual loads of nitrogen discharged to Cockburn Sound decreased substantially, from about 1800 to 900 tonnes (Figure 8a). This was largely due to improvements in the

Figure 7 —
Copper inputs to the southern metropolitan coastal waters: a) annual loads; b) sources



treatment of industrial wastewaters, during the 1980s, and to the diversion, in 1984, of the domestic wastewater outfall in Cockburn Sound to an offshore site in Sepia Depression. In 1992, nitrogen loads had decreased to about 600 tonnes (Martinick *et al.* 1993). Further planned reduction in industrial discharges to Cockburn Sound should reduce nitrogen discharges to these waters to 316 tonnes per annum by the year 2021, with most coming from groundwater inflow to the Sound (Figure 8b).

The discharge of heavy metals to Cockburn Sound was substantially reduced between 1979 and 1990, again due to improved industrial treatment and effluent diversion to Sepia Depression. Discharges of heavy metals are predicted to rise between 1990 and 2021, with the bulk of these coming from groundwater inputs, with some contribution from atmospheric sources.

Hydrocarbon loads to Cockburn Sound from direct industrial discharges has fallen sharply since 1979 and is projected to be almost zero by 2021 (Figure 9). Data on hydrocarbon loads via surface drainage and groundwater are not available and, therefore, loading estimates from these sources cannot be made.

The major predicted source of contaminants to Cockburn Sound by 2021 will be from groundwater. It is estimated that groundwater will contribute 80% of the total annual load of 316 tonnes of nitrogen and more than 80% of heavy metals such as copper, zinc and lead. These estimates should be treated with caution as groundwater data are limited.

Owen Anchorage

Current and past point source discharges into the waters of Owen Anchorage have been mainly from a variety of animal processing plants, with wastewaters having high organic, heavy metal and nutrient loads. With the planned development of the Coogee Biotechnology Park and the relocation of industries, all discharges of industrial wastewaters will cease resulting in a major reduction in contaminant loads. By 2021, the dominant source of nutrients and metals to Owen Anchorage waters will be from atmospheric deposition with some contribution from groundwater. Annual nitrogen loads are anticipated to decrease from a 1990 value of 137 tonnes to 66 tonnes by 2021. However, predictions are that heavy metal loads to Owen Anchorage will increase. These predictions are based on tenuous estimates of loads from atmospheric sources with no confirmatory measurements. The predicted increases are not of significant magnitude.

Figure 8 —
Nitrogen inputs to Cockburn Sound: a) annual loads; b) sources

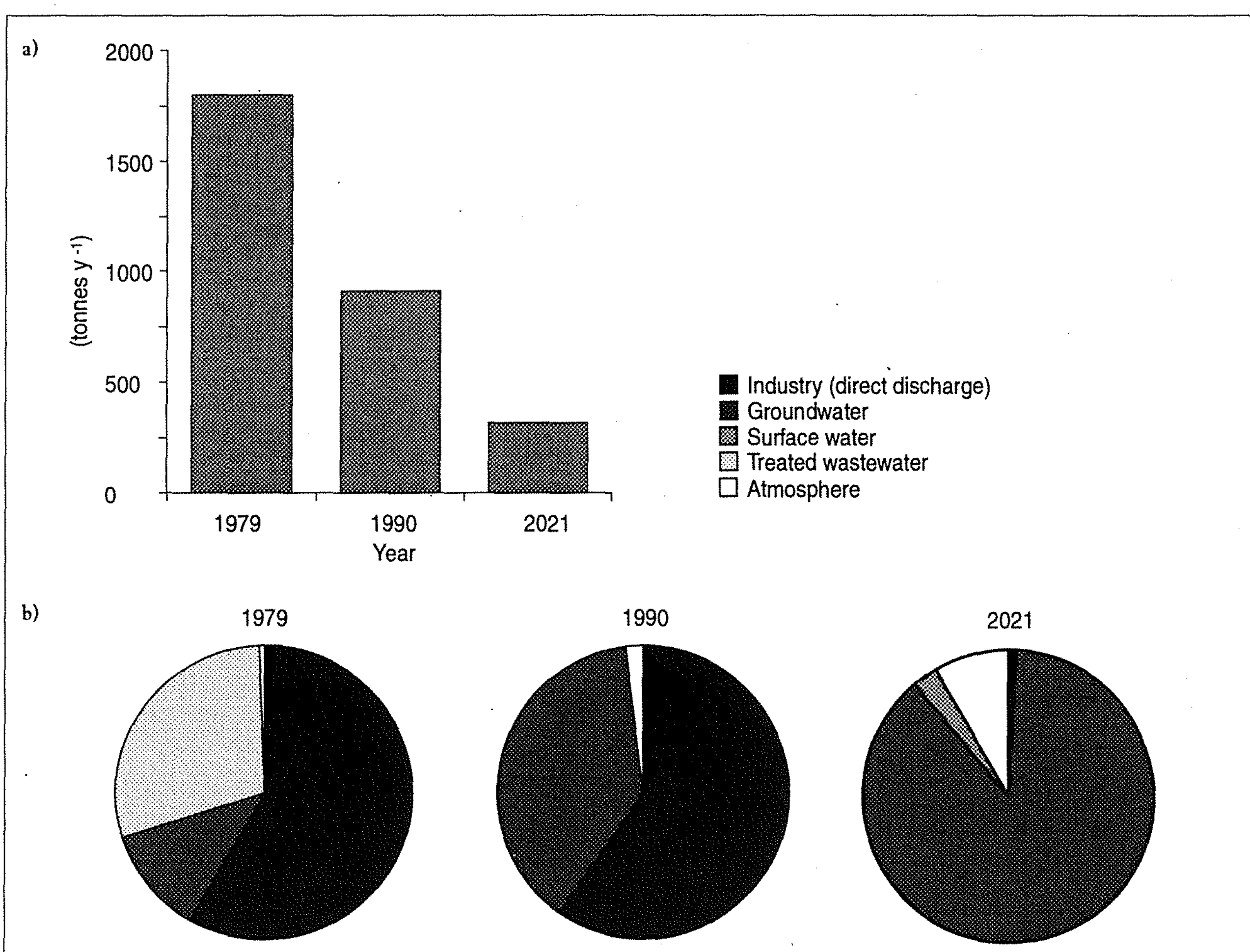


Figure 9 —
Direct discharge of oil to Cockburn Sound by industry

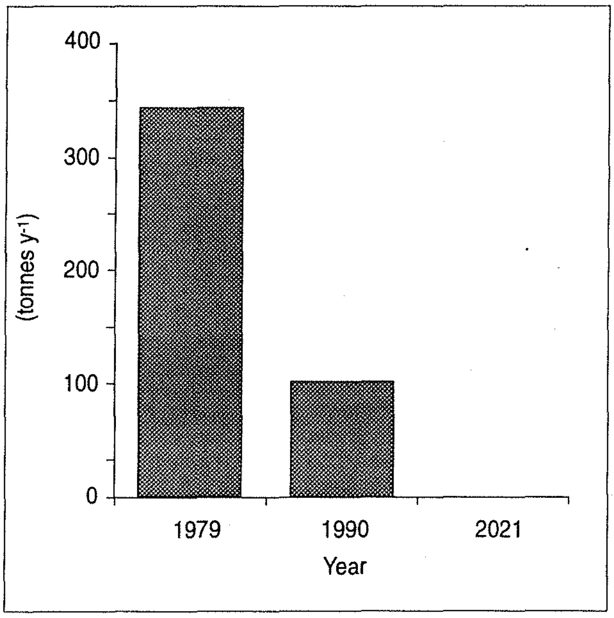
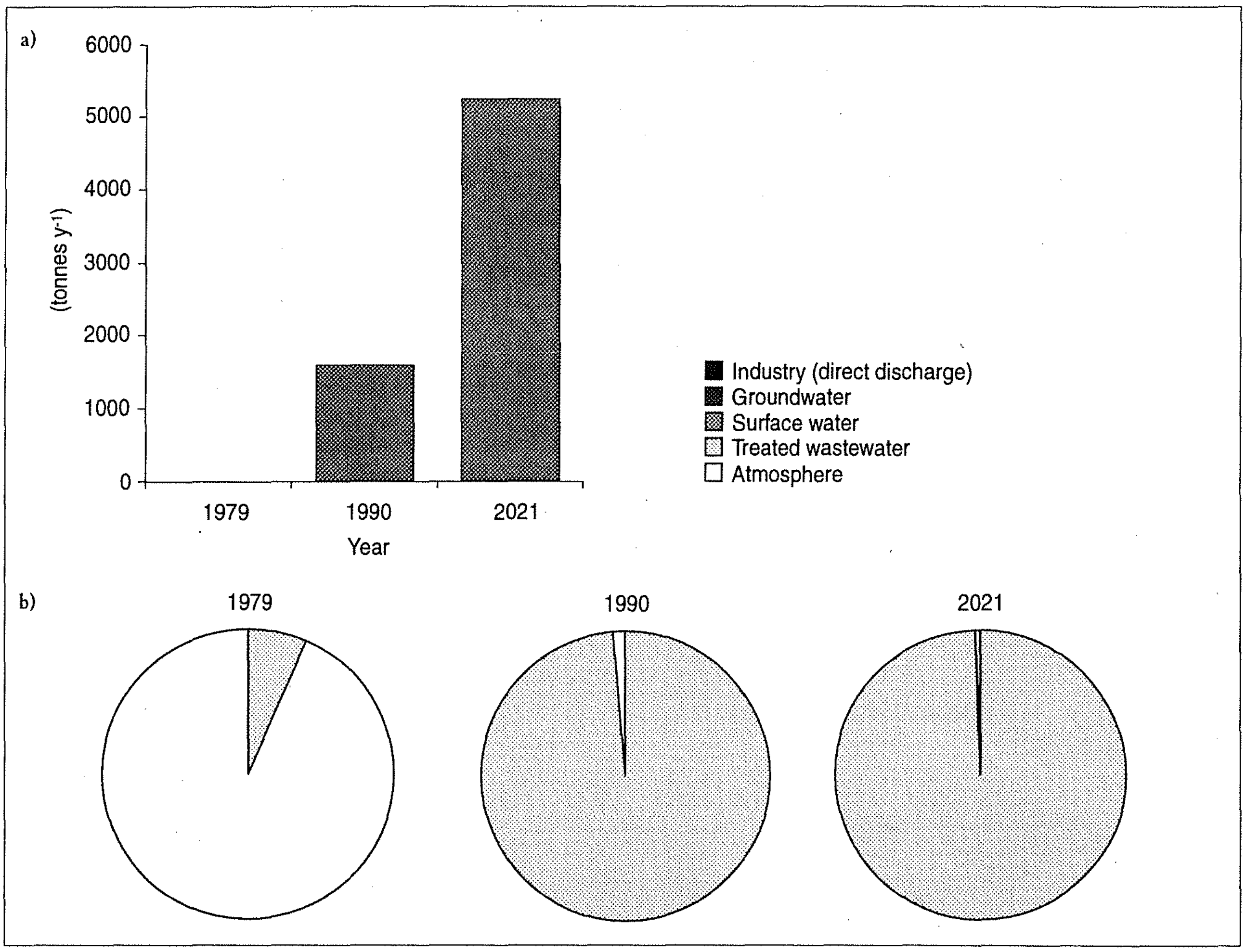


Figure 10 —
Nitrogen inputs to Sepia Depression: a) annual loads; b) sources



Warnbro Sound

Contaminant loads to this area have been, and are presently, very low. There are no industrial point source discharges to the Sound, and the main sources of contaminant inputs are via surface drains and atmospheric deposition with minor contributions from groundwater. Current annual nitrogen loading to Warnbro Sound is 17 tonnes and is predicted to be about 23 tonnes by 2021. Remote sensing data indicate that, under certain conditions, contaminants enter the Shoalwater Islands Marine Park from the Peel-Harvey Estuary outflow and the Cape Peron wastewater outfall. The significance of these inputs is not presently known.

Sepia Depression

The waters of Sepia Depression receive treated wastewater from the Point Peron and Woodman Point wastewater treatment plants with primary treated effluent discharged to these waters via a submarine outfall 4 km offshore. Treated wastewater flows are anticipated to increase by approximately two and a half times by the year 2021, with commensurate increases in loads of nutrients, heavy metals and other materials if current treatment and disposal methods remain (Figure 10).

Source document —
Martinick *et al.* (1993).

4.5 Contaminants in sediments

As part of the characterisation phase of the SMCWS, surveys were conducted to determine the mineralogical and chemical characteristics of the marine sediments of the study area. Grain size, organic and carbonate fractions, nutrient, heavy metal, organophosphate (OP) and organochlorine (OC) pesticides, including polychlorinated biphenyls (PCBs), aliphatic & polyaromatic hydrocarbon (PAHs) and organotin concentrations were determined. These surveys were undertaken to provide a synoptic view of the mineralogical and chemical status of the marine sediments of the study area, and to identify areas of significant contamination. The surveys also provided a quantitative baseline for future reference as well as, in some cases, providing data for comparison with similar surveys carried out in the past.

Sediments for heavy metal analysis were collected in 1989 in collaboration with Murdoch University. The concentrations of As, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Sn, V and Zn in the sediments from 71 sites were determined by X-ray fluorescence spectrometry carried out by the Geology Department at the University of Western Australia. Mercury analyses were carried out by Atomic Absorption Spectrophotometry. Grain size (<75µm), organic and carbonate content analyses were carried out by Murdoch University. Detailed methodologies can be found in Monk (1989) and Monk & Murray (1991). Heavy metal (Cu, Zn, Cd, Fe, Mn, Pb, Cr, Ni) concentrations in sub-samples of these sediments from 25 sites were also analysed by Atomic Absorption Spectrophotometry by the Chemistry Department at Curtin University using similar methods to Chegwidden (1979). This allowed direct comparisons with Chegwidden's 1977 survey of heavy metals in the sediments of Cockburn Sound.

In 1991 sediment samples were collected from 178 sites throughout the study area. Analyses were carried out by the Western Australian Chemistry Centre and included grain size distribution, organic and carbonate fractions, the percentage of Ca, Mg, Sr and S, total and inorganic nutrients (63 sites), OP and OC pesticides (including PCBs), aliphatic hydrocarbons & PAHs and organotin concentrations. The OC pesticides were aldrin, dieldrin, alpha and beta chlordane, oxychlordane, heptachlor, heptachlor epoxide, HCB, lindane, p-p'DDE, p-p'DDD, o-p' & p-p'DDT and the OP pesticides included chlorpyrifos, fenitrothion and maldison (malathion). Analysis of PAHs targeted naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo-(a)anthracene, chrysene and benzo-(a)pyrene. Detailed description of the methods used for determining the concentrations of these organic pollutants can be found in Burt *et al.* (1993). Organotin (monobutyl, dibutyl, tributyl tin) concentrations were determined in sediments from 64 of these sites by the CSIRO Division of Advanced Analytical Chemistry at Lucas Heights (methods in Batley *et al.* 1988). The results of these surveys are tabulated in Burt *et al.* (1993).

A selection of the results is presented below.

Nutrient concentrations

The sediments of the deep basin of Cockburn Sound, particularly the south-eastern section, are significantly enriched with nutrients compared to the shallow banks of the Sound and the deep basin sediments of Warnbro Sound.

Heavy metal concentrations

Heavy metal contamination of sediments is generally higher in Cockburn Sound than in other parts of the study area.

Figure 11 —
Heavy metals in sediments from Cockburn Sound (Fe and Cd have been divided by 100 and multiplied by 10 respectively)

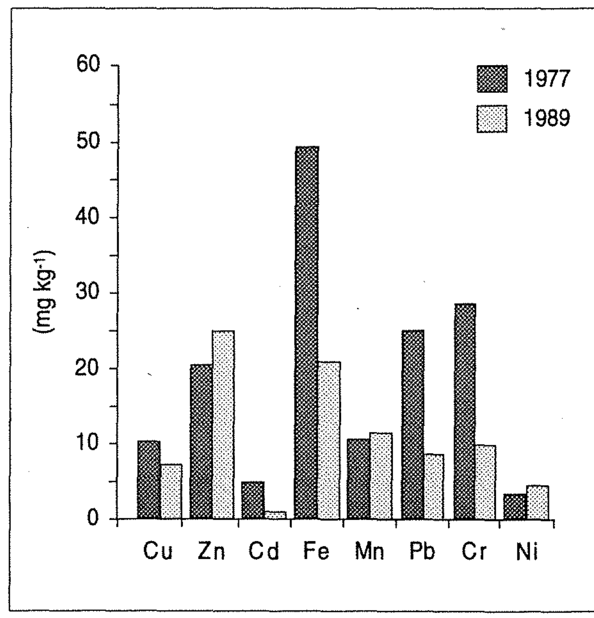
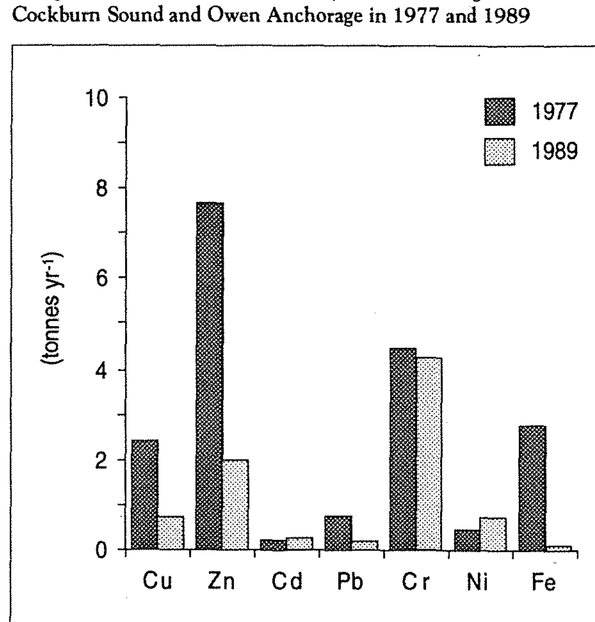


Figure 12 —
Comparison of annual loads of heavy metals discharged into Cockburn Sound and Owen Anchorage in 1977 and 1989



Comparisons of the mean concentrations of the heavy metals in the sediments of Cockburn Sound in 1977 and 1989, show significant reductions have occurred over that period, particularly for Cu, Cd, Fe, Pb and Cr (Figure 11) reflecting significant reductions in the discharges of these metals into the waters of the Sound over the same period (Figure 12). World-wide comparisons, however, indicate that the sediments of Cockburn Sound are now relatively uncontaminated with the heavy metals measured in this survey.

Organochlorine & organophosphate pesticides and PCBs

Measurable quantities of pesticides were recorded in sediment samples in less than 5% of the sites surveyed. The OC pesticides, DDT and dieldrin, were detected in sediments from Success and Fremantle Harbours and at a site in the Cockburn Sound basin. DDT was also found in sediment from Success Harbour. The OP pesticide, malathion, was detected in the sediments of Fremantle Harbour and at a site in the Cockburn Sound basin. The latter site also contained fenitrothion. Traces (< 10 $\mu g\ kg^{-1}$) of PCBs were detected at two sites in the Cockburn Sound basin. These results are significantly lower than concentrations in comparable areas elsewhere (Sericano, 1990) indicating that the sediments of the areas surveyed are not significantly contaminated with these substances.

Organotin

Organotin compounds were detected at all 64 sites and concentrations of tributyl tin (TBT), the most toxic of the organotin compounds, was detected at 53 sites. These results indicate widespread contamination of the study area by these compounds. TBT contamination of sediments was highest in the Fremantle boat harbours, the eastern side of Owen Anchorage and Cockburn Sound, Careening Bay and Thomson Bay on Rottnest Island (Figure 13). These areas are all associated with high shipping/boating activity or ship building/maintenance operations.

TBT concentrations in sediments at approximately 20% of the sites was medium to very high according to a classification by Waite *et al.* (1991). The widespread TBT contamination in sediments throughout the study area is of concern as this substance is known to cause deformities and reproductive disorders in a variety of marine organisms (see Section 4.8).

Aliphatic and polyaromatic hydrocarbons

Contamination of sediments by aliphatic hydrocarbons was not widespread throughout the study area and was restricted to sites in harbours and adjacent to industrial outfalls on the eastern shelf of Cockburn Sound. Measurable (> 1$\mu g\ g^{-1}$) quantities were detected at a site in Fremantle Harbour and at two sites in Cockburn Sound with traces (< 1$\mu g\ g^{-1}$) detected at a further seven sites. The presence of even-numbered carbon compounds in these samples suggest that petroleum products were the origin of the hydrocarbons.

The concentration and distribution of hydrocarbons in sediments in Perth's coastal waters, are considerably lower than levels detected in the late 1970s (Alexander *et al.* 1979; Chegwidden, 1979), and compared with other part of the world, are indicative of uncontaminated waters (Risebrough *et al.* 1983). The concentration of aliphatic hydrocarbons in sediments from unpolluted waters range from two to 26 $\mu g\ g^{-1}$ (Sleeter *et al.* 1980). In 1991, the highest concentration of aliphatic hydrocarbons in sediments was 11.8 $\mu g\ g^{-1}$, in Fremantle Harbour. Outside the confines of a harbour, the highest concentration was 1 $\mu g\ g^{-1}$.

PAHs were detected in sediments at 60 sites, indicating a widespread distribution of these compounds in the study area (Figure 14). The most frequently detected PAH compounds in sediments were pyrene and benzo(a)anthracene. PAHs are ubiquitous in marine sediments, with background concentrations of 10 to 15 $\mu g\ kg^{-1}$ in deep sea sediments (Hites *et al.* 1980). Significantly elevated concentrations of PAHs in sediments (>100 $\mu g\ kg^{-1}$) were detected in Fremantle and Challenger Harbours, Jervoise Bay, Woodman Point and Careening Bay, near the AJS and FPA jetties in Cockburn Sound and at a shoreline site in Owen Anchorage.

Source documents —
Monk (1989); Monk and Murray (1991); Burt *et al.* (1993).

Further work —

- A more comprehensive survey of the nutrient concentrations in the interstitial water of the sediments of the study area will be undertaken in 1993/94;
- A repeat of the 1991 survey of organotin compounds in sediments will be undertaken, in 1993/94, in areas where significant contamination was present in 1991; and
- A repeat of the 1989 survey of the heavy metal concentrations in the sediments of the study area will be undertaken in 1993/94.

Figure 13 —
Distribution of tributyl tin concentrations in sediments in 1991

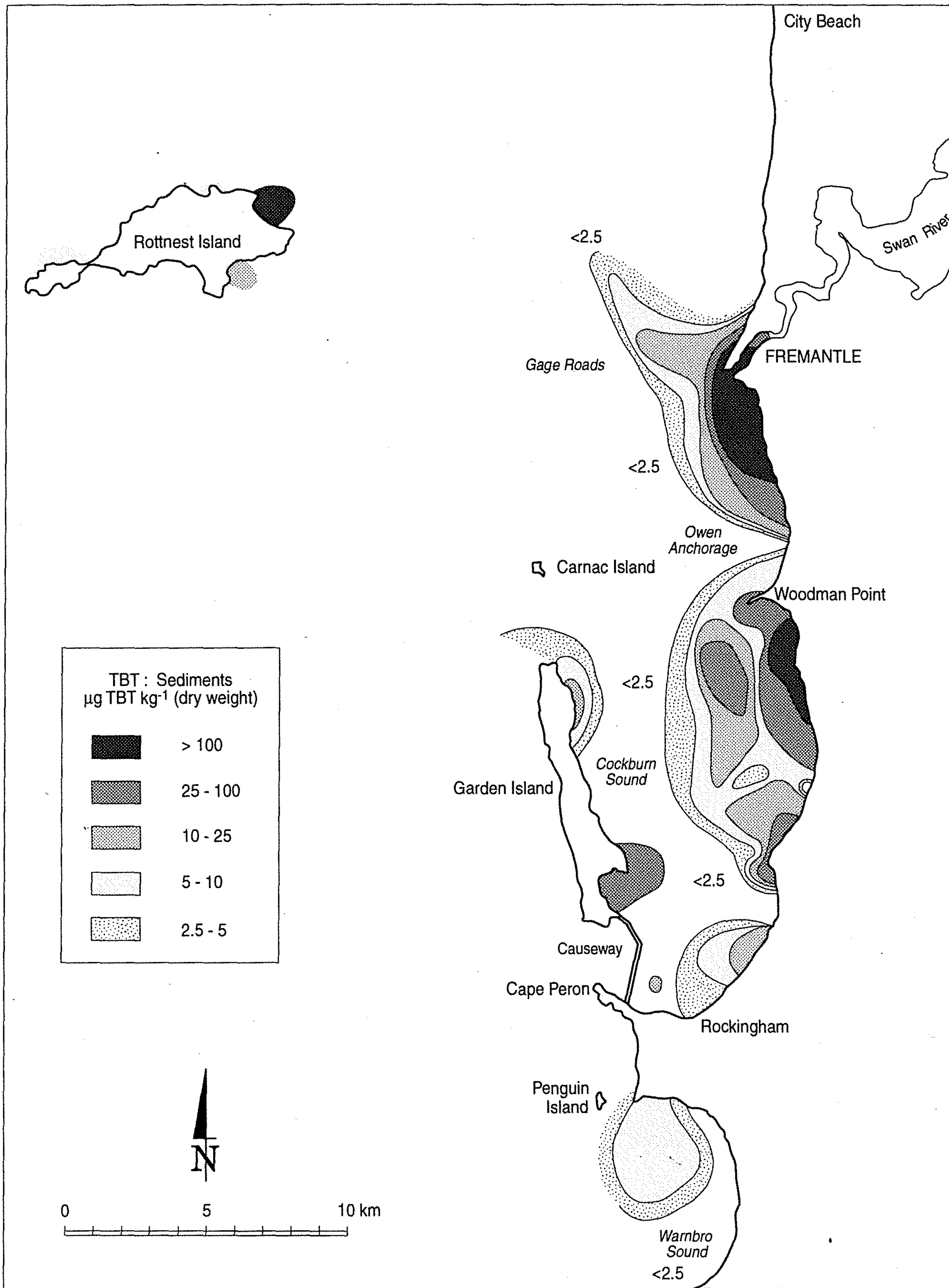
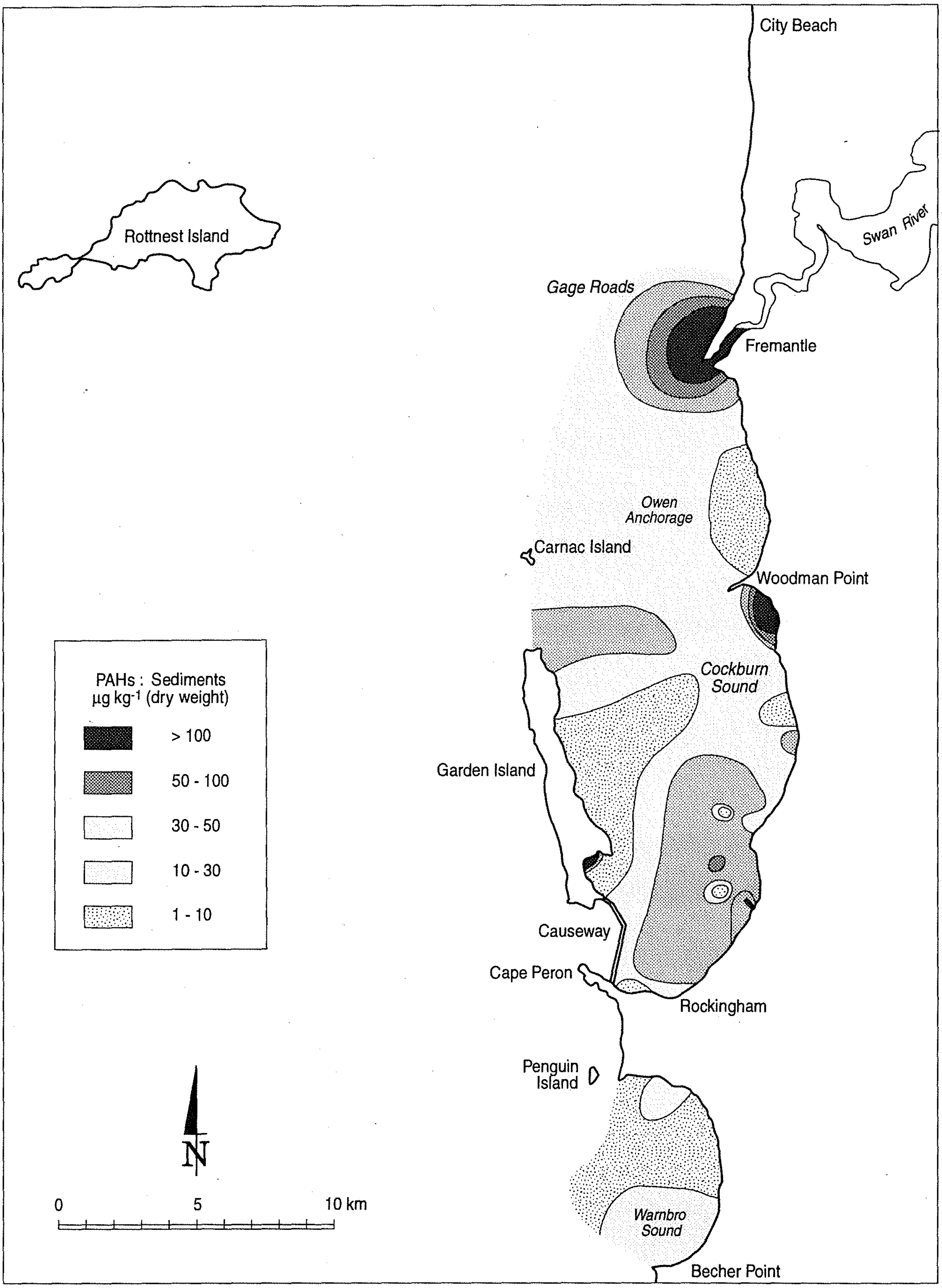


Figure 14 —
Distribution of polyaromatic hydrocarbon concentrations in sediments in 1991



4.6 Contaminants in biota

As part of the characterisation phase of the SMCWS, surveys were conducted throughout the study area to determine the concentrations of heavy metals, organophosphate (OP) and organochlorine (OC) pesticides, including polychlorinated biphenyls (PCBs), aliphatic & polyaromatic (PAHs) hydrocarbons and organotin concentrations in the mussel, *Mytilus edulis*. Mussels bioaccumulate these materials and, as such, concentrations in their tissues provide a time-integrated measure of the concentrations of these substances in the water column. The surveys provide a quantitative baseline for future reference as well as, in some cases, providing data for comparison with similar surveys carried out in the past.

In 1989, mussels were sampled at 27 sites, usually from fixed man-made structures such as posts, jetties and beacons and were either the same sites as the 1977 study of Chegwidden (1979) or the closest alternative. The heavy metals Cu, Zn, Cd, Fe, Mn, Pb, Cr and Ni were analysed by Atomic Absorption Spectrophotometry at the Western Australian Chemistry Centre. Detailed methodology can be found in Burt and Scrimshaw (1993).

In 1991, mussels were collected from 34 sites throughout the study area. Samples from 31 sites were analysed for OP and OC pesticides, including PCBs, aliphatic hydrocarbons and PAHs. The OC pesticides were aldrin, dieldrin, alpha and beta chlordane, oxychlordane, heptachlor, heptachlor epoxide, HCB, lindane, p-p'DDE, p-p'DDD, o-p' & p-p'DDT and the OP pesticides included chlorpyrifos, fenitrothion and maldison (malathion). Analysis of PAHs targeted naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo-(a)anthracene, chrysene and benzo-(a)pyrene. Detailed description of the methods used for determining the concentrations of organic pollutants in mussels can be found in Burt *et al.* (1993). Organotin (monobutyl, dibutyl, tributyl tin) concentrations were determined in mussels from 33 sites. Analyses were conducted by the CSIRO Division of Advanced Analytical Chemistry at Lucas Heights (methods in Batley *et al.* 1988). The results of these surveys are tabulated in Burt *et al.* (1993).

Heavy metals concentrations

The mean concentrations of heavy metals in mussels for all sites surveyed in 1989 were significantly lower than the levels in 1977 (Figure 15; Chegwidden, 1979). These reductions were associated with a substantial decreases in the discharge of heavy metals into the waters of the study area over the same period (Figure 12). The largest decreases were at sites adjacent to the Kwinana Industrial area along the eastern shoreline of Cockburn Sound (Figure 16).

In 1977, the concentrations of cadmium and lead in mussels at a number of sites adjacent to the Kwinana Industrial area exceeded the levels recommended by the Western Australian Health Department for metals in seafood. The concentrations of zinc at some of these sites, and chromium at several sites in Owen Anchorage, were also cause for concern (Chegwidden, 1979). In 1989, the mean concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe in mussels, at all 27 sites in the study area, were below the Western Australian health standards (NHMRC, 1990).

Figure 15 —
Mean heavy metal concentrations in mussels from Cockburn Sound (Zn and Fe have been reduced by a factor of 10)

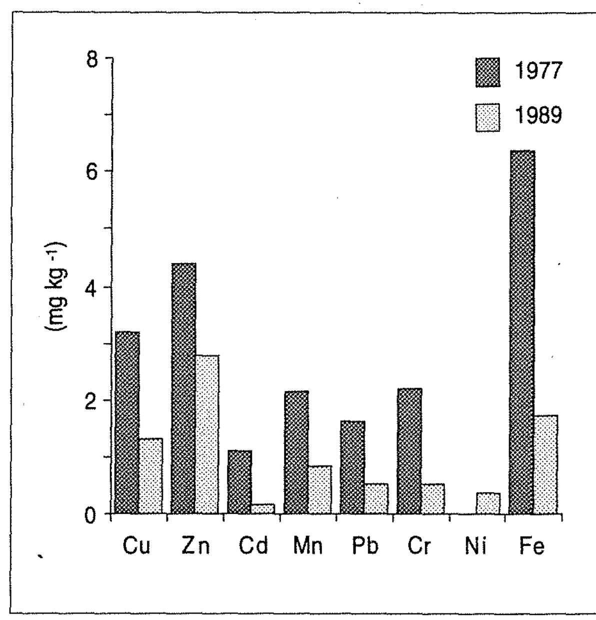
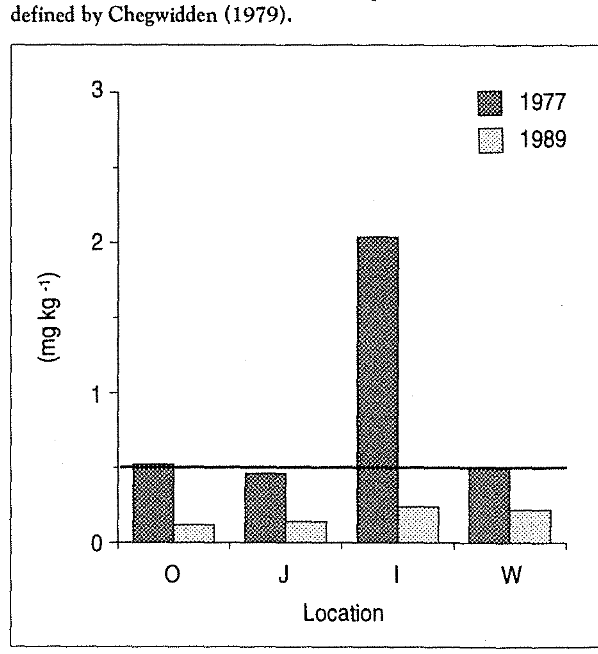


Figure 16 —
Mean concentration of cadmium in mussels at four locations within the study area. (O) Owen Anchorage, (J) Jervoise Bay, (I) Industrial Area, (W) Western Area near Garden Island. The horizontal line indicates the limit of acceptable contamination as defined by Chegwidden (1979).



In 1977, the mean concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe in mussels exceeded the levels of acceptable ecological contamination as defined by Chegwidden (1979). In 1989, the mean concentrations of all these metals, except chromium, were below these levels.

Organochlorine & organophosphate pesticides and PCBs

OC pesticides were detected (>1µg kg^{-1}) in mussels at two sites in Owen Anchorage. Chlordane, DDT, dieldrin and heptachlor were detected in mussels at a site off Success Harbour and chlordane was detected in mussels from Fish Rocks. OP pesticides and PCBs were not detected in the tissue of mussels at any sites.

The distribution of pesticides and PCBs in mussels was confined to harbours or immediately adjacent to harbours and ship-building facilities. These concentrations are considerably lower than concentrations in other comparable parts of the world and compare favourably with levels from the northern Californian coast, considered to be relatively unpolluted (Risebrough *et al.* 1983).

Organotin

Organotin compounds were detected in mussels at all but one of the 33 sites, indicating that these substances are widely distributed. TBT was detected at 29 sites, and concentrations were above background levels at 90% of these sites (Figure 17). Background concentrations (i.e. < 0.5 µg TBT kg^{-1} wet weight) occurred at sites in Warnbro Sound and in Challenger Passage, at the northern entrance to Cockburn Sound (Figure 1). TBT contamination of mussels was highest in Fremantle Harbour and mussels from this site, and at a site adjacent to Jervoise Bay, exceeded the World Health Organisation health standards (i.e. 146 µg TBT kg^{-1} wet weight) for the consumption of food containing this substance (WHO, 1989). Highest TBT contamination in mussels was centred around harbours/marinas and sites associated with high shipping activity or ship building/ maintenance operations.

According to a classification of TBT concentrations in mussels by Page and Widdow (1991), mussels at 25% of the sites were moderately contaminated by concentrations likely to cause physiological stress. The high proportion of samples with elevated concentrations of TBT is of some concern, especially as marine gastropods (*Conus* spp.) from Rottnest Island have shown the reproductive disorder *imposex* (Kohn and Almasi, 1993), which has been linked to TBT contamination (see Section 4.8).

Aliphatic and polyaromatic hydrocarbons

Measurable concentrations of aliphatic hydrocarbons (>1 µg g^{-1}) occurred in mussels at two sites in Cockburn Sound, Woodman Point and the SEC outfall. Traces (<1 µg g^{-1}) were detected in mussels at a further seven sites. At the two sites where concentrations exceeded 1 µg g^{-1}, the analyses indicated the presence of even-number carbon compounds, suggesting petroleum products as the origin of the hydrocarbons.

The concentrations of aliphatic hydrocarbons in the tissue of mussels recorded during the 1991 survey were considerably lower than levels detected in the late 1970s (Alexander *et al.* 1979; Chegwidden, 1979), and compared with other part of the world, are indicative of uncontaminated waters (Risebrough *et al.* 1983).

PAHs were detected in mussel tissue at 27 sites indicating widespread distribution of these compounds over the area surveyed (Figure 18). The most frequently detected PAH compound in mussels was naphthalene. Significant concentrations (>100 µg kg^{-1}) of PAHs were not found at any sites and total concentrations exceeded 10 µg kg^{-1} at only three sites on the eastern margin of Cockburn Sound. The most likely source is from petrogenic inputs (i.e. diesel, fuel oil, etc). Total PAH concentrations in the tissue of mussels in uncontaminated waters range between 50 to 140 µg kg^{-1} (Rainio *et al.* 1986). In the 1991 survey, the highest concentration was 12 µg kg^{-1}.

Source documents —
Burt and Scrimshaw (1993); Burt *et al.* (1993).

Further work —
A repeat of the heavy metal and organotin surveys will be undertaken in 1993/94.

Figure 17 —
Distribution of tributyl tin concentrations in mussels in 1991

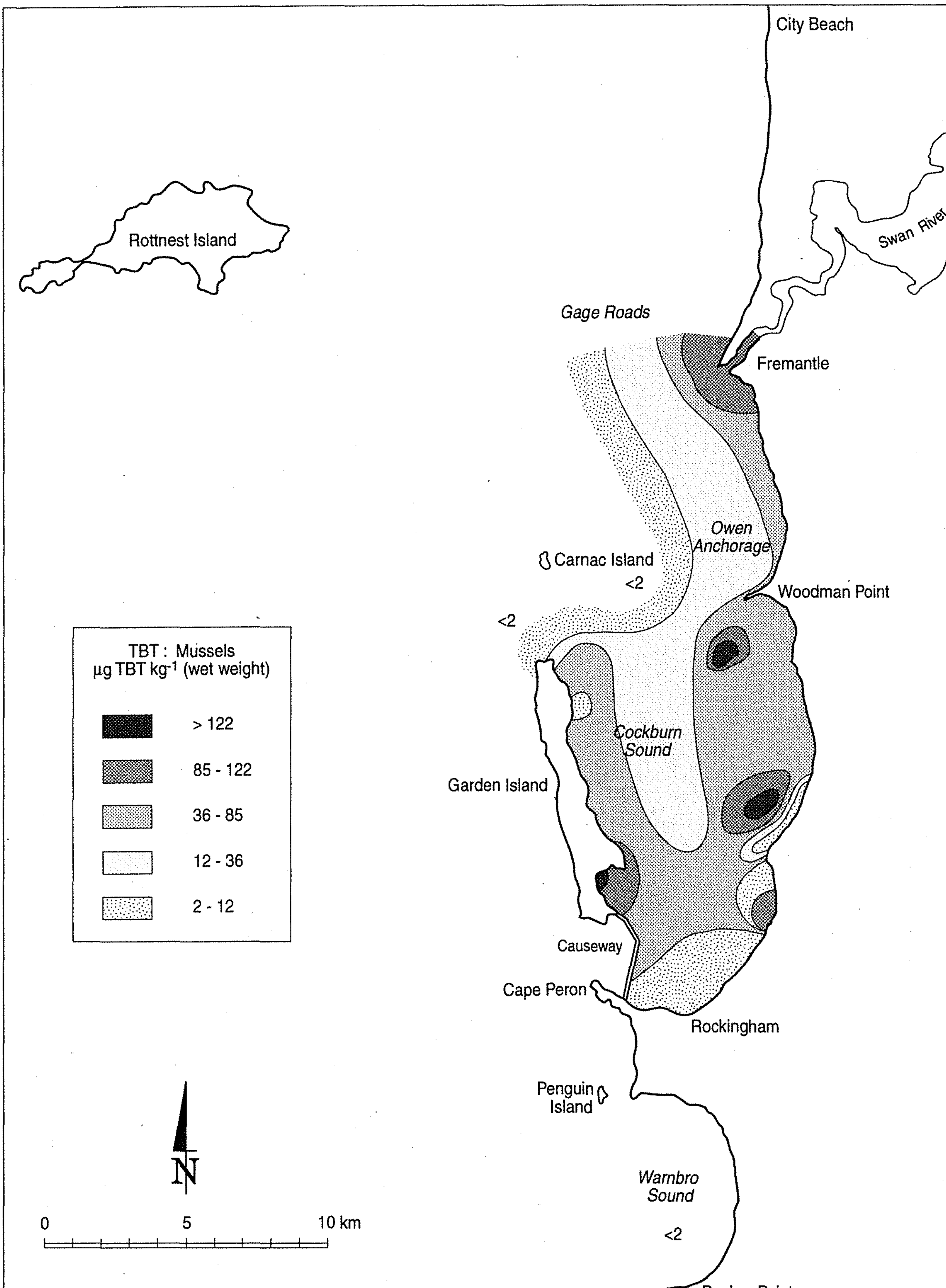
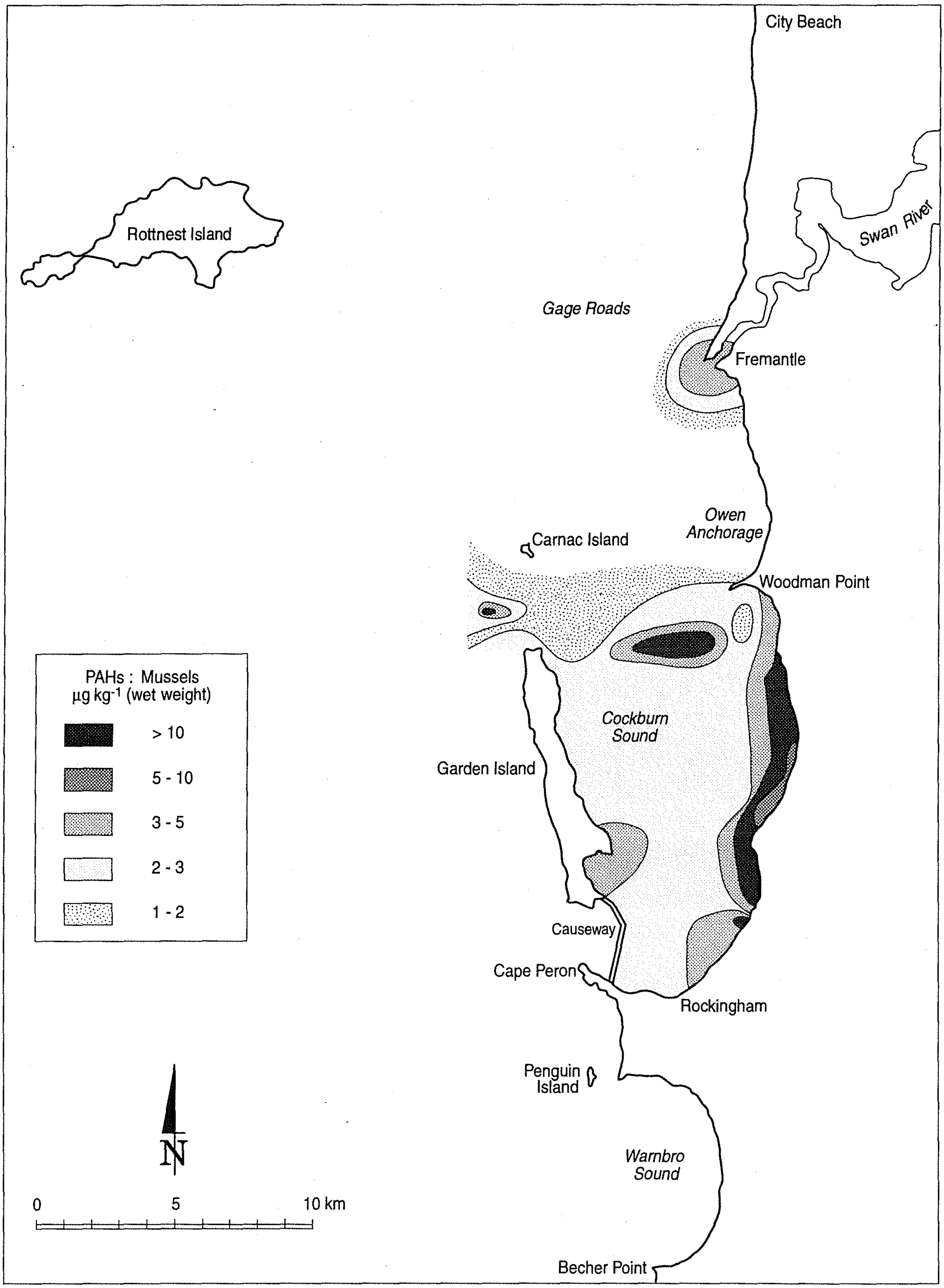


Figure 18 —
Distribution of polyaromatic hydrocarbon concentrations in mussels in 1991



4.7 Deep basin invertebrate fauna

Introduction

A survey of the benthic invertebrate fauna of the deep (>10 m) basins of Cockburn Sound and Warnbro Sound was undertaken as part of the characterisation phase of the SMCWS. The objectives of this study are to provide a quantitative description of the species composition and abundance of the benthos of the deep basins, to provide baselines for future reference, and to determine if temporal changes in species composition and abundance of selected taxa in Cockburn Sound have occurred since the studies of Wells (1978) and Wells & Threlfall (1980). The distribution and abundance of the benthos in Cockburn Sound and Warnbro Sound will be compared to the chemical and mineralogical characteristics of the sediments.

A pilot study was conducted in March 1993 to assess the small-scale spatial patchiness of the benthic invertebrate communities in Cockburn Sound. The field programme was undertaken in early April 1993 to coincide approximately with the seasonal timing of the study of Wells (1978). Four replicate samples were taken by Van Veen grab at 30 sites in Cockburn Sound and 15 sites in Warnbro Sound. Samples were processed in the field through 1.7 mm and 1 mm sieves. The location of sites was based on those used for sediment sampling by Chegwidden (1979), Monk & Murray (1991) and Burt *et al.* (1993). In Cockburn Sound, these sites are evenly spaced on a grid throughout the deep basin. The species diversity and abundance of the phyla Echinodermata, Mollusca, Annelida and Crustacea will be determined.

The samples collected in the April survey are currently being processed.

Further work —
A collaborative study with the University of Western Australia, involving a more intensive sampling regime (i.e. nine grabs per site) was conducted, in July 1993, at three of the April survey sites in Cockburn Sound and Warnbro Sound (see Section 8.2).

4.8 Frequency of imposex in Thais orbita

Tributyl tin (TBT) is the most toxic component of organotin based antifouling paints and has been used widely around the world since the 1950s. In the late 1960s, deformities were recorded in marine animals living in the vicinity of marinas and these abnormalities were linked to TBT contained in the antifoulants used on the hulls of boats. In 1990, the EPA conducted a pilot study of TBT contamination of sediments in the vicinity of selected yacht clubs in the Swan River and near ship-building facilities in Cockburn Sound (EPA, 1990). Several sites were significantly contaminated with TBT. Since November 1991, the use of organotin antifouling paints in Western Australia has been prohibited on boats with hulls under 25 m in length. Boats over 25 m, however, are still permitted to use low leaching forms of these paints. International ships are outside state jurisdiction.

In November 1991, a survey of TBT contamination of sediments and biota was undertaken in the southern metropolitan coastal waters of Perth as part of the SMCWS. Sediments and mussels throughout the study area were found to be contaminated with TBT and some of these results are presented in Sections 4.5 and 4.6. The most surprising result was that the sediments of Thomson Bay, at Rottnest Island, were significantly contaminated with levels about 400 times higher than background values.

In 1991, a study of *Conus* (cone shells) at Rottnest Island found 80% of female specimens from 6 species of *Conus* displayed evidence of the reproductive disorder, imposex (imposed sexual characteristics (Kohn and Almasi (1993)). A recent examination of preserved museum specimens collected from Rottnest Island in 1975 showed no abnormalities.

Imposex in molluscs has been linked to TBT contamination in many other parts of the world. The occurrence of imposex in molluscs at Rottnest Island and the widespread contamination of TBT in the southern metropolitan coastal waters, raises concern as to the potential impact of TBT on inshore mollusc populations closer to areas of high contamination. The EPA is collaborating with the Zoology Department of the University of Western Australia and the WA Museum to partly answer this question (see Section 8.2). A pilot study will examine the frequency and spatial extent of imposex in *Thais orbita*, a neogastropod that is widespread on intertidal reef platforms throughout the study area. This species is known to be affected by TBT. Preliminary surveys have been undertaken to find unaffected animals for use in experiments to confirm the link between TBT contamination and imposex in *T. orbita*. A survey of imposex in *T. orbita* will be carried out in August 1993 on intertidal reefs along a north-south transect from Ocean Reef to Becher Point, and an east-west transect from Fremantle to Rottnest Island. This study will be completed in November 1993.

Source documents —
EPA (1990); Burt *et al.* (1993).

Further work —
The need for further work will depend on the results of this study.

PHYSICAL OCEANOGRAPHY

The hydrodynamic flushing characteristics of receiving waters are important in determining the relationships between pollutant load and its effects on the ecosystem. Water circulation, density stratification and the energetics of mixing affect the horizontal and vertical distribution and concentration of contaminants throughout the waterbody. Hence an understanding of the coastal oceanography of the southern metropolitan coastal waters is essential to meeting the goals of the overall study. The objectives of the physical oceanography component of the SMCWS are —

- to characterise the hydrodynamic response of the southern metropolitan coastal waters to both local forcings (e.g. local wind stress) and larger scale forcings (e.g. low frequency variations in sea level on the continental shelf);
- to characterise the time and space scales of transport and dispersion of materials (e.g. contaminants, phytoplankton), characterise potential transport paths (linkages) between contaminant sources and areas of ecological significance, and determine the relative influence of contaminant inputs to these basins from internal and external sources; and
- to implement, calibrate and validate hydrodynamic and transport models of the study area and supply the necessary oceanographic inputs to an ecological model.

The oceanographic programme was designed to fill critical gaps in existing information that had been identified in past studies and in the review phase of this study (Section 2.3). The field programme covered the period August 1991 to February 1993 and included the following components:

Intensive oceanographic surveys

Two intensive field exercises were mounted to characterise the hydrodynamic processes operating on time scales ranging from hours to several days over the entire study area (Figure 19). The physical measurements were carried out in conjunction with complementary water quality measurements which provided additional tracers of water movement. 'Winter' (13-22 August 1991) and 'summer' (9-27 March 1992) periods were chosen for the intensive field exercises. Fixed-point current meter, meteorological, wave and water level data were recorded concurrently with the following measurements during both periods —

- CTD profiles (twice in August 1991 and five times in March 1992) along Transect A, from Trigg Island to 80 km offshore (to a maximum depth of 300 m);
- CTD or ST profiles along transects B, C, D, E and F (generally daily);
- ST profiles along transects G, H and I (generally daily, March 1992 only);
- ST profiles along transects J through Q (generally daily);
- CTD profiles along transects covering the Swan River mouth, Owen Anchorage, Cockburn Sound and Sepia Depression (generally covered two to three times per day, with some selected transects visited up to five times in any one 24-hour period); and
- Acoustic Doppler Current Profiler (Cockburn Sound, two days during March 1992), drogue tracking (Cockburn Sound, seven days in August 1991, eight days in March 1992) and vertical current profiling at four sites (Cockburn Sound, six days in August 1991).

Seasonal time-series

Time-series of water temperature, current speed and direction, generally at two depths in the water column, and at locations within and external to Cockburn Sound, were measured over a 12-month period. Additional current meters were deployed during the summer and winter intensive surveys. Concurrent meteorological time-series data were available from a number of coastal stations, and from Rottnest Island. A long-term water level recorder was installed at Rockingham for the SMCWS by the Department of Marine and Harbours. Other water level time-series were obtained from Mandurah, Fremantle and Hillarys. Wave data have been collected at a site to the southwest of Rottnest Island by the Department of Marine and Harbours since July 1991. Water discharge data for the Swan River were obtained from the Water Authority of Western Australia. Discharge data for the Peel-Harvey catchment were supplied by the Waterways Commission.

Seasonal CTD surveys

The seasonal evolution of the vertical and horizontal structure of temperature, salinity and density of the nearshore basins and of the surrounding mid-shelf waters was tracked at approximately monthly intervals from October 1991 to February 1993.

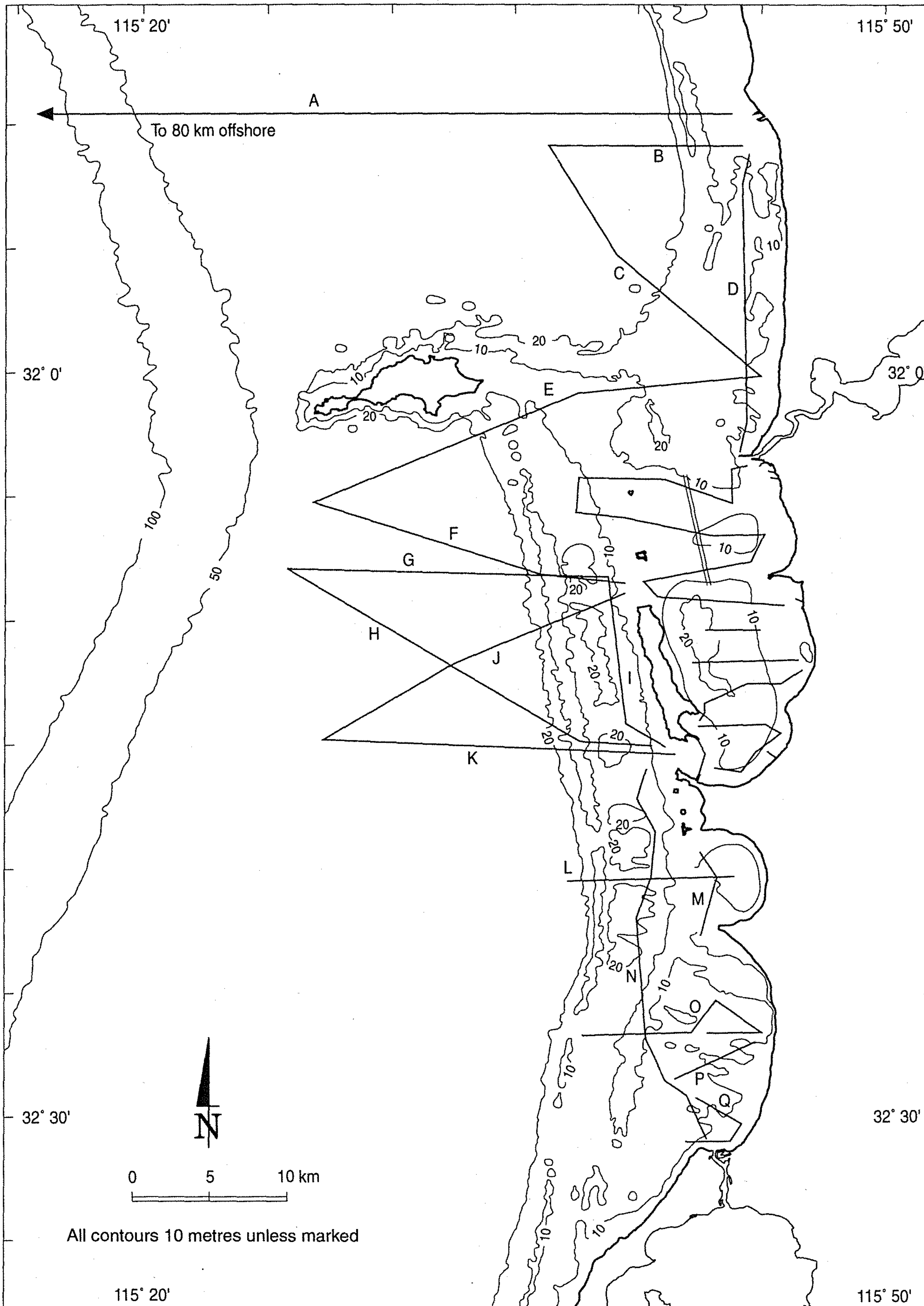
Remote sensing

NOAA-AVHRR imagery of sea surface temperature was used to analyse large scale oceanographic features offshore, and to aid the interpretation of the cross-shelf CTD data. More resolute LANDSAT imagery (pseudo colour and thermal bands) was used to aid the interpretation of the cross-shelf CTD structure, and to track the fate of water emanating from the Swan-Canning and the Peel-Harvey estuaries.

Data analysis

Salinity and temperature data have been calibrated and produced as vertical profile plots and contour plots along standard transects. Current and wind data have been plotted as time-series. Summary statistics derived from these records include joint speed/direction frequency of occurrence and persistence distributions. Cross-spectra between various temporally concurrent time-series data sets will be used to investigate

Figure 19 —
Location of salinity and temperature transects in the study area



relationships between meteorological forcings and hydrodynamic responses. Satellite images have been rectified and processed in colour in collaboration with the Remote Sensing Applications Centre of DOLA.

5.1 Shelf-scale processes

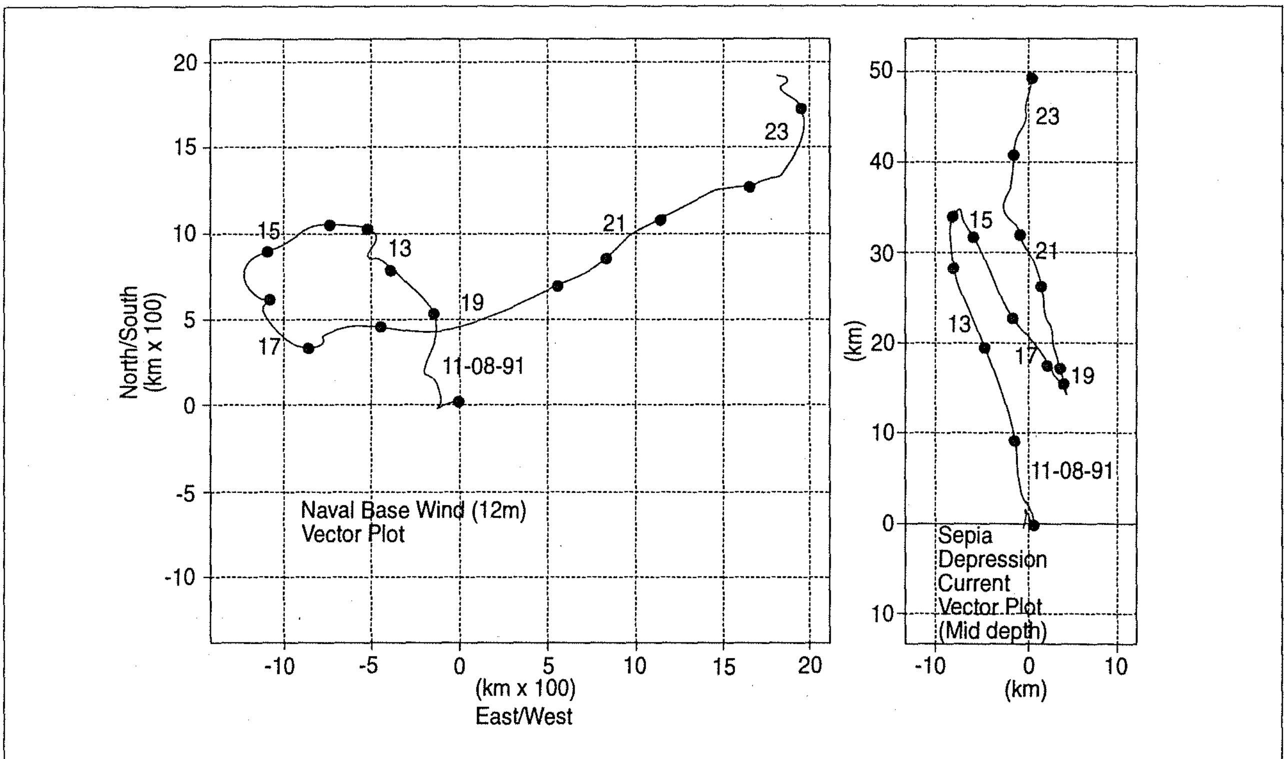
Water currents over the continental shelf off metropolitan Perth are driven principally by wind stress, regional scale poleward pressure gradients associated with a drop in sea level along the west coast of Australia, and meso-scale pressure gradient forces. In shallow water, the wind stress is the dominant forcing; in deeper offshore water, the long-shelf pressure gradient dominates. Where wind stress opposes the pressure gradient force, the shore parallel current may reverse at some distance off the coast, with downwind current nearshore, and reversed current offshore. The bathymetric distribution of the area (including the shape of the coastline and the presence of islands and reefs) guides the water flow. The influences of the earth's rotation and bottom friction are important, particularly in introducing a component of movement and exchange of water in the cross-shelf direction. The interaction and response of different water masses (whose temperature-salinity-density characteristics were determined either nearshore, or further offshore) to the above forcings depends critically on the density differences between these water masses, and the energy available for mixing.

Winter dynamics

Atmospheric high pressure systems and intervening cold fronts migrate eastward over southwest Australia. Winter winds are typically cyclic (period 7-8 days) with episodic northwest to west gales associated with passing cold fronts, followed by longer periods of moderate and weak winds swinging through the south and the east as extensive high pressure systems move through. The wind vector plot in Figure 20 is from the 13-23 August 1991 intensive survey and shows one such typical winter wind cycle. These winds drive longshore coastal currents with speeds of order 0.1 m s^{-1}, with current direction reversals (accompanying major wind shifts) occurring at intervals of about 3-4 days. This current pattern is typified by the current vector plot in Figure 20, obtained from a moored current meter in central Sepia Depression, west of Cape Peron. The coastal water therefore tends to flow longshore several tens of kilometres before reversing upon itself. This is a small distance compared to the length of the metropolitan coastline. Hence, in winter, the potential for longshore flushing of pollutants from Perth's coastal waters can be limited. It is therefore important to understand to what extent flushing of coastal waters can occur in the cross-shelf direction.

The Leeuwin Current advects, warm, tropical water poleward along the edge of the continental shelf. The August 1991 intensive oceanographic survey clearly identified the presence of

Figure 20 —
Wind and current runs in Sepia Depression showing current reversals associated with changes in wind direction



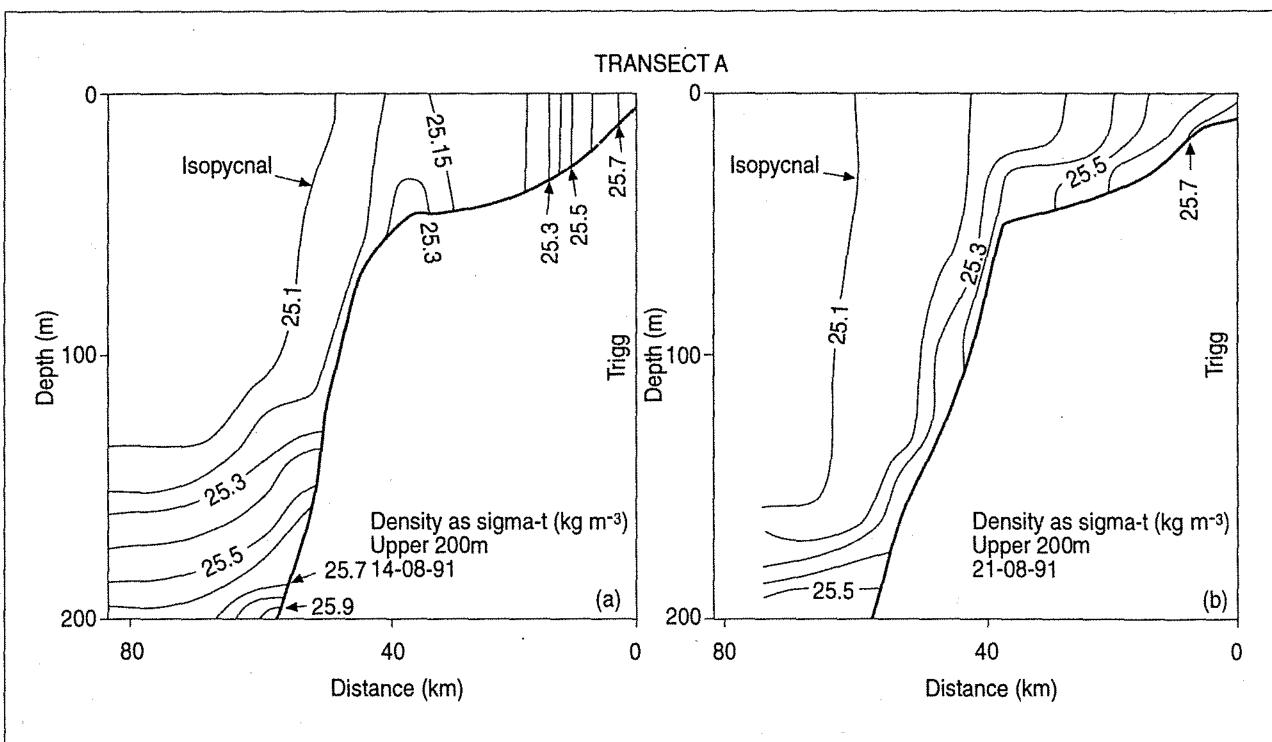
this current (as a 160 m deep, well-mixed, warm water core) located over the outer continental shelf and slope (see back cover, and Figure 21). Relatively cool, fresh coastal water is formed by enhanced cooling in the shallows and mixing with freshwater sources (rivers and groundwater). Generally, the cool coastal water is denser than the warm Leeuwin Current water, except in the vicinity of estuarine outlets. The cross-shelf exchange of these waters is governed to a large degree by the interaction between wind stress, pressure gradient, the effect of the earth's rotation, and the density differences (both horizontal and vertical) between these adjacent water masses.

While the Leeuwin Current flows southward close to the edge of the continental shelf, there is a secondary transport of warm water onto the shelf, due to shoreward geostrophic flow, which tends to be balanced by offshore flow in a frictional boundary layer near the seabed. This situation leads in winter to layered cross-shelf exchange, with denser coastal water moving obliquely offshore beneath incoming lighter (warmer) water. This occurred between 14 and 21 August 1991, and the resultant change in density structure is shown in Figure 21. The details of this layered cross-shelf circulation are influenced by mixing due to wind and bottom frictional stresses, and by density differences between the coastal and offshore waters. Because of the depth (~150 m) of the Leeuwin Current surface mixed layer, and the general absence of strong, sustained southerly winds, wind-induced upwelling of deeper waters onto the mid-shelf is unlikely to occur in winter (and was not observed).

Mesoscale instabilities of the Leeuwin Current (i.e. meanders of the Current growing seaward) are common. They induce anticlockwise circulation of the warm Leeuwin Current water, which moves away from the continental shelf as it enters and begins to circulate about the meander. On the inner side of the meander, northward flow over the continental shelf and slope may be generated, and such reversals of the typical flow direction may persist for a week or more. Such a northward flow was observed to induce weak sub-surface "upwelling" of deeper water (>160 m) over the outer shelf (but not up to the mid-shelf) and to inhibit cross-shelf exchange of waters across the mid and inner shelf. Under these conditions, denser coastal waters, including nutrient-rich estuarine plumes were trapped on the shelf for about one week, during which time mixing and dilution rates of these plumes were low. The long-shore extent of this behaviour was probably governed by the corresponding north-south size (about 100 km) of the offshore Leeuwin Current meander.

Plate 1 presents satellite images of the study region from the August 1991 survey period and highlights the spatial variability of features associated with the Leeuwin Current, and with mixing processes over the shelf. Plates 1a and 1b shows the regional sea-surface temperature (SST) structure associated with the Leeuwin Current for 15 August 1991. Two large mesoscale meanders off Perth are clearly evident. Plates 1c and 1d are higher resolution images of water colour and SST, respectively, from the Landsat TM satellite pass of 0930 on 14 August 1991. These images highlight the range of spatial scales associated with the billows,

Figure 21 —
Density structure in winter off Trigg showing a) shelf-scale upwelling and trapping of coastal waters in the nearshore zone and b) offshore movement of dense nearshore waters along the bottom



meanders and fronts associated with the mid-shelf region between the Leeuwin Current and the coastal zone.

A major incursion of the Leeuwin Current onto the mid and inner shelf off Trigg was observed to persist for about 10 days during August 1991 (Plates 1c and 1d). A marked temperature-density front was located at the boundary between this warm water incursion and cooler coastal water. This front was generally located within 16 km of the coast. It was observed to migrate shoreward during conditions of predominantly northerly winds and southward coastal current, and subsequently to reach the coast following the onset of strong westerly winds and longshore coastal current reversal. The warm water moved shoreward on top of an offshore underflow of denser coastal water. During southerly winds and northward coastal currents, the surface front again moved to an offshore position. Under these conditions, the frontal structure became almost vertical and tended to limit the extent of offshore movement of coastal water.

Estuarine plumes from the Peel-Harvey and the Swan-Canning estuary have been identified using *in situ* salinity, temperature, nitrate and phytoplankton measurements, and remotely-sensed LANDSAT imagery (Plates 1c and 1d (14 August 1991) and 1e and 1f (23 August 1991)). These plumes have been observed to extend more than 50 km northward over the mid and inner continental shelf. The data suggest that inshore embayments and basins such as Comet Bay, Warnbro Sound and Sepia Depression can be significantly influenced by the Peel-Harvey estuary plume.

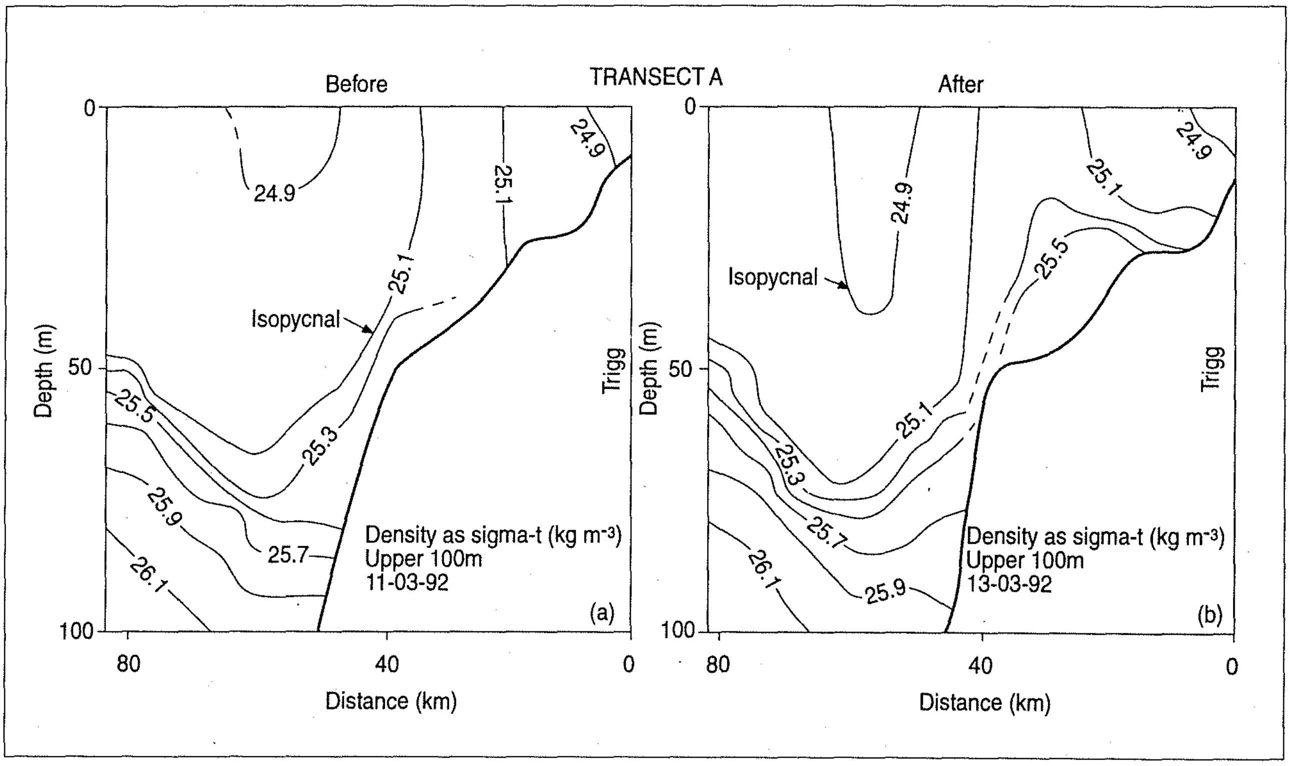
The Swan River plume has been traced as far as 60 km north of the source (Plates 1c and 1d), but under northerly to northwesterly wind conditions enters Owen Anchorage and Cockburn Sound. The injection of this buoyant, less saline water to these water bodies has a marked effect on their hydrodynamics.

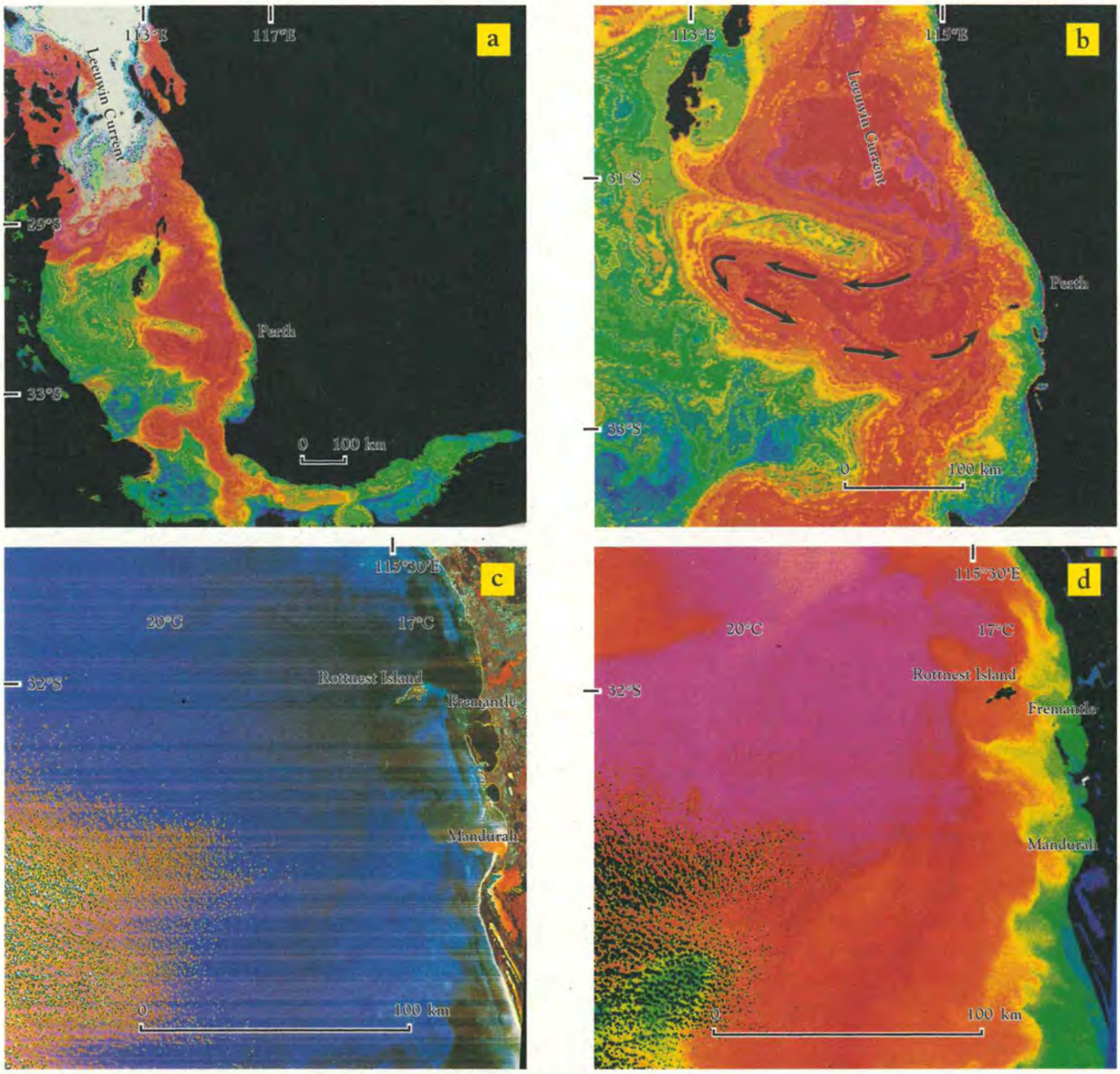
Analysis of the winter shelf-scale dynamics is continuing.

Summer dynamics

In March 1992, CTD measurements across the continental shelf again indicated the presence of warm Leeuwin Current water over the outer shelf. However at this time of the year the depth of the well-mixed warm core of the Current was typically 60 m, considerably shallower than for the preceding winter observations. Five repeated CTD transects across the shelf over a three week period suggest that transient upwelling of cooler water from depths greater than 60 m over the outer shelf occurred. For example, between 11 - 13 March 1992, upwelled water was observed to move across the mid-shelf to within about 10 km of the coast, where it was overlain by warmer, more buoyant coastal water, which tended to spread offshore as it drifted northward under the influence of predominantly southerly winds. Figure 22 presents the cross-shelf density structure along Transect A (see Figure 19) of the 11 and 13 March 1992. The upwelling is indicated, for example, by following the shoreward movement of the 25.5 kg m^{-3} isopycnal which moved vertically upwards from the 80 m to the 20 m depth and shoreward from 45 km offshore

Figure 22 —
Density structure in summer off Trigg a) before and b) after transient upwelling of shelf waters into the nearshore zone north of Rottnest following strong southerly winds





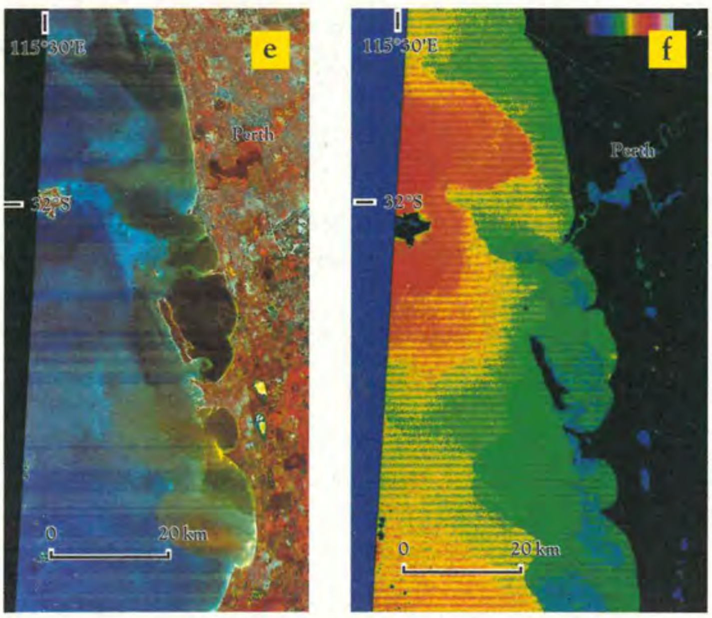


Plate 1 —
Satellite imagery of sea-surface temperature and water colour structures from NOAA-AVHRR and Landsat TM data collected in August 1991
(Plates 1a to d reproduced from Wyllie *et al.* 1992)

a) NOAA-AVHRR sea-surface temperature image of the Leeuwin Current on 15 August 1991

b) Detail of the meander west of Rottnest Island from the NOAA-AVHRR sea-surface temperature image of 15 August 1991

c) Colour Landsat TM image of the southwest Australian coastal zone on 14 August 1991

d) Pseudo colour thermal band Landsat TM image of the southwest Australian coastal zone on 14 August 1991

e) Colour Landsat TM image of the southwest Australian coastal zone on 23 August 1991

f) Pseudo colour thermal band Landsat TM image of the southwest Australian coastal zone on 23 August 1991 to within about 10 km of the coast at Trigg. The upwelling occurred following strong (>10 m s^{-1}), sustained (>12 h) northward wind events suggesting wind as the principal cause.

Analysis of the summer shelf-scale dynamics is continuing.

Source documents —
Hearn, 1991; D'Adamo, 1992; Mills *et al.* (submitted); Mills *et al.* (in preparation).

5.2 Basin-scale processes

The objectives of the hydrodynamic studies of the semi-enclosed nearshore basins were to identify the dominant characteristics of water movements and mixing within individual basins and the exchange characteristics between the basins and adjacent oceanic waters.

Seasonal characteristics

There is a clear seasonal trend in the salinity and temperature of the nearshore zone with highest values in late summer due to evaporation and solar heating and lowest values in winter due to freshwater inputs via rivers and atmospheric cooling. In addition, the nearshore zone fluctuates more widely in these characteristics than the waters offshore. In summer, the nearshore zone is more saline and warmer than offshore waters because it is relatively shallow and the differential effects of evaporation and heating are most pronounced. In winter the reverse is true, with the nearshore zone significantly less saline due to dilution by coastal freshwater fluxes (e.g. the Swan River) and differential cooling. Reversals in these trends occur during the spring and autumn periods. Figure 23 highlights these features for Cockburn Sound and Sepia Depression.

Finer details of the spatial characteristics of the inner shelf structure were revealed by monthly CTD data collected along transects throughout the nearshore basins and the waters south of Rottnest during 1991-1993. Significant vertical and horizontal structure in salinity (S), temperature (T) and density (D) was identified to be characteristic of the nearshore zone throughout the year, with the elimination of vertical stratification only occurring during particularly strong wind events (>10 m s^{-1}). Figure 24 exemplifies the characteristic spatial variability in the vertical and horizontal stratification captured by CTD profiling in the region Cottesloe-Rottnest-Cockburn Sound on 21 October 1992; winds speeds preceding and during that day were between 3 and 8 m s^{-1}.

The following factors were found to be primarily responsible for the characteristic 'patchiness' in the STD structure of the nearshore zone —

- the injection of pulses of estuarine water into the nearshore coastal zone during winter and spring from the Swan-Canning and Peel-Harvey estuarine systems (see Plate 1) with their timing associated with tidal periodicities (diurnal and semi-diurnal) and rainfall-runoff events (of order 10 or more events occur throughout winter and spring);
- the effect of differential heating and cooling, and the spatially variable salinity increases by evaporation due to depth variation around the region and within the basins;
- upwelling and downwelling caused by wind stress on a vertically stratified basin, and differential deepening by a spatially variable wind stress field resulting from sheltering by land features; and
- the introduction of Leeuwin Current water into the nearshore zone and other regional influences (see Section 5.1).

Intensive oceanographic surveys were conducted to detail more accurately the hydrodynamics of the basins, and the following discussion focusses on the major mechanisms in the Cockburn Sound region.

Winter dynamics

Freshwater flux into Cockburn Sound

During the winter/spring rainfall season coastal freshwater sources significantly reduce the salinity of the nearshore zone, with salinities between 34 and 35 parts per thousand common in Cockburn Sound. Pulses of Swan River discharge flows are advected into Owen Anchorage and Cockburn Sound by southward winds as buoyant surface plumes. This occurred on 17 August 1991 during 5-8 m s^{-1} north-northwest winds (Figure 25). These data also typify the mean stratification in these basins during winter for winds less than 5-10 m s^{-1}, which is usually more than 50% of the time. When winds are stronger than this (i.e. during the passage of NW storm fronts), then full depth mixing can occur.

Diurnal heating and penetrative convection

During the day solar radiation warms the water column with greatest effect near the surface. This temperature stratification enhances the density stratification caused by freshwater flux. At night, heat loss to the atmosphere led to regular surface mixing by penetrative convection, although this mechanism was unable to penetrate below about 15 m depth, due to the presence of what appeared to be a strong parent pycnocline (zone of strongest density gradient), reflecting a strong salinity gradient zone at that depth.

Vertical mixing and horizontal transport by winds

Winds greater than about 10 m s^{-1} were required for full-depth mixing in central Cockburn Sound during the winter intensive survey of 13-23 August 1991. For example, the storm of 19 August (during which winds were 13-15 m s^{-1} for approximately 12 hours) eliminated the strong vertical stratification that preceded this event (Figure 26). Predictive analytical calculations suggest that this wind event would have fully-mixed the water column within 10 hours. Before and after this event, winds ranged between about 3 and 8 m s^{-1} but the basin remained stratified (Figure 26).

Wind stress is one of the principal forces driving horizontal transport of surface waters in the nearshore zone. Preliminary analyses of drogue tracks and current meter records suggest that wind stress can cause strong surface currents of order 0.05-0.30 m s^{-1} during sea-breezes both within Cockburn Sound and across the openings.

Density driven exchange

Basin-scale stratification data suggest that the return to vertically stratified conditions soon after the full-depth mixing of the storm on 19 August 1991 (Figure 26) was in part due to baroclinically enhanced inflow of relatively dense (higher salinity) adjacent oceanic waters via the northern and southern openings of Cockburn Sound (D'Adamo *et al.* in preparation). This appears to be a characteristic exchange mechanism for the Sound in winter. Analyses of the post-storm stratification data (20-23 August 1991) suggest that denser water entered via the openings (over the northern sill, and through the shipping channel and causeway openings) and sank, thereby displacing the less dense bottom water upwards. Southerly winds then drove a northward flow of surface waters out of Cockburn Sound across Parmelia Bank. This is an important finding because it suggests that this baroclinic

Figure 23 —
Seasonal trends in salinity and temperature in Cockburn Sound and Sepia Depression

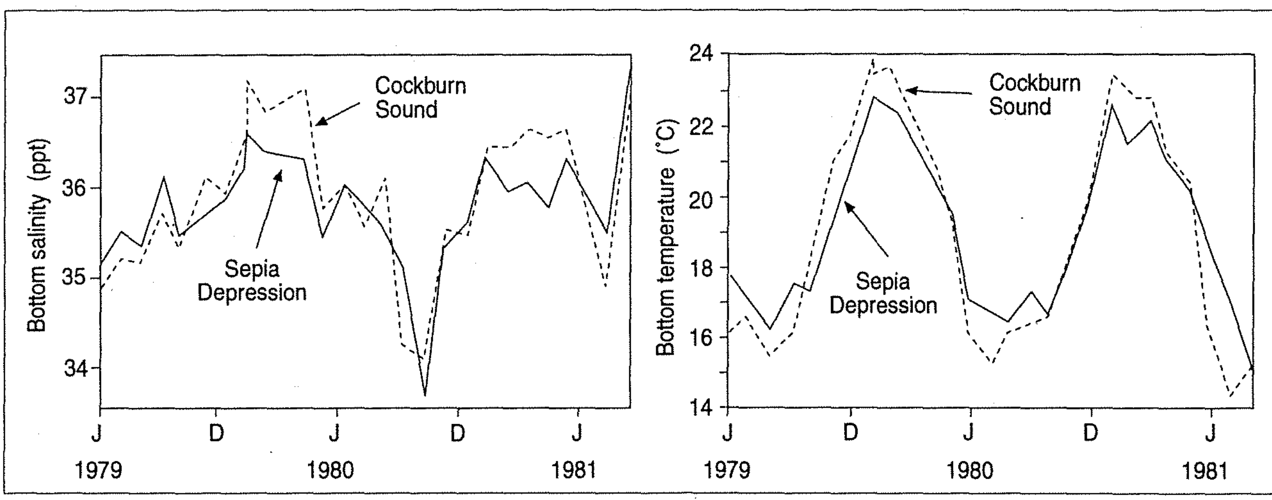
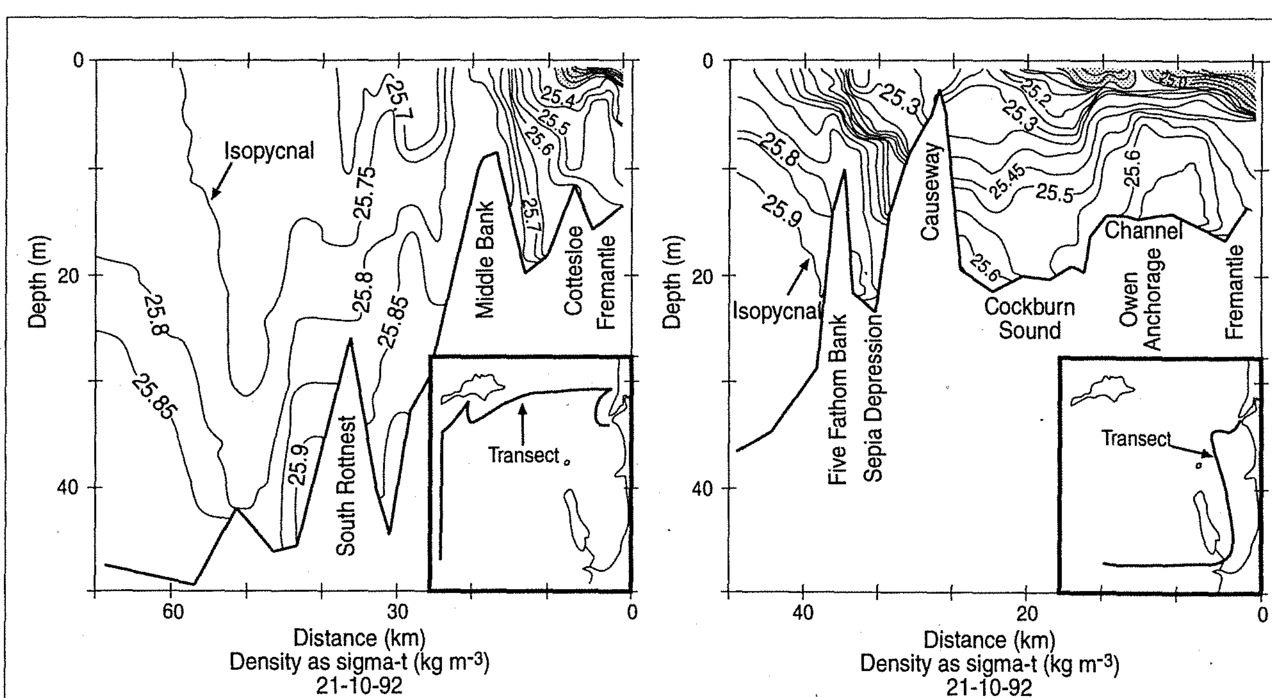
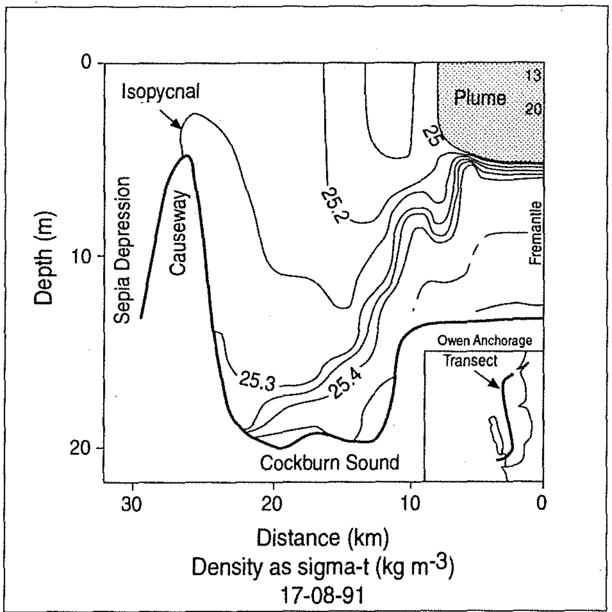


Figure 24 —
Density structure along two transects in the study area showing characteristic spatial variability



process leads to the periodic upward transport of bottom waters which can then be expelled from Cockburn Sound by wind-driven surface advection.

Figure 25 —
Density structure along a transect through Cockburn Sound and Owen Anchorage showing southward movement of the Swan River plume during northwest winds



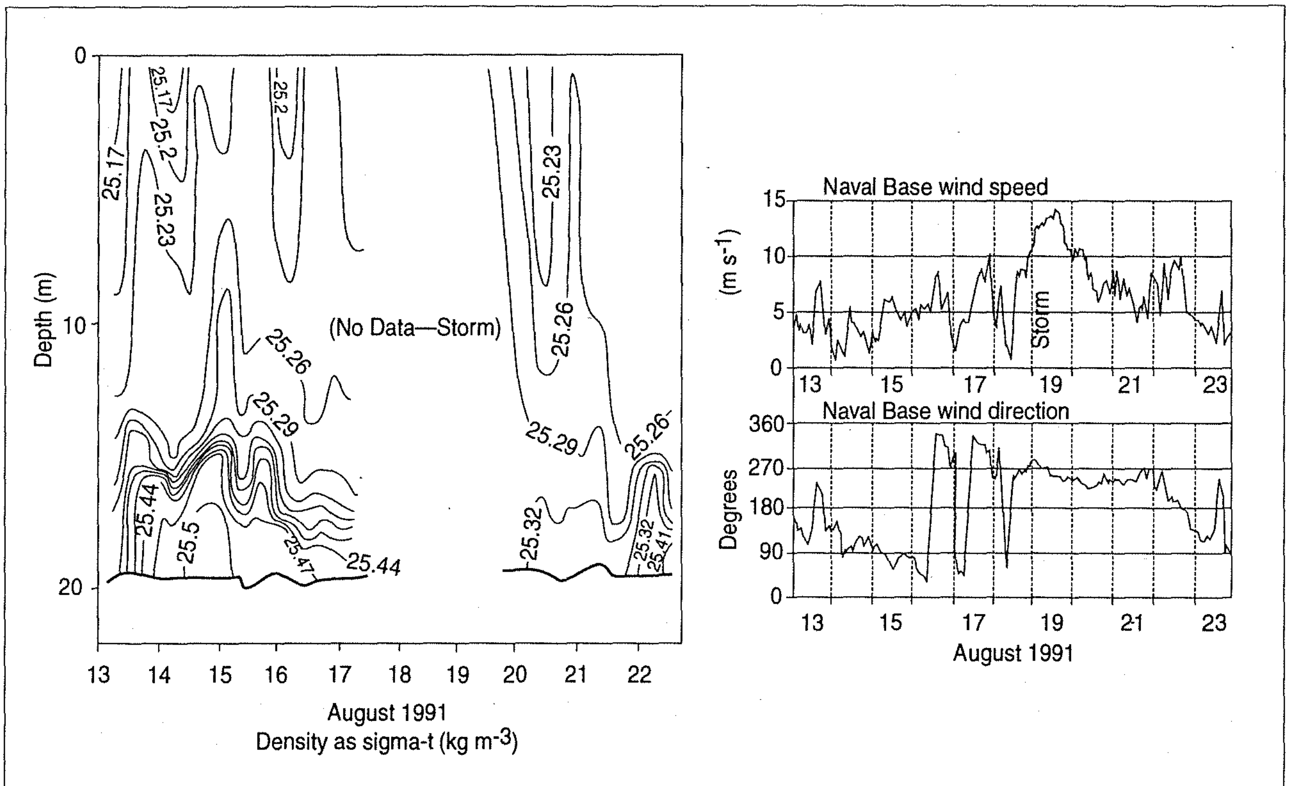
Summer dynamics

The analysis of the summer data is in its preliminary stages. It is apparent, however, that some of the fundamental characteristics of the hydrodynamics of Cockburn Sound in summer are similar to those found in winter. Cockburn Sound and adjacent waters were found to be typically vertically stratified, but with solar heating being more important than freshwater buoyancy flux in influencing the density structure of the water column. Evaporation raises the salinity of the nearshore zone to values above those of adjacent oceanic waters, and this mechanism contributed to the vertical salinity stratification that was observed in the nearshore basins during the intensive summer exercises. Horizontal density stratification was again found to be a characteristic of the basin-scale density structure.

Solar radiation was found to increase surface water temperatures during the day by up to approximately 1°C. This temperature stratification was reflected in the associated density stratification. At night the surface water cooled, due to heat losses to the atmosphere, and this caused penetrative convection. It appears, however, that the vertical stratification set up during the day by solar heating, is able to restrict mixing by penetrative convection to about 15 m depth.

Wind mixing by daily sea-breezes is another important destratifying mechanism in summer with the strongest sea-breezes (>10 m s^{-1}) found to be capable of appreciable vertical mixing of

Figure 26 —
Time series of vertical density structure in central Cockburn Sound in winter showing changes as a result of the passage of a typical winter wind cycle including a storm



the water column. Further statistical analyses of the wind patterns for the region are now required to better define the relationship between wind forcing (speed, direction, duration) and the resultant mixing.

Horizontal transport throughout the water column during summer requires further investigation and this is currently underway. Preliminary analyses of the basin-scale stratification data from the summer survey indicate that the system is characteristically horizontally stratified. The potential therefore exists for horizontal advective exchange between the basins and adjacent oceanic waters by baroclinic mechanisms. This is being investigated.

The results indicate that baroclinic processes are significant to the overall hydrodynamic behaviour of the nearshore basins. Because vertical stratification of density appears to be a characteristic feature of the water structure for more than 50% of the year, numerical hydrodynamic models that simulate baroclinic as well as barotropic processes are necessary for the nearshore zone.

Source documents —
Hearn (1991); D'Adamo (1992); D'Adamo *et al.* (in preparation).

BIOLOGY

This section provides summaries of the various biological programmes being undertaken as part of the SMCWS. These programmes involve the generation of boundary condition data and biological process information which, together with complementary information being gathered by the WAWA, is required for the development of an ecological nutrient-effects model.

6.1 Shelf-scale water quality

To predict the effects of anthropogenic point source and diffuse inputs of contaminants on ambient water quality, it is essential that background conditions are characterised and the relative importance of local and larger scale factors that influence these conditions are understood. The seasonal variation in water quality of Perth's coastal waters can be broadly explained on the basis of river flow and non-river flow, and on seasonal differences in the flow of the Leeuwin Current (i.e. weak during summer and strong during winter).

Shelf-scale water quality surveys were carried out during August 1991 and March 1992. Although these surveys were temporally limited, the data nevertheless provide a spatial perspective for the longer-term basin-scale water quality data that have been collected in the southern metropolitan coastal waters of Perth since the 1970s. The specific objectives were to determine the spatial and temporal distribution of water clarity, nutrient (principally nitrate-N) and chlorophyll *a* concentrations in surface and bottom waters for 'typical' conditions in summer and winter, and to identify any large-scale influences on the water quality of the study area.

Sampling was conducted over a grid comprising some 100 sites located between the mouth of the Peel-Harvey estuary in the south to Sorrento in the north, and across the continental shelf, to 70 km offshore. This grid is a sub-set of the physical oceanography sampling stations described earlier (Figure 19). All sites were sampled on one or more occasions during a ten-day period in winter and during two five-day periods in summer. During these surveys, satellite images and nutrient data from the previous day were used to identify specific features which were then sampled to provide additional information. Surface water samples were collected for total and inorganic nutrients and chlorophyll *a*. Bottom water samples were also collected at a sub-set of the surface water sampling sites. Secchi depth measurements provided information on relative water clarity. Nutrient and chlorophyll *a* analyses were carried out by the Nutrient Analysis Laboratory at Murdoch University. The study area was divided into 10 regions. Data for each region were pooled to provide a seasonal background value. Some results are presented below.

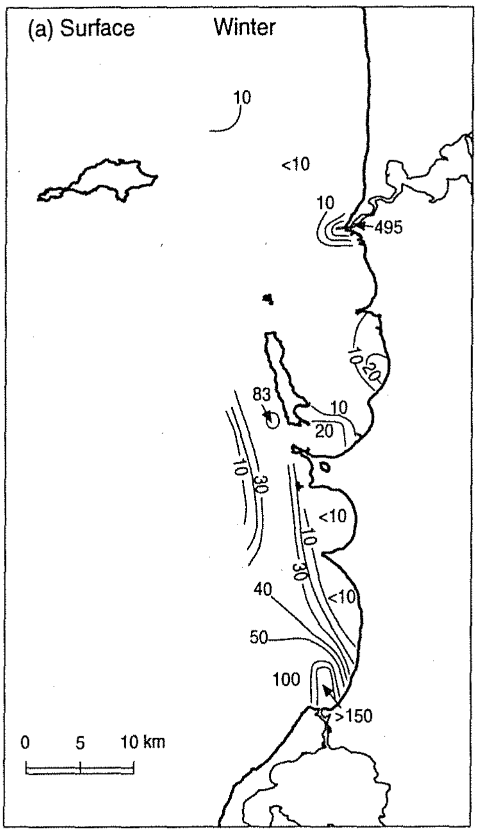
The data for August 1991 are presented in Table 2. Inorganic N:P ratios are generally low throughout the study area, except near the river mouths and in the offshore regions. These data suggest that nitrogen is the limiting nutrient in the nearshore regions. River discharges provide a significant source of nitrogen to Perth's coastal waters in winter as is clearly shown in the nitrate-N data for the Swan River entrance (Table 2). Here a mean nitrate-N concentration of 189 $\mu g\ l^{-1}$ was recorded in the surface waters of the outflow whereas the more dense marine

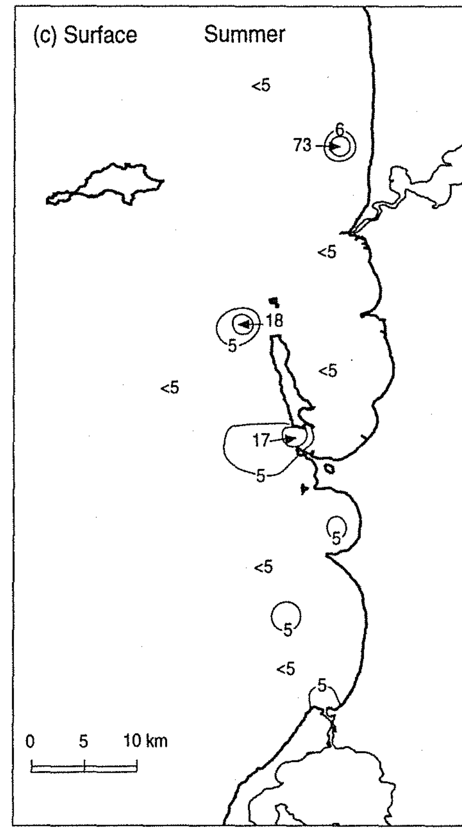
Table 2 —
Shelf-scale water quality data for 13-14 August 1991

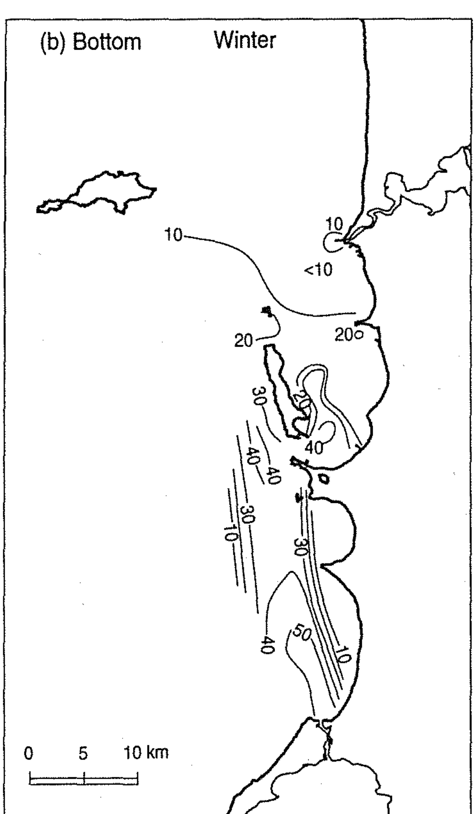
Sub-region	NH_4-N ($\mu g\ l^{-1}$)		Kjeldahl-N ($\mu g\ l^{-1}$)		NO_3-N ($\mu g\ l^{-1}$)		PO_4-P ($\mu g\ l^{-1}$)		Inorganic N:P ratio		Chlorophyll *a* ($\mu g\ l^{-1}$)		Secchi depth (m)
	S	B	S	B	S	B	S	B	S	B	S	B	
Swan River entrance	35.2	1.2	327	123	189.0	6.0	28.2	4.5	8.0	1.6	6.6	5.5	5.8
Owen Anchorage	1.0	1.0	106	118	3.0	5.8	2.2	1.4	1.8	4.9	4.6	3.9	7.7
Cockburn Sound	1.1	8.5	166	182	6.3	26.0	2.9	9.5	2.6	3.6	4.5	3.0	7.1
Gage Roads	1.0	-	157	-	5.3	-	1.1	-	5.7	-	11.3	-	5.2
West of Sepia Depression	1.0	-	117	-	5.0	-	1.0	-	6.0	-	2.4	-	5.3
Sepia Depression	2.5	1.8	81	114	23.8	17.5	7.5	5.0	3.3	-	2.6	1.4	5.0
Mandurah/Comet Bay	1.4	1.2	279	165	59.7	30.6	26.1	18.6	2.3	1.7	11.8	4.0	2.6
Warnbro Sound	1.0	1.0	110	158	2.7	33.4	4.0	4.0	0.9	-	3.7	3.5	5.1
Inshore Marmion	2.2	-	180	-	6.0	-	1.9	-	4.3	-	2.9	-	8.8
Offshore Marmion	1.0	-	135	-	6.0	-	1.0	-	7.0	-	0.9	-	12.3

S - surface B - bottom

Figure 27 —
Nitrate-nitrogen concentrations (µg l^{-1}) over the study region during winter in a) surface waters and b) bottom waters and during summer in c) surface waters







water underneath had a nitrate-N concentration of 6 µg l^{-1}. Coincident satellite imagery shows areas of stained water extending about 30 km from the river mouth (see front cover image).

The satellite images, in combination with nitrate, salinity and water temperature data provide evidence for inter-connectedness between areas. Elevated (30 µg l^{-1}) nitrate-N concentrations in both surface and bottom waters extend north from Mandurah to Sepia Depression, west of Garden Island (Figure 27a and b). Another plume, which is clearly evident on the satellite image, heads northwest from Mandurah before veering north along the western side of Rottnest Island. Although this plume was not clearly discernible beyond about 80 km from Mandurah, sea surface temperature and water chemistry data suggest that it was entrained into an anticlockwise circulating meander of the Leeuwin Current causing it to arc to the southwest.

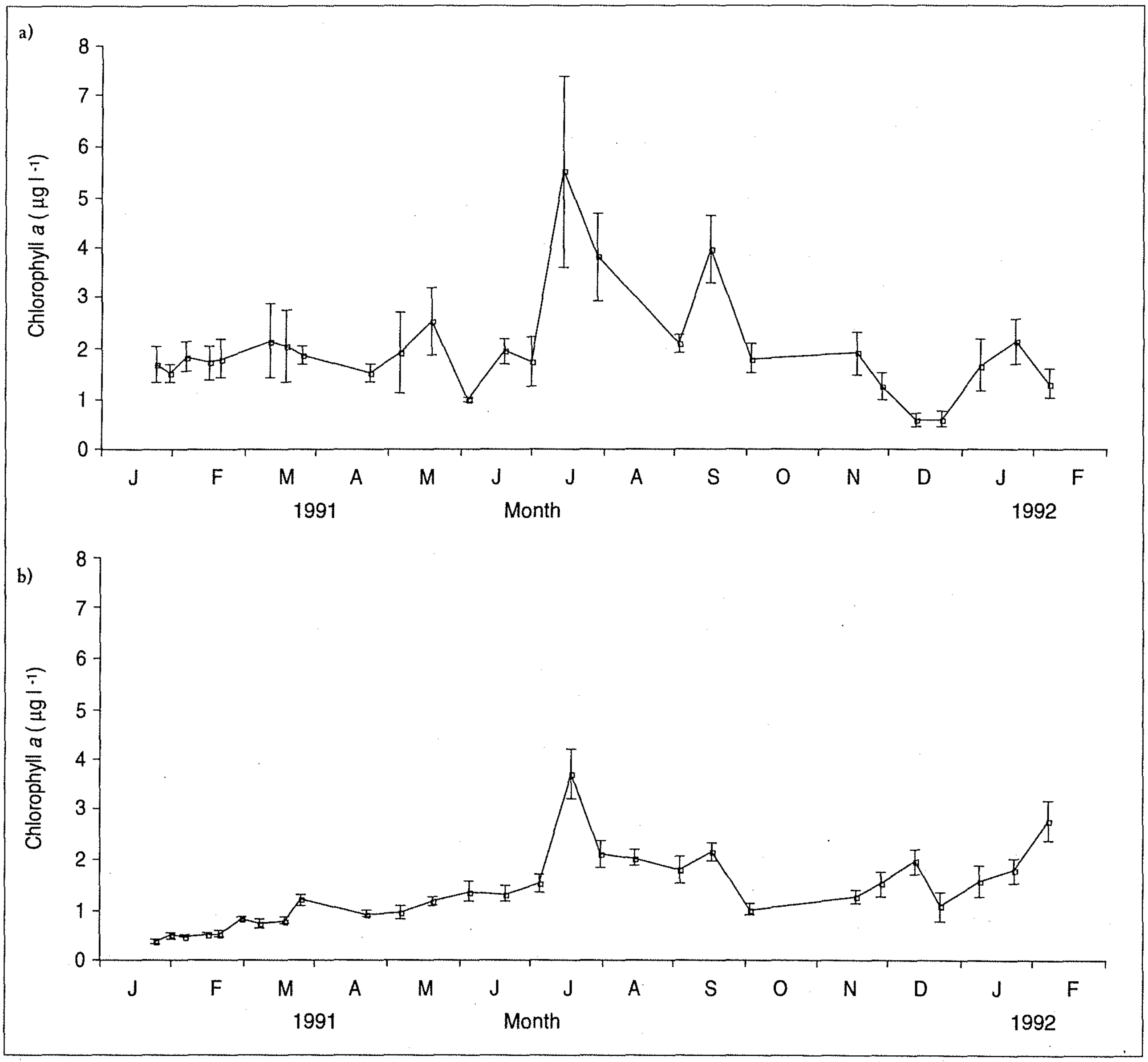
Data for summer indicate that riverine influences are weaker, the water is generally clearer and nutrient levels are much lower than in winter. Apart from the areas around wastewater outfalls and in close proximity to the river mouths, background nitrate-N levels in surface waters were generally less than 5 µg l^{-1} (Figure 27c). Nitrate-N concentrations in bottom waters were slightly higher.

6.2 Basin-scale water quality

As a result of recommendations of the Cockburn Sound Environmental Study (1976-79), the EPA has regularly monitored the water quality of Cockburn Sound during summer every 2-3 years since 1982/83. In contrast, little data have been gathered on the water quality of Warnbro Sound, the only other protected marine embayment in the southern metropolitan coastal waters of Perth. Industrial and domestic wastes have never been discharged directly into Warnbro Sound and, as a result, the waters of this embayment are considered to be largely 'pristine' and, as such, provide an important natural 'baseline' for Cockburn Sound. As part of the SMCWS, the physical, chemical and biological properties of the waters of both Cockburn Sound and Warnbro Sound were monitored concurrently for a 14-month period in 1991/92. The objectives of this study were to compare seasonal variations in the water quality of these embayments and provide baseline information on the water quality of Warnbro Sound for future reference.

Water quality was sampled at eight sites in Warnbro Sound, one site in Sepia Depression and four sites in Cockburn Sound. All sites were sampled weekly between January to March 1991. During this period the Cockburn Sound sites were sampled at the same frequency by Murdoch University for CSBP Pty Ltd. Between April 1991 and February 1992 all sites were sampled approximately every two weeks. Phytoplankton (as chlorophyll *a*) concentrations, total nitrogen, total phosphorus, temperature, salinity and light profiles were measured at each site except in Cockburn Sound between January and March 1991. During this period only phytoplankton concentrations, temperature and light profiles were measured. Total dissolved nitrogen, total particulate

Figure 28 —
Phytoplankton (as chlorophyll *a*) concentrations in a) Cockburn Sound and b) Warnbro Sound

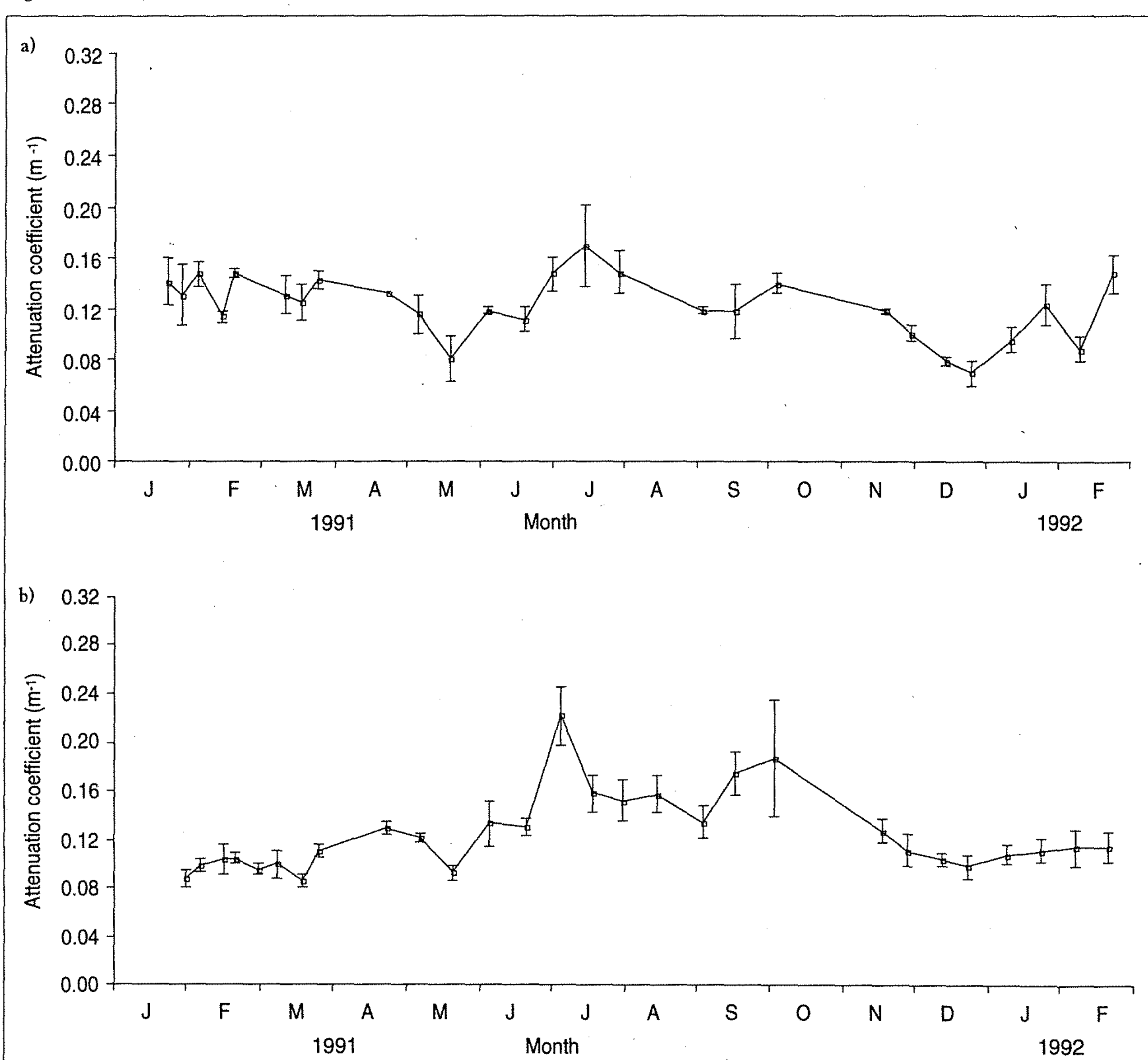


nitrogen, total dissolved phosphorus and total particulate phosphorus were measured in Warnbro Sound from January 1991 to July 1991 and from April 1991 to July 1991 in Cockburn Sound. Nitrate-nitrogen, ammonium-nitrogen and orthosphosphate were measured every two weeks from July 1991 to February 1992. Nutrient analyses were carried out by the Nutrient Analysis Laboratory at Murdoch University. Detailed descriptions of sampling and analytical methodology can be found in Cary *et al.* (1991). Some of the preliminary results from this study are outlined below.

In general, mean chlorophyll *a* concentrations in both Cockburn Sound and Warnbro Sound followed similar seasonal trends with highest concentrations occurring in winter (Figure 28). Chlorophyll *a* concentrations in Cockburn Sound over the study period were significantly higher than in Warnbro Sound. During June-August 1991 variations in chlorophyll *a* in both areas were significantly correlated ($r^2 = 0.85$, $p < 0.005$) suggesting that the same processes were controlling phytoplankton abundance in these two embayments during winter. The species composition of the phytoplankton population in both areas support this conclusion (see Section 6.4). Mean chlorophyll *a* concentration in Warnbro Sound during January-March 1991 was about 0.7 $\mu g\ l^{-1}$. This level was not significantly different to the mean concentration in summer at a site in Warnbro Sound during the late 1970s. However, mean chlorophyll *a* concentrations in January and February 1992 were significantly higher than 1991 indicating that significant inter-annual variations occur in Warnbro Sound.

The mean vertical light attenuation coefficient in Cockburn Sound was not significantly different from Warnbro Sound over the study period (Figure 29). This parameter varied seasonally in

Figure 29 —
Light attenuation coefficients in a) Cockburn Sound and b) Warnbro Sound



Cockburn Sound but showed greater seasonal variation in Warnbro Sound, varying from a mean value of about 0.16 m^{-1} from April-October 1991 to about 0.11 m^{-1} in the summer months.

Source document —
Cary and Masini (in preparation).

6.3 Shelf-scale phytoplankton

Phytoplankton are at the base of the food chain and use light energy to convert carbon dioxide, water and nutrients into organic matter. This matter, in turn, provides food for animals further up the food chain. In the process of absorbing and scattering light, phytoplankton influence the amount of light available for benthic plant growth. The relationship between light reduction and phytoplankton abundance is, therefore, a critical process to consider when modelling the effects of nutrient inputs to shallow coastal waters.

Phytoplankton vary considerably in size, shape and physiological characteristics. Some species are motile, while others simply drift passively with water currents and some (e.g. cyanobacteria) convert dissolved nitrogen gas into a form that is available for growth. The relationships between nutrient concentrations and phytoplankton growth, and between photosynthesis and irradiance, are species specific. As such, modelling the growth of an 'assemblage', comprised of many different species, is a daunting, if not impossible, task. This complexity can be reduced by applying relationships specific to the dominant phytoplankton groups within the assemblages (e.g. diatoms, dinoflagellates, cyanobacteria or silicoflagellates) provided the species composition and abundance of these assemblages are known.

As part of the characterisation phase of the SMCWS, phytoplankton populations were characterised at two temporal and spatial scales. This study determined the shelf-scale distribution of phytoplankton species composition and abundance in surface waters during a range of conditions in 'summer' and 'winter'.

Surface waters at 44 sites, located between the mouth of the Peel-Harvey Estuary in the south, to Sorrento in the north, and across the continental shelf, some 70 km offshore, were sampled (Figure 19). All sites were sampled in 'winter' (August 1991) and 'summer' (March 1992). Species composition and abundance of phytoplankton were determined by the Biology Department at Curtin University. Multivariate techniques were used to identify phytoplankton assemblages.

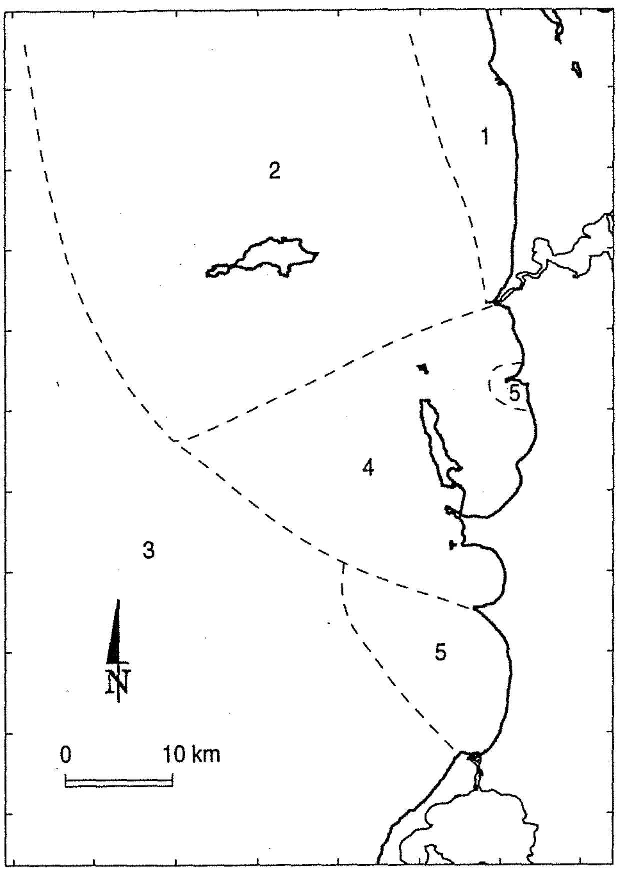
One hundred and thirty species of phytoplankton were identified from the winter survey. The species present were assembled into three main taxonomic groups: bacillariophyta (diatoms), dinophyta (dinoflagellates) and chrysophyta (silicoflagellates). The relative contribution of each group to the phytoplankton assemblage in each sub-region was expressed as a percentage of the total (Table 3). Overall the silicoflagellate group dominated the phytoplankton community in the study area during winter in 1991. The areas adjacent to the river entrances had low percentages of silicoflagellates, which suggests this group did not originate in the rivers or estuaries. The highest concentration of silicoflagellates occurred in the Warnbro Sound region, comprising approximately 77% of the population in this area, 70% in Sepia Depression and 68% in the waters west of Sepia Depression. The high percentage of silicoflagellates is unusual by Australian standards; typically silicoflagellates comprise some 5% of the total cells present.

The 'winter' data were analysed by correspondence analysis and five general groups were identified (Figure 30). Processing of 'summer' samples is currently underway.

Table 3 —
Percentage composition of the three major phytoplankton groups in each sub-region during August 1991

	Phytoplankton group		
Sub-region	Dinoflagellates	Silicoflagellates	Diatoms
Peel-Harvey entrance	43.5	5.9	50.6
Mandurah/Comet Bay	23.4	36.0	40.6
Sepia Depression	9.7	70.9	19.4
Warnbro Sound	14.0	77.0	9.0
West of Sepia Depression	12.2	68.1	19.7
Swan River entrance	3.3	7.5	89.2
Cockburn Sound	36.2	36.6	27.2
Gage Roads	26.3	25.0	48.7
Inshore Marmion	12.3	38.2	49.5
Offshore Marmion	13.8	26.5	59.7
Study area	17.6	47.6	34.8

Figure 30 —
Location of phytoplankton assemblages in the study area during winter 1991

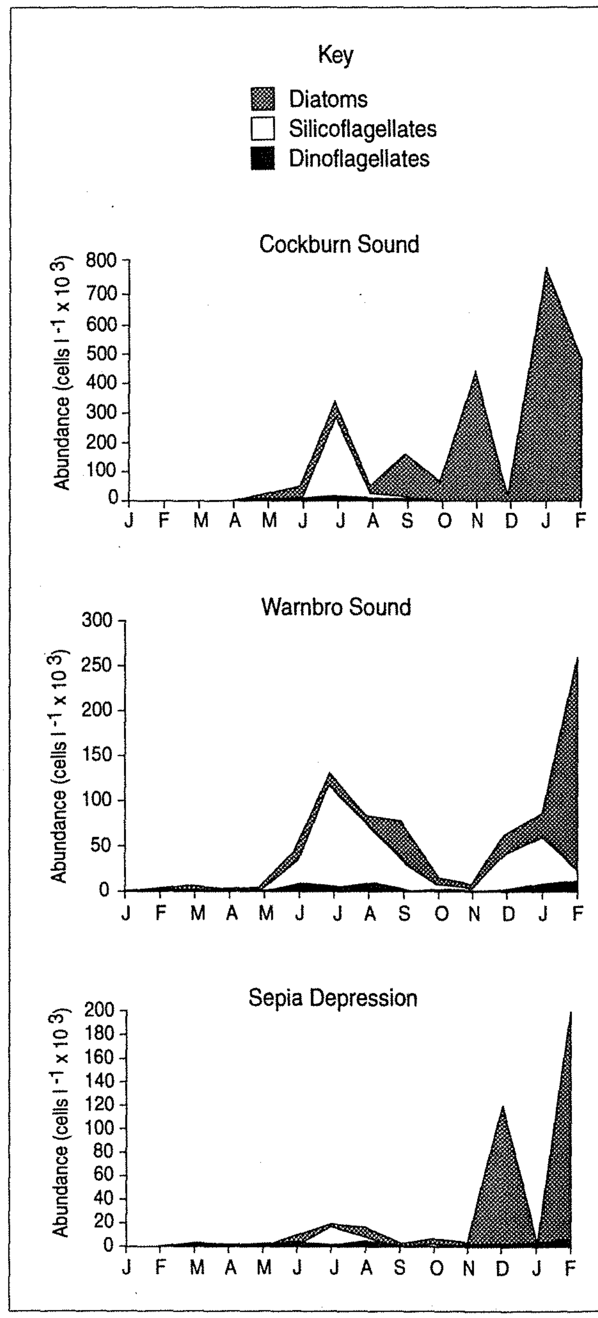


6.4 Basin-scale phytoplankton

Phytoplankton species composition and abundance were measured at selected sites within Cockburn Sound and Warnbro Sound and in Sepia Depression, between January 1991 and February 1992. Four sites in Cockburn Sound, eight sites in Warnbro Sound and one site in Sepia Depression were sampled approximately monthly in conjunction with the basin-scale water quality monitoring programme discussed earlier in Section 6.2. Water samples were collected from 1 m below the surface, 1 m above the seabed and mid-way between these two samples, and mixed together. The bulked water sample was sub-sampled for chlorophyll *a* analysis and for phytoplankton species composition and abundance. Multivariate analyses were performed on the species composition and abundance data to determine the degree of similarity of sites between and within embayments. Details of sampling and analyses can be found in Cousins (1991).

One hundred and eleven species of phytoplankton were identified during this study. The species composition and abundance data are summarised in Figure 31. Phytoplankton abundance was generally higher in Cockburn Sound than Warnbro Sound while the site in Sepia Depression generally had the lowest abundance. Correspondence analyses indicated a higher degree of similarity between sites within embayments, than between embayments, on 13 out of 14 occasions. Although Cockburn Sound had the highest phytoplankton abundance, it generally had the lowest species diversity, a characteristic of impacted environments. There was considerable interannual variation in abundance ranging from 190 cells l^{-1} in Cockburn Sound in January 1991, to 775 500 cells l^{-1} in January 1992. Of the major phytoplankton groups, dinoflagellates were present year round, but at low abundances. Silicoflagellates dominated during the winter months and diatom blooms occurred during summer.

Figure 31 —
Dominant phytoplankton groups in nearshore waters during 1991/92



A relationship was derived between chlorophyll *a* and total phytoplankton cell numbers. The most unusual finding of this study were the winter silicoflagellate blooms. Silicoflagellates are found in all marine systems but generally comprise less than 10% of the total species present: Chaney (1978) found silicoflagellates to comprise less than 2% of the phytoplankton flora of Cockburn Sound in 1978. In this study however, silicoflagellates comprised more than 80% of the phytoplankton flora on occasions. At one site in Cockburn Sound silicoflagellates comprised 95% of the phytoplankton present and occurred at a density of 853 230 cells l^{-1}, almost an order of magnitude greater than the largest recorded silicoflagellate bloom anywhere in the world (Smayda, 1980). These silicoflagellate blooms were not confined to the embayments but occurred across the continental shelf, dominating the phytoplankton flora in winter over much of the study area (see Section 6.3). The significance of these blooms is presently unknown.

Source documents —
Cousins M (1991); Cousins *et al.* (in preparation).

6.5 Phytoplankton/zooplankton interactions

Phytoplankton respond rapidly to nutrient enrichment and are important in controlling light attenuation in coastal waters. A phytoplankton sub-model is being constructed as part of the SMCWS to predict the biomass of phytoplankton in Perth's coastal waters under a range of conditions. The biomass of phytoplankton at any time is dependent on the interplay between growth and loss functions. In the model, growth is related to available light, water temperature and nutrient concentrations. These relationships will be specific to the phytoplankton assemblages present at the time. Losses in biomass result from grazing by zooplankton, sedimentation and from advection. Advection and sedimentation can be calculated whereas zooplankton grazing rates are dependent on the structure of both the phytoplankton and zooplankton assemblages.

This study is being undertaken in collaboration with the Biology Department of Curtin University and builds upon the research described earlier (see Section 6.4). The objectives are to determine the temporal and spatial variation of the phytoplankton and zooplankton assemblages of Cockburn Sound and Warnbro Sound and to develop growth/loss algorithms specific to these assemblages for incorporation into the phytoplankton sub-model.

Four sites in both Warnbro Sound and Cockburn Sound were selected as being representative of these embayments and a fortnightly sampling programme was initiated in August 1992. Secchi depths are taken at each site as a measure of water clarity and phytoplankton are sampled at three depths and analysed separately to provide data on the vertical distribution of phytoplankton biomass (measured as chlorophyll *a*) and species composition and abundance. Zooplankton are also sampled at three depths to provide information on species composition and abundances at each depth.

Samples have been collected on 18 occasions to date and preliminary analyses confirm the general pattern of assemblage succession identified previously (Section 6.4). Diatoms are the most diverse group, followed by dinoflagellates, silicoflagellates and cyanobacteria, which are represented by only one species *Trichodesmium (Oscillatoria) erythraea*. Zooplankton data are not yet available.

6.6 Light requirements of seagrasses

Seagrasses have been identified as a sensitive and important ecological component of Perth's coastal ecosystem. As a key indicator of ecological health, these communities are a major focus of the SMCWS. The most critical factor controlling the growth and survival of seagrasses is the amount of light reaching the seagrass leaf. Light availability to seagrasses is determined by a combination of biological and physical processes. Phytoplankton in the water column and epiphytes attached to seagrass leaves absorb and scatter light, thereby reducing the amount of light reaching the seagrass leaf. Physical forcings, such as wind waves and swell, resuspend organic and inorganic matter from the sediments into the water column resulting in further absorption and scattering of light.

Seagrasses can only survive in waters where photosynthetic production exceeds respiratory losses. Prolonged increases in light attenuation, due to the factors mentioned above, can reduce light reaching seagrasses to below critical levels, causing their death. Seagrasses growing at the limits of their depth distribution, where the light regime at the seabed is just sufficient for survival, would be the first to be affected if ambient light conditions changed.

The objectives of this study are to characterise the annual cycle of light availability and temperature at the different depth limits of two *Posidonia sinuosa* seagrass meadows; to characterise the annual cycle of vertical light attenuation coefficients at each site; to determine the relationships between the physical and biological factors that influence light attenuation through the water column at these sites and to determine the relationship between the epiphyte layer on the surface of seagrass leaves and light attenuation through this layer.

Data loggers were deployed at sites on the south-east (12 m depth) and north-west (15 m depth) slopes of Success Bank (Figure 1). The south-eastern site is considered to be broadly representative of the inshore 'protected basin' zone whereas the north-western site is representative of the 'semi-exposed' offshore zone. Two data loggers, simultaneously recording integrated light levels for 20-minute periods and instantaneous water temperature at the beginning of each 20-minute period, were deployed at each site. The 'bottom' logger (sensor 0.3 m above the seabed) was located at the depth limit of the meadow at each site. The 'top' logger was located 3 m below the water surface. The loggers were deployed for six 42-day periods centred around the winter and summer solstices, and each equinox, between March 1992 and June 1993. De-fouling of the light sensors was carried out every five days in summer and every seven days in winter, these periods being determined from field trials of fouling rates conducted in early 1992.

At each site, an array of sediment traps (50 mm diameter, aspect ratio of 6) were deployed at 3 m below the surface (n = 4) and 0.5 m above the seabed (n = 6) for four 10-day periods during each sampling period. The contents of the traps were analysed for total dry weight, organic and carbonate fractions at the Chemistry Centre of Western Australia.

During each 42-day deployment, a series of instantaneous measurements were undertaken every 5 -7 days. Vertical profiles of salinity and temperature were recorded at each site to determine if the water column was stratified. If so, water samples were collected for nutrient (TN, TP, NO_3-N, NH_4-N, PO_4-P), chlorophyll *a*, phaeophyton and particulate (total dry weight, organic and carbonate fractions) analyses from the mid-depth of the upper and lower layers. Instantaneous light profiles were also measured for each layer. For an unstratified water column, 'top' water samples were taken at 3 m depth and the 'bottom' samples were taken at 3 m and 5 m above the seabed at the south-east and north-west sites respectively. Nutrient and photosynthetic pigment analyses were carried out by the Nutrient Analysis Laboratory at Murdoch University. Particulate analyses were conducted at the Chemistry Centre of Western Australia.

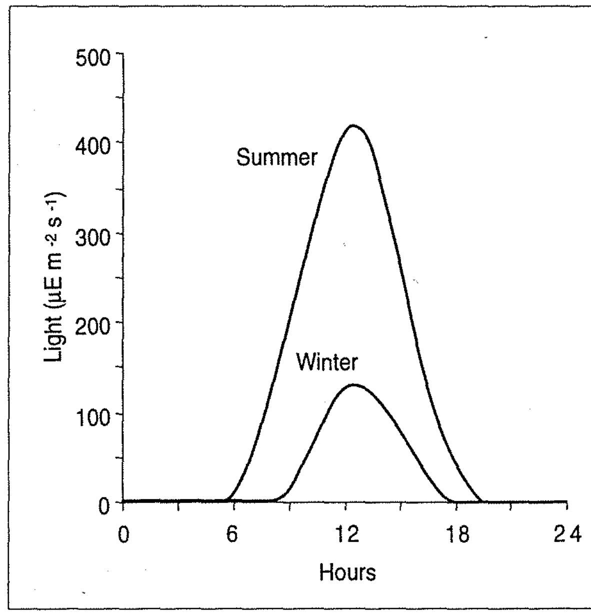
Artificial seagrass consisting of transparent plastic strips, designed to mimic seagrass leaves, were deployed at each of the above sites for approximately 70 days (i.e. the approximate mean age of *P. sinuosa* leaves). Following harvesting, the relationship between periphyton biomass and light transmission was determined. Data from repeated deployments will be used to determine the general relationship between periphyton biomass and light transmission. These data, coupled with the light measured at the canopy level, will allow estimates of light reaching the surface of the seagrass leaves to be determined.

The field component of these programmes finished on 30 June 1993. Chemical and biological analyses are almost complete and preliminary data processing for the first five deployment periods has been completed.

Some preliminary results are presented below.

There are significant seasonal differences in the light climate at the level of the seagrass canopy and these differences related to changes in incident light intensity, photoperiod and water clarity. On a cloudless day in mid-summer, the photoperiod is 14 hours and the maximum light intensity, at 0.3 m above the seabed in Owen Anchorage, is typically about 400 $\mu E\ m^{-2}\ s^{-1}$. In mid-winter, the photoperiod is 10 hours, and maximum light intensity under the same conditions is about 150 $\mu E\ m^{-2}\ s^{-1}$ (Figure 32).

Figure 32 —
Diel light curves for a cloudless day in summer and winter at 12 m depth in Owen Anchorage



Light attenuation through the water column at the 'inshore' site was significantly higher and more variable in winter (Figure 33) and preliminary interpretations suggest that this was associated with increased re-suspension of sediments and organic material by swell and wind waves. A preliminary analysis of the results also suggests that the light attenuation at the 'offshore' Success Bank site was significantly lower than at the 'inshore' site, during winter. In summer, the two sites were similar.

In winter, there is a positive correlation between the concentration of total suspended solids and light attenuation in the lower layer at both sites. At the 'inshore' Success Bank site in spring, there was a positive correlation between total suspended solids and light attenuation in the lower layer and between chlorophyll *a* and light attenuation in the upper layer (Figure 34).

There is a significant relationship between the biomass of periphyton at both sites and the attenuation of light through this layer (Figure 35). The mean biomass of epiphytes on seagrasses at the 'offshore' site in spring, summer and autumn resulted in approximately 25%, 30% and 50% reduction in light reaching the seagrass leaf.

Source documents —
Burt (in preparation); Burt (in preparation); Burt and Daly (in preparation).

Figure 33 —
Mean daytime light attenuation coefficients in summer and winter in Owen Anchorage

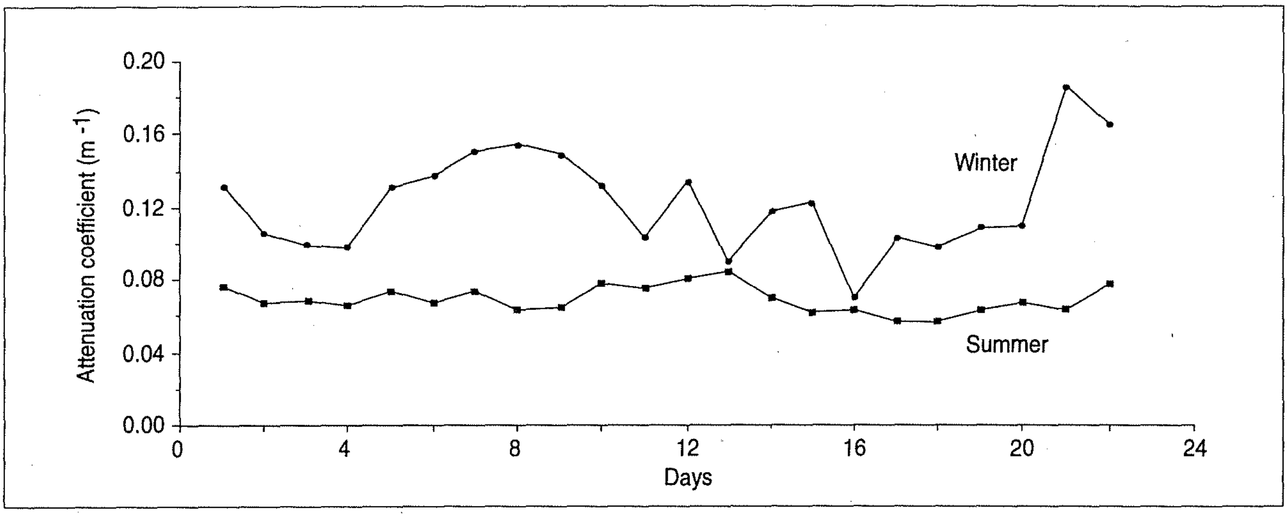


Figure 34 —
Relationship between chlorophyll *a* concentration and light attenuation in the upper layer of the water column in Owen Anchorage during spring

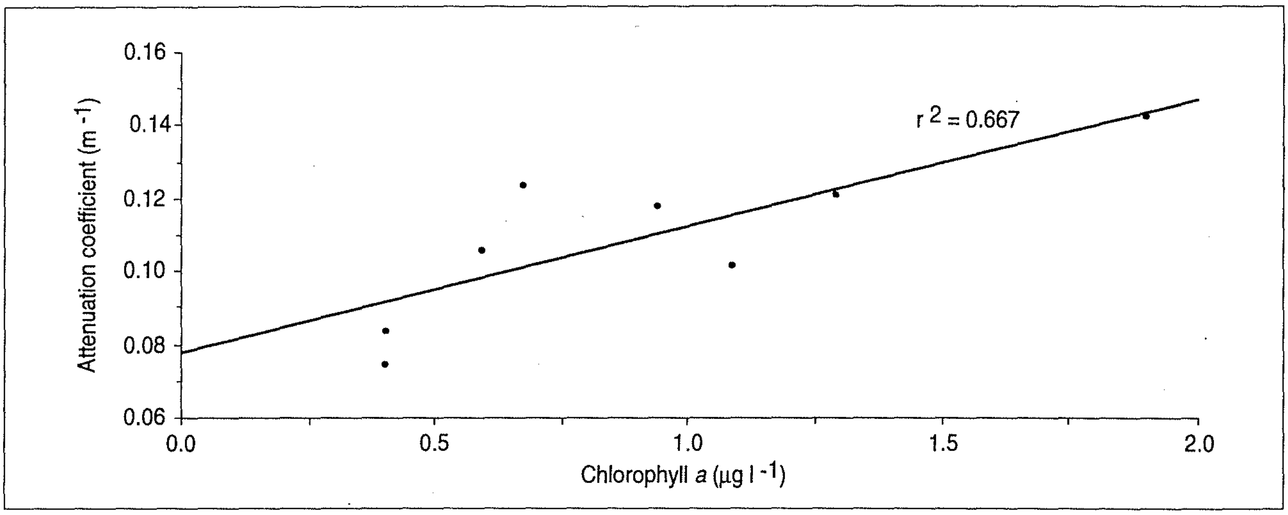
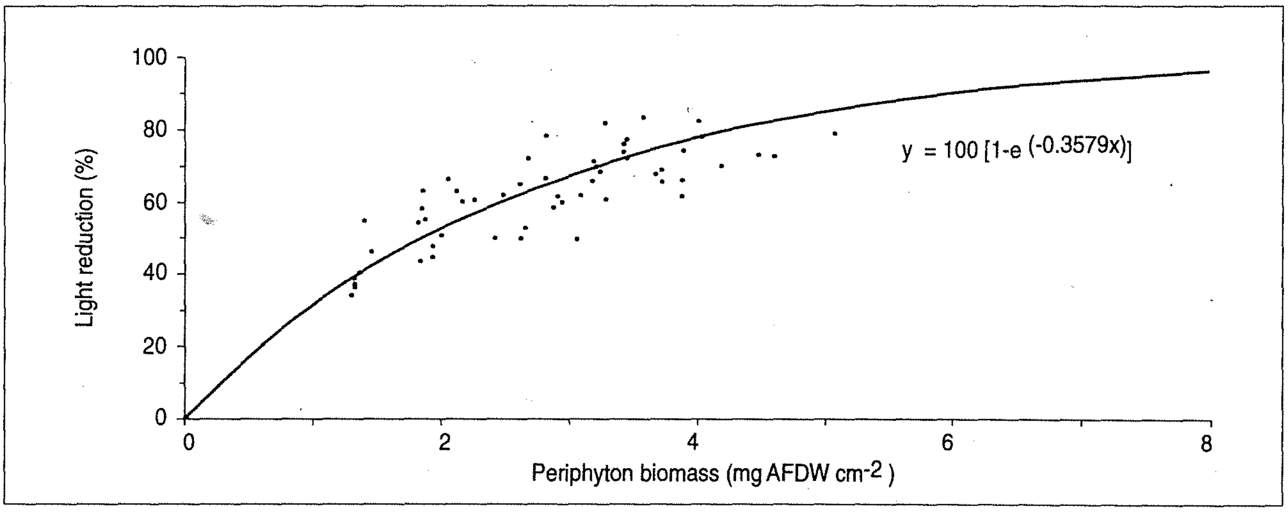


Figure 35 —
Relationship between the biomass of periphyton and light reduction



AFDW - ash free dry weight

6.7 P-I relationships of seagrasses

Seagrasses are known to be highly susceptible to the effects of nutrient enrichment. In both Cockburn Sound and in Princess Royal Harbour, Western Australia, long-term chronic nutrient loading has resulted in the loss of some 90% of the seagrass meadows that formerly vegetated these embayments. The seagrasses died as a result of light starvation, caused by higher than normal standing crops of algae, a direct consequence of high nutrient loadings to these ecosystems. Clearly, knowledge of the light requirements of the seagrasses is important in developing and implementing management strategies to protect the long-term health of seagrass meadows.

This collaborative programme with the CSIRO is examining the relationships between photosynthetic activity of seagrass plants under variable irradiance and temperature regimes to provide information on their light requirements. The specific objectives of the study were —

- to determine the relationships between irradiance (light) and photosynthesis of the four main meadow-forming seagrass species (*Posidonia sinuosa*, *P. australis*, *Amphibolis antarctica and A. griffithii*) in the study area. These relationships provide information on critical light values (e.g. light required to achieve maximum photosynthetic rate or to balance photosynthesis and respiration) and important metabolic parameters (e.g. maximum photosynthetic rate, respiration rate) for these species;
- to determine the effect of a range of water temperatures on the parameters listed above;
- to determine the extent of any seasonal differences in these parameters;
- to determine the extent of physiological adaptation of plants growing at their depth/light limit compared with those growing in high light fields;
- to determine the extent of any latitudinal differences in these parameters; and
- to develop appropriate algorithms to predict seagrass growth from incident irradiance (at the seagrass leaf) and water temperature.

A laboratory method was used to measure the photosynthetic response of different seagrass species under different light and temperature regimes as a rate of change in dissolved oxygen in a metabolic chamber. Details of this technique can be found in Masini *et al.* (1990). Some results are presented below.

The metabolic determinations in the laboratory have been completed. Information has been collected for the four species at three temperatures spanning the range of water temperatures over a typical annual cycle in the metropolitan waters of Perth. The results of these experiments allow a photosynthesis versus irradiance (P-I) curve to be generated for each seagrass species for a given water temperature. For *P. sinuosa* a positive relationship exists between critical irradiances and water temperatures between 13 and 18°C. Critical irradiances between 18 and 23°C, however, were not significantly different (Table 4). Preliminary results suggest that the effect of temperature on the photosynthetic response of the other seagrass species is similar. There were no major differences in critical irradiances for *P. sinuosa* collected from Perth and Albany (Table 4). The P-I characteristics of *P. sinuosa* plants collected from 4 m depth were similar to those collected from about 15 m, the depth limit of this species in Perth's southern coastal waters. Seasonal differences in P-I characteristics were not apparent.

Table 4 —
Critical irradiances at three temperatures for *P. sinuosa* from Albany and Perth (mean and standard errors (*n*=4) are shown)

Temperature (°C)	Compensating Irradiance (I_c) ($\mu E\ m^{-2}\ s^{-1}$)		Theoretical Saturating Irradiance (I_k) ($\mu E\ m^{-2}\ s^{-1}$)	
	Albany	Perth	Albany	Perth
13	21.9 (2.1)	18.2 (1.3)	36.7 (3.3)	38.2 (3.0)
18	23.6 (1.6)	21.2 (0.5)	54.8 (3.2)	55.1 (2.5)
23	28.2 (2.4)	22.2 (2.0)	56.1 (3.6)	53.6 (5.9)

Table 5 —
Comparison of critical irradiances at 18°C of two seagrass species from Albany and Perth (mean and standard errors (*n*=4) are shown)

Species	Compensating Irradiance (I_c) ($\mu E\ m^{-2}\ s^{-1}$)		Theoretical Saturating Irradiance (I_k) ($\mu E\ m^{-2}\ s^{-1}$)	
	Albany	Perth	Albany	Perth
Posidonia australis	25.0 (1.2)	25.7 (1.4)	89.8 (4.1)	68.1 (8.9)
Amphibolis griffithii	20.0 (0.9)	19.4 (1.7)	70.5 (2.1)	58.2 (11.7)

These findings suggest that the P-I characteristics of *P. sinuosa* determined at one locality can be transferred and applied to the same species at different locations within these latitudinal, depth and seasonal ranges. These results greatly facilitate the development of a seagrass production model that is generally applicable around the southwest coast of Australia. Preliminary data (Table 5) suggest that this generality may also apply to the other temperate meadow-forming species.

The photosynthesis versus irradiance curve can be expressed mathematically in several ways. These expressions are all functions of the critical irradiance that theoretically saturates photosynthesis (I_k) and maximum photosynthetic rate for that species. Mathematical functions that best approximate the P-I relationships are being tested and algorithms based on these functions are being developed to form the basis of the seagrass sub-model.

Source documents —
Masini *et al.* (1990); Masini and Manning (1992); Masini and Manning (in preparation).

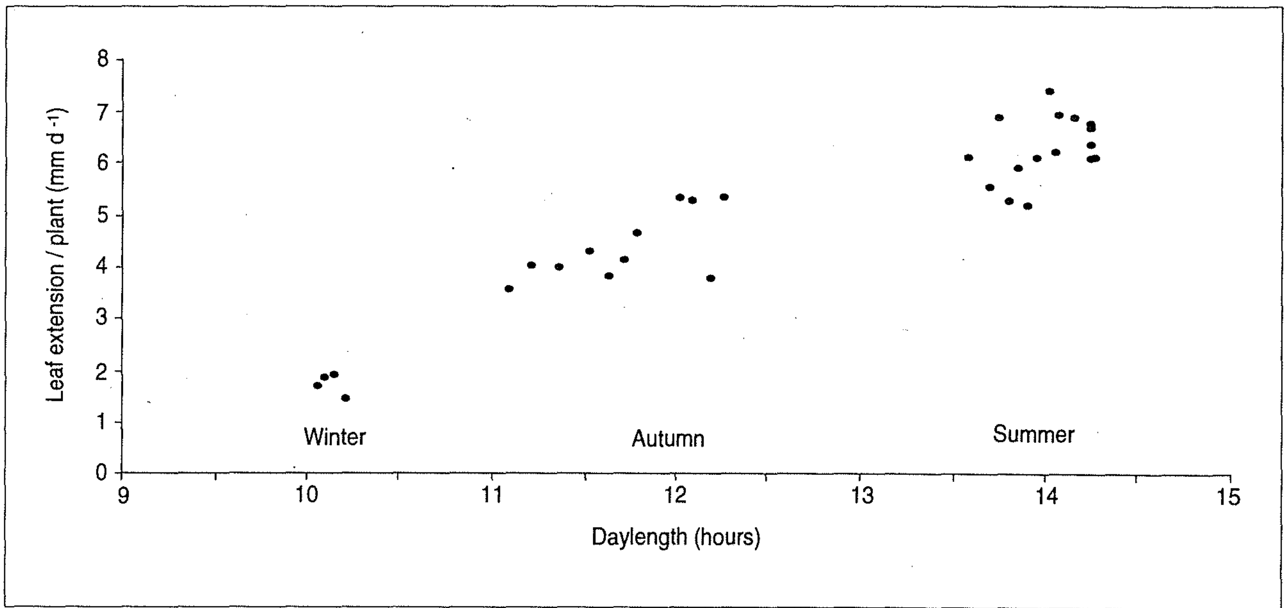
6.8 Seagrass model validation

To determine the degree of confidence that can be placed on the output of the seagrass sub-model, it is essential that predicted growth responses of seagrasses be validated with growth measurements under similar conditions in the field. The first step in the validation process is to collect field data to be used to refine or 'calibrate' the laboratory-derived model algorithms to best approximate the changes that occur in the natural environment. Changes in the above-ground seagrass biomass, or standing crop, during a given time interval, result from a combination of growth and erosion processes. Growth rates are linked to photosynthetic carbon assimilation which is controlled principally by light and temperature, whereas erosion rates are largely controlled by the age of the leaf and by the mechanical action of water currents.

In order to calibrate the seagrass sub-model, field experiments were undertaken to measure growth and erosion rates of *Posidonia sinuosa* shoots over a range of photoperiod, water temperature and light conditions representative of the range of these conditions over an annual cycle. These experiments were conducted during the austral summer to winter period to avoid the confounding effects of the spring reproductive period of *P. sinuosa*. *P. sinuosa* was chosen as the experimental organism as this species is the dominant meadow-forming seagrass in the metropolitan waters of Perth and is highly susceptible to the effects of eutrophication.

A non-destructive method for measuring seagrass growth in the field over short time intervals was developed. Each leaf on 27 individual seagrass shoots of *P. sinuosa* was tagged along a fixed transect at a site in Owen Anchorage on the south-east side of Success Bank (Figure 1). The transect was located at a depth of approximately 12 m, the lower limit of *P. sinuosa* at this site, to ensure a maximum response to changing seasonal conditions. The growth increments of each leaf, relative to a fixed marker, were measured at two to seven-day intervals over periods of four to six weeks. These periods were centred around the December 1992 summer solstice, the March 1993 equinox and the June 1993 winter solstice to provide a range of photoperiods of approximately 10 to 14 hours. Integrated light levels and instantaneous water temperatures were measured continuously nearby (see Section 6.6).

Figure 36 —
Growth of *Posidonia sinuosa* shoots versus daylength



Meters measuring current speed and direction were also deployed at this location to provide information on bottom currents at the site. The field experiments were completed in June 1993. Some of the results are presented below.

Preliminary results indicate a high degree of uniformity in growth rates between individual shoots and a rapid growth rate of greater than 6 mm $shoot^{-1}$ d^{-1} in December 1992 reducing to less than 2 mm $shoot^{-1}$ d^{-1} in June 1993. Growth rates were correlated significantly with daylength (Figure 36). These data are yet to be fully analysed and compared with the seagrass model output.

Source documents —
Masini (1993); Masini (in preparation).

Further work —
Further work will depend on the results of the data collected so far.

MODELLING

One of the prime objectives of the current studies being coordinated by the EPA and the WAWA is to develop an ecological model to predict the response of the coastal marine ecosystems off Perth to a range of nitrogen loading scenarios. Aspects of this model are discussed in greater detail below. The ecological model requires, as input, a simulation of the hydrodynamic behaviour of the study area to model the mixing and dispersion of nutrients, suspended matter and phytoplankton, and hence to simulate the nutrient exposure, algal stimulation and light attenuation conditions in areas of ecological sensitivity.

7.1 Hydrodynamic models

This section deals with the numerical modelling of major physical processes of relevance to the ecological study. The physical oceanographical modelling falls into two categories:
(i) *hydrodynamic modelling* which simulates the physical response of the water body (e.g. surface elevation, currents) to imposed forces (e.g. wind stress) and (ii) *transport modelling* which simulates the spread and dispersion of materials either naturally present in seawater (e.g. salt) or discharged from specified sources (e.g. pollutants). Chemical/biological transformation or loss terms (e.g. particulate settling) may be included to model non-conservative behaviour.

The physical modelling will provide an understanding of the important temporal and spatial scales of transport in the study area, the hydrodynamic connectedness between sub-regions within the study area, the hydrodynamic response to forcings (both local and remote), the vertical mixing and horizontal dispersion characteristics of the study area, and the residence times of water and materials. Results from the hydrodynamic model will be input to the ecological model which will simulate the dispersion of materials and the geochemical and biological interactions of relevance to the viability of seagrass meadows.

The choice of the hydrodynamic model was based on the oceanographical characterisation of the study area, summarised in Sections 2 and 5, and on a review of available models. The characterisation highlighted the finely balanced competition existing in the study region between natural stabilising processes that cause lighter water to form over heavier water (i.e. surface heating and freshwater runoff) and destabilising processes, such as mixing by turbulent kinetic energy, generated by shear stresses adjacent to the boundaries, or penetrative convection. The characterisation also highlighted the role of the earth's rotation at basin-scale and shelf-scale, and the essentially three-dimensional nature and time dependence of the water circulation and mixing regimes.

The hydrodynamic model was therefore required to be general, three-dimensional, time-dependent, and to be able to incorporate responses to a wide range of forcings, including large scale horizontal pressure gradients, local pressure gradients (due to water surface slopes and horizontal density gradients) surface wind stress, Coriolis and bottom friction effects, tidal forcing, horizontal buoyancy flux (from estuaries) and air/sea transfer of heat and water. The model needed to be adaptable to the bathymetry of the study area and to be able to simulate a range of mechanisms, both barotropic and baroclinic, with realistic vertical and horizontal structure in water movement and water properties, and realistic vertical mixing.

There are several considerations in implementing the model to represent the study area. The open (sea) boundaries of the model need to be located as far as practicable away from the area of immediate interest, to minimise the influence of perturbations in the applied boundary conditions. The model needs to be able to operate at appropriate horizontal and vertical resolution. Fine horizontal resolution is required about nearshore embayments to resolve areas of rapidly varying bathymetry. Coarser resolution may suffice away from the areas of primary interest to the study. In the vertical dimension, the model needs to be able to resolve the surface and bottom boundary layers, and to resolve the vertical density and current profiles. Variable density models (such as outlined above) generally contain transport equations for salt and heat. Hence the model, once calibrated, can be used to assess the transport and dispersion of other substances.

The hydrodynamic model chosen for application to the SMCWS was formulated at Princeton University (Blumberg and Mellor, 1987). Over recent years, this model has undergone continual development and successful application to study such diverse regions as Chesapeake Bay, the Mid-Atlantic Bight, the Gulf of Mexico, the Great Lakes, and many other areas, including the east coast of Australia.

This time dependent, fully three-dimensional model solves the non-linear primitive equations for the conservation of momentum, volume, salt and heat. The modelled salinity and temperature fields are used to derive water density fields, which can be fed back into the model dynamics. The model contains an imbedded turbulence closure sub-model to provide vertical mixing coefficients. It has a free surface, and can be run either in barotropic or baroclinic mode. The model employs a vertical coordinate, scaled to the local water depth. Details of the model itself are described in Blumberg and Mellor (1987).

This model is currently being implemented for the SMCWS study area. Work in progress has confirmed that it will be able to deal with the range of significant hydrodynamic mechanisms identified during the oceanographical characterisation phase of the study. Preliminary modelling to date has examined the response of shelf waters to combined forcing from long-shelf pressure gradients and surface wind stress. At a basin-scale, the preliminary modelling has studied the three-dimensional circulation and mixing response of density stratified waters to imposed wind stress, forced convective flows due to surface heating or cooling, and the relaxation of an initially perturbed density structure.

Figure 37 illustrates the modelled time history of wind-induced vertical mixing at a particular location in a stratified water body. Figure 38 illustrates the model-simulated process of gravitational

Figure 37 —
Model results showing the time taken (by a 15 m s^{-1} wind) to completely mix a stratified water column of 20 m depth

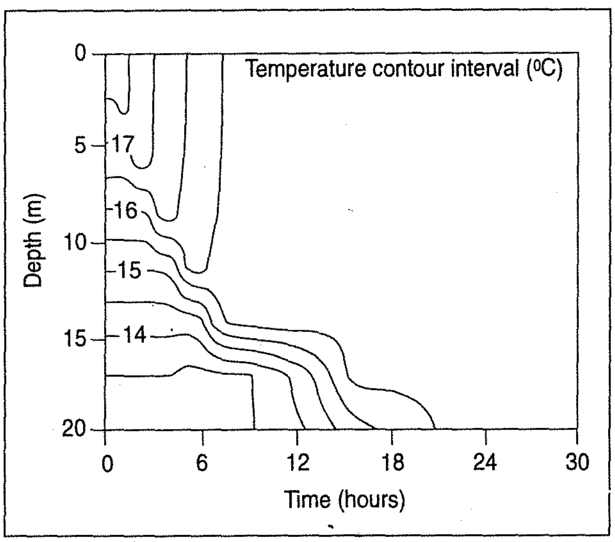
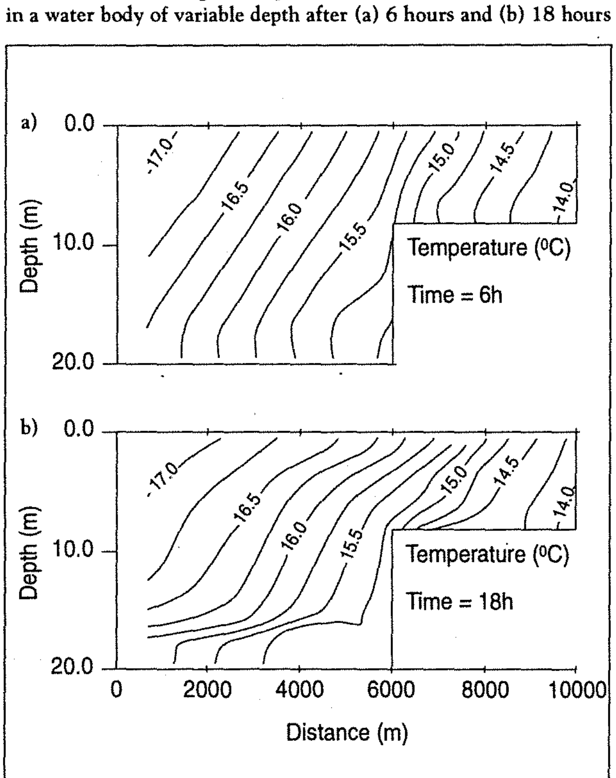


Figure 38 —
Model results showing the response of a disturbed density structure in a water body of variable depth after (a) 6 hours and (b) 18 hours



adjustment and stabilisation of an initially unstable density distribution in a basin of variable depth.

Work on the hydrodynamic modelling is continuing.

7.2 Biological models

The most noticeable effect of nutrient enrichment on aquatic ecosystems is the stimulation of plant growth. Nutrient uptake, conversion rates and photosynthetic responses to light and temperature can vary markedly between different plant types and even between species in the same genus. It would be very difficult to determine these relationships for all the species present in an ecosystem, however it is possible to determine these relationships for major assemblages or even individual species if they are dominant components of the ecosystem being modelled. For the purpose of this study, four broad categories of primary producers and the types of relationships considered important for the model, have been identified (Table 6).

For each group of primary producer in the model, some of these relationships are considered more important than others. For example, the response of seagrasses to water nutrient concentrations is much slower than epiphytes and other algae. Thus, for the purposes of this study, nutrient concentration versus growth relationships of seagrasses can be ignored. Similarly, it appears that the kelp (*Ecklonia radiata*) is not nutrient limited under the predominantly oligotrophic conditions normally found in these waters, and hence there is no need to include a nutrient concentration versus growth relationship for this species. By contrast, the high rate of nutrient uptake of *E. radiata* suggests that this process is important in stripping nutrients from the water and, coupled with a high biomass, will influence the nutrient concentration field and, therefore, is included in the model. Light and temperature on the other hand are growth controlling factors for all primary producers and therefore relationships between these physical factors and growth are required for all key groups or species of primary producers. The broad types of relationships that will be established for each of the major categories and groups of primary producers are summarised in Table 6.

Historical evidence indicates that the direct effects of increased nutrient loads, in the temperate ecosystems of Western Australia, are more pronounced in the primary producers rather than in the consumers. Grazing is, however, considered an important loss function for determining net growth of the primary producers. The other important loss mechanism for attached plants such as macrophytes and epiphytes is mechanical erosion. For the purposes of the model, erosion is considered here to be related solely to water movement and relationships between these two factors are being established (see Section 6.8). Clearly, simulation of this process will require linkage with the hydrodynamic models.

Source documents —
Paling (1991); Masini *et al.* (1991); Masini and Simpson (1992).

Table 6 —
Key categories of primary producers in the ecological model and the relationships/processes being modelled

Category	Group/species	Light/temp: growth	Nutrient: growth	Grazing losses	Nutrient stripping	Biomass: light attenuation
Epiphytes		+	+	+	-	+
Macroalgae						
	kelp	+	-	-	+	-
	small turf	+	+	-	+	-
Phytoplankton						
	diatoms	+	+	+	+	+
	dinoflagellates	+	+	+	+	+
	silicoflagellates	+	+	+	+	+
Seagrasses						
	Posidonia sinuosa	+	-	-	-	-
	Posidonia australis	+	-	-	-	-
	Amphibolis antarctica	+	-	-	-	-
	Amphibolis griffithii	+	-	-	-	-

7.3 Ecological model

Ecosystems are comprised of a vast array of physical and biological factors and the inter-relationships between them. The complete set of inter-relationships is large and impossible to simulate accurately with present technology and levels of scientific understanding. Therefore, any attempt to simulate the response of an ecosystem to perturbation will first require a conceptual simplification of that ecosystem to the components that are both ecologically important and linked to the perturbation being simulated. When such a model is constructed to predict the effects of elevated nutrient loadings on an ecosystem, assumptions must be made as to the most susceptible component of that ecosystem to nutrient enrichment. The pathways of effect between nutrient loading and the most susceptible component of that ecosystem must be established so that investigations can focus on these pathways. In most cases these processes are likely to be ecosystem or even habitat specific. Historical information suggests that the meadow-forming seagrass community is the component of the temperate coastal ecosystems of Western Australia most susceptible to nutrient enrichment. The symptoms included thinning and loss of the meadows and this is mediated through shading by algae stimulated by excessive nutrient loadings.

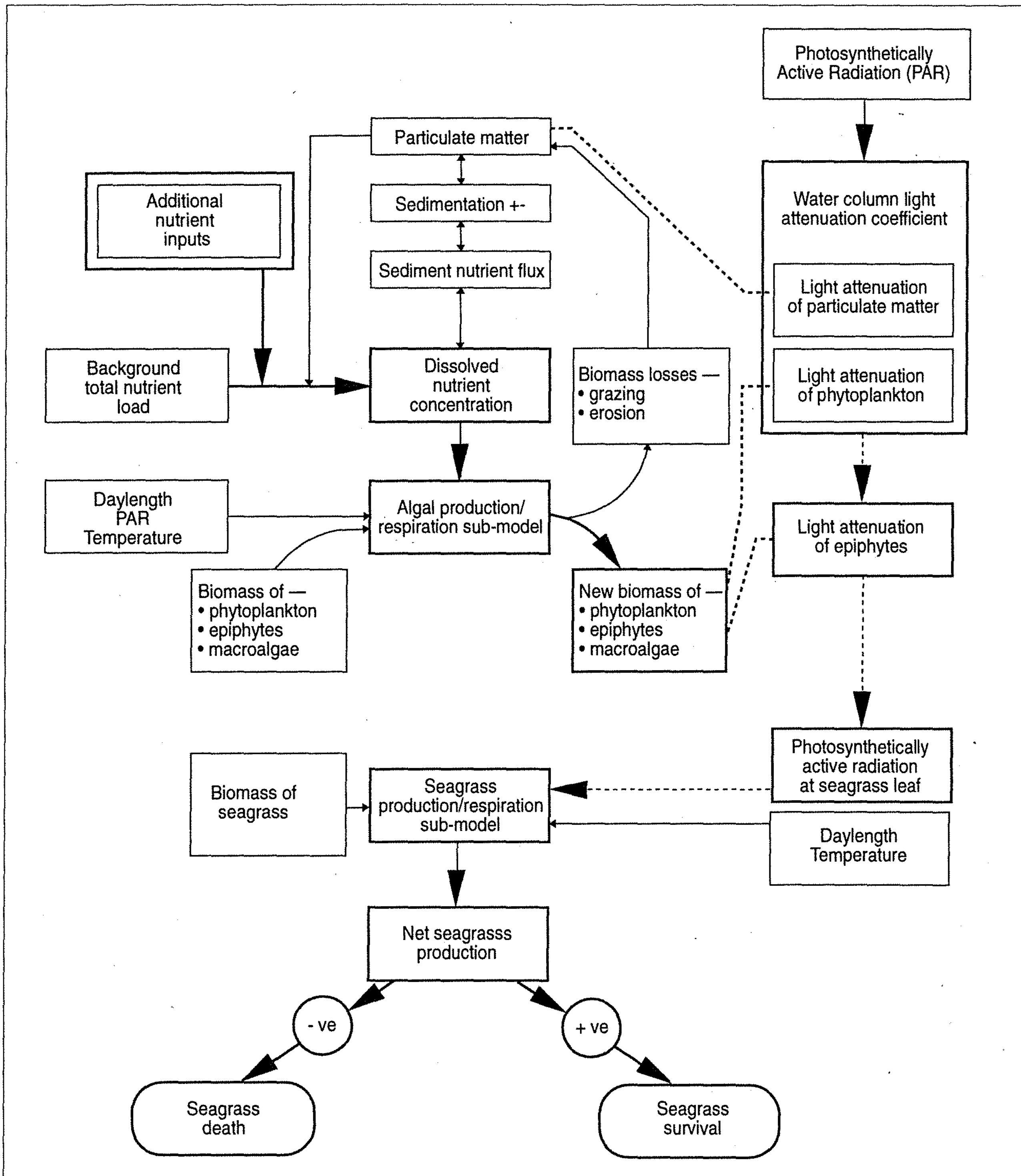
A preliminary nutrient effects ecological model (COASEC), based on this conceptual cause-effect pathway, has been constructed in collaboration with the WAWA (Masini *et al.* 1991; van Senden and Button, 1992). The complexity in modelling natural systems is reduced in COASEC by gridding the area to be modelled into rectangular cells which are assigned a mean depth and habitat type. COASEC has three major components: a hydrodynamic model, a dispersion model and a biological model.

The hydrodynamic model predicts advection fields which characterise the velocity and direction of water movement (see Section 7.1).

The transport or dispersion component of the model uses the advection fields predicted by the hydrodynamic module to determine the concentration of water-borne substances, such as dissolved nutrients or phytoplankton, at each grid cell at each time step of the model. The chemical dispersion field is further modified by the uptake of nutrients by benthic plants and phytoplankton and through sediment nutrient uptake and release. Sediment nutrient flux becomes increasingly important in areas that have high organic loading. These organic rich sediments are characteristic of depositional environments such as the central basin of Cockburn Sound. The high oxygen demand associated with bacterial mediated decomposition of organic matter can reduce the oxygen concentration of the overlying water if the rate of demand exceeds the rate of transport through the water column from the atmosphere. This effect will be most pronounced during periods of calm weather and high water temperatures. Under these conditions nutrient release from the sediments can be high and significantly alter the nutrient concentration of the overlying water.

The biological model is comprised of a number of sub-models with various degrees of linkage between each other and with the hydrodynamic and chemical dispersion components of the ecological model (Figure 39). These biological sub-models serve to simulate the assimilation of dissolved inorganic nutrients in the water column into organic matter. The organic matter for the purposes of this model is either phytoplankton, epiphytes or macroalgae as outlined above in Section 7.2.

Figure 39 —
Conceptual nutrient effects ecological model for the temperate coastal waters of Western Australia



The resultant phytoplankton standing crops and the epiphytic algae growing on seagrass leaves will serve to influence the amount of light available for seagrass photosynthesis and growth. The relationships between phytoplankton biomass and light transmission and between epiphyte biomass and light transmission are used in this component of the model to predict available light at the seagrass leaf blade. The seagrass submodel then uses this final piece of information to predict whether the seagrass communities will survive or perish. The survival or otherwise of the seagrasses provides the final end point of the simulation.

Point or diffuse sources of nutrients can be inserted in any cell and the model run for a number of simulation years to predict the consequences of a range of nutrient loading scenarios on key components of the major habitat type at each grid coordinate.

Source documents —
Masini *et al.* (1991); Masini *et al.* (1992); van Senden and Button (1992).

Further work —
Field calibration and validation of the ecological model is currently being planned.

COLLABORATIONS

This section outlines specific project collaborations, completed and current, with other organisations. These collaborations will form part of the information base of the SMCWS. Some collaborations have been included in the main part of the report and are not mentioned below (e.g. Sections 4.7). Project titles have been abbreviated. The ongoing collaboration with the Water Authority of Western Australia is covered briefly in Section 1.3.

8.1 Completed

HEAVY METALS IN THE SEDIMENTS OF COCKBURN SOUND AND SURROUNDING WATERS.
Murdoch University. Contacts: Dr. F Murray and R. Monk.
EPA. Contact: Dr. C. Simpson.

MAPPING OF THE MARINE RESOURCES IN THE SOUTHERN METROPOLITAN COASTAL WATERS OF PERTH.
University of Western Australia. Contacts: Dr. I. Eliot and A. Sanders.
EPA. Contact: J. Burt.

EDUCATIONAL MATERIAL FOR THE ENVIRONMENTAL STUDIES IN PERTH'S COASTAL WATERS.
Water Authority of Western Australia. Contact: M. French.
EPA. Contact: J. Cary.

GROUNDWATER NUTRIENT FLUX INTO THE COASTAL WATERS OF PERTH
Department of Minerals and Energy, Hydrogeology Section.
Contact. S. Appleyard
EPA. Contact: J. Cary.

COMPARISON OF THE LARVAL FISH ASSEMBLAGES IN HEALTHY AND DEGRADED SEAGRASS MEADOWS IN COCKBURN SOUND, WESTERN AUSTRALIA.
Murdoch University. Contacts: Dr. F. Neira and L. Jonker.
EPA. Contact: Dr. C. Simpson.

USE OF REMOTE SENSING AS A MONITORING TOOL IN THE COASTAL WATERS OF PERTH.
Centre for Water Research, University of Western Australia.
Contact: Dr. C. Pattiaratchi.
Remote Sensing Applications Centre, Department of Land Administration. Contact: A. Wyllie.
EPA. Contact: Dr. R. Masini.

CONTAMINANTS IN SEDIMENTS AND BIOTA IN THE SOUTHERN METROPOLITAN WATERS OF PERTH
Chemistry Centre of Western Australia. Contact: D. Ingraham.
EPA. Contact: J. Burt.

8.2 Current

A STUDY OF THE SPECIES COMPOSITION, DISTRIBUTION AND ABUNDANCE OF INVERTEBRATE AND JUVENILE FISH ASSEMBLAGES OVER BARE AND VEGETATED HABITATS IN COCKBURN SOUND.
CSIRO Marmion. Contact: Dr. C. Jacoby.
EPA. Contact: Dr. C. Simpson.

THE USE OF GEOSCAN IMAGES FOR ACCURATE HABITAT MAPPING.
Remote Sensing Applications Centre, Department of Land Administration. Contact: A. Wyllie.
EPA. Contact: J. Burt.

COMPARISON OF DISTURBANCE OF THE BENTHIC FAUNA OF THE DEEP BASINS IN COCKBURN SOUND AND WARNBRO SOUND.
University of Western Australia. Dr. I. Eliot, Dr. B. Knott and L. Chalmers.
EPA. Contact: J. Cary.

COMPARISON OF FILTER FEEDING COMMUNITIES IN SEAGRASS MEADOWS IN COCKBURN SOUND AND THE MARMION LAGOON.
CSIRO Marmion. Contact: Dr. H. Kirkman.
EPA. Contact: Dr. C. Simpson.

THE USE OF THE NEOGASTROPOD MOLLUSC, *THAIS ORBITA*, AS A BIOINDICATOR FOR TRIBUTYL TIN CONTAMINATION IN PERTH METROPOLITAN WATERS.
University of Western Australia. Contact: Dr. R. Black, Dr. M. Johnson and S. Field.
WA Museum: Contact: Dr. F. Wells.
EPA. Contact: Dr. C. Simpson.

THE SOUTHERN METROPOLITAN COASTAL WATERS STUDY: EDUCATIONAL MATERIAL RELEVANT TO MINISTRY OF EDUCATION CURRICULA.
Ministry of Education. Contacts: N. Tame, R. Beresford.
Water Authority of Western Australia. Contact : R. Hallam.
EPA. Contacts: J. Cary, J. Harris.

THE USE OF LANDSAT THEMATIC MAPPER AND NOAA-AVHRR FOR ENVIRONMENTAL INVESTIGATIONS OF THE PERTH METROPOLITAN COASTAL WATERS.
Remote Sensing Applications Centre, Department of Land Administration. Contact: A. Wyllie.
EPA. Contact: Dr. D Mills, N. D'Adamo.

CLIMATOLOGY OF EDDY/MEANDER STRUCTURES OF THE LEEUWIN CURRENT OFF SOUTHWEST AUSTRALIA USING AVHRR IMAGERY.
CSIRO Marmion. Contact: A. Pearce.
EPA. Contact: Dr. D Mills, N. D'Adamo.

PUBLICATIONS AND TECHNICAL PRESENTATIONS

9.1 Publications

Reports published

Appleyard S J (1990). The flux of nitrogen and phosphorus from groundwater to the ocean in the Perth metropolitan region. (Hydrogeology Report No. 1990/64, WA Geological Survey, Perth, Western Australia, 6000). Report to the Environmental Protection Authority of Western Australia. Pp. 11.

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Cary J L and Ryall T (1991). Bibliography of environmental studies of the southern metropolitan coastal waters of Perth. (Environmental Protection Authority, Perth, Western Australia, 6000). Technical Series No. 45. Pp. 63.

Cary J L and Simpson C J (1991). Protecting Perth's coastal waters and beaches: a plan for doing it better. (Environmental Protection Authority, Perth, Western Australia, 6000). Bulletin No. 511. Pp. 22.

Cary J L, Simpson C J and Chase S (1991). Water Quality in Cockburn Sound: results of the 1989/90 summer monitoring programme. (Environmental Protection Authority, Perth, Western Australia, 6000). Technical Series No. 47. Pp. 14.

Cousins M (1991). A comparative study of phytoplankton in Warnbro Sound and Cockburn Sound, Western Australia. (Honours Thesis, Curtin University of Technology, Perth, Western Australia). Pp. 96.

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Environmental Protection Authority (1990). The environmental impact of organotin anti-fouling paints in Western Australia. (Environmental Protection Authority, Perth, Western Australia, 6000). Bulletin No. 447. Pp. 13.

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Masini R J (1993). Growth, erosion and morphometrics of *Posidonia sinuosa* in Owen Anchorage. (Environmental Protection Authority, Perth, Western Australia, 6000). Data Report SMCWS ECOL4-150793. Pp. 28.

Masini R J and Manning C (1992). Seagrasses, epiphytes and macroalgae: critical irradiances and metabolic rates. (Environmental Protection Authority, Perth, Western Australia, 6000). Data Report SMCWS ECOL2-171192. Pp. 28.

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Mills D A, D'Adamo N, Wyllie A and Pearce A F (submitted). The role of barotropic and baroclinic processes in the winter flushing of shelf waters off Perth, Western Australia. In: Proceedings of the 6th International Biennial Conference on Physics of Estuaries and Coastal Seas, 8-10 Dec 1992, Margaret River, Western Australia. Journal of the American Geophysical Union.

Monk R J (1989). Heavy metal status of the sediments of Cockburn Sound and surrounding region. (Honours Thesis, School of Biological and Environmental Sciences, Murdoch University, Perth, Western Australia, 6150). Pp. 155.

Monk R J and Murray F (1991). A survey of the heavy metals in the marine sediments of Cockburn Sound and surrounding waters. (School of Biological and Environmental Sciences, Murdoch University, Perth, Western Australia, 6150). Report to the Environmental Protection Authority. Pp. 31.

Paling E I (1991). The relationship between nitrogen cycling and productivity in macroalgal stands and seagrass meadows. (PhD

Thesis, University of Western Australia, Nedlands, Western Australia, 6000). Pp. 316.

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Wyllie A, Buchanan A, D'Adamo N and Mills D A and Pearce A F (1992). The use of Landsat Thematic Mapper and NOAA AVHRR for environmental investigations of the Perth metropolitan coastal waters. Proceedings: 6th Australasian Remote Sensing Conference, 2-6 Nov, 1992, Wellington, New Zealand, 3: 203-208.

Reports in preparation

Burt J S (in preparation). The factors determining the temporal and spatial variation of light attenuation in the southern metropolitan coastal waters. (Environmental Protection Authority of Western Australia, Perth, Western Australia, 6000).

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