ALBANY HARBOURS ENVIRONMENTAL STUDY 1988 - 1989

ENVIRONMENTAL PROTECTION AUTHORITY

Bulletin 412

Front Cover

Landsat Thematic Mapper image of the Albany area, recorded from an altitude of 720km (February, 1988).

Acknowledgement:
Image provided by
Remote Sensing Applications Centre,
Department of Land Administration.

Back Cover

Posidonia sinuosa seagrass meadow in King George Sound.
Also shown are vertical profiles of temperature, salinity and density in Oyster Harbour (top), and temperature and light measured in 1.7 m of water above a seagrass meadow in Princess Royal Harbour in summer (bottom).

Albany Harbours Environmental Study

(1988-1989)

A Report to the Environmental Protection Authority
from the
Technical Advisory Group

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Preface

At the turn of the century, the population of Albany was about 3500 and at this time the town depended almost entirely on the economic benefits of local agriculture. Princess Royal Harbour was dredged between 1901 and 1904 to deepen the northern part of the harbour for shipping. A whaling company began operating from Frenchman Bay in 1912, but closed shortly after. A freezing works was established on the Albany foreshore in 1913 and several years later it was expanded to include the killing of sheep. In 1924, the Albany Woollen Mills opened. During the depression, the population of Albany fell to around 2000, but by the end of the World War II it had risen to about 4500.

The post-war economic boom in Australia was reflected in the dramatic increase in the population of Albany which almost doubled over the next ten years. In 1947, a fish factory began canning fish caught in local waters and in the early 1950s a sewage treatment plant was constructed at King Point, near the entrance to Princess Royal Harbour. The Cheynes Beach Whaling Company established its station at Frenchman Bay in 1952 and operated for the next 26 years. By 1954, the population was over 8000 and in the same year a fertilizer manufacturing plant was established on the western shores of Princess Royal Harbour to supply an increasing demand for fertilizers in the Albany region. Clearing of land for agriculture was still proceeding at a rapid rate, and to meet the requirements for increased grain exports, Co-operative Bulk Handling constructed silos and an unloading facility on the Albany foreshore in 1956.

Concern for the water quality of Princess Royal Harbour dates back to the early seventies when WAIT-Aid Ltd undertook a survey of the waters of Princess Royal Harbour on behalf of the Albany Port Authority. In response to the recommendations made in this report the Department of Conservation and Environment then commissioned a further survey of the waters of Princess Royal Harbour which indicated that some visual pollution of the harbour waters was occurring, although the long-term effects of waste discharge on the water quality of Princess Royal Harbour were unclear.

In 1976 the Albany Waterways Management Advisory Committee (AWMAC) was established to ensure that the water quality of the Albany harbours remained high. In response to a request from AWMAC, the Department of Conservation and Environment, in collaboration with the University of Western Australia, undertook a water quality survey of Princess Royal Harbour between December 1978 and December 1979. Although some areas of the harbour were found to be polluted by faecal bacteria, the overall nutrient status of the water was low and the harbour was considered to be sufficiently well-flushed to cope with the nutrient loads at the time.

In 1983, a routine sample of fish, taken from the Perth metropolitan fish markets, was analysed by the Health Department and found to be contaminated by mercury. Subsequent investigations found that these fish had been caught in Princess Royal Harbour. An intensive survey of the sediments and biota in Princess Royal Harbour found that the western end of the harbour was extensively contaminated with lead and mercury. These findings led to the stoppage of further discharges of lead and mercury and the closure of the western end of Princess Royal Harbour to fishing.

In 1981 and 1984 the Department of Conservation and Environment funded surveys of the major marine plant communities in the Albany harbours. The latter survey reported extensive loss of seagrasses in both harbours and a considerable build-up of attached and unattached algae, usually a symptom of waterbodies that are severely polluted. In response to these findings, the Environmental Protection Authority prepared an overview report in June 1986 on the current state of the environmental problems in the Albany harbours. This report considered the situation in both harbours to be serious and requiring urgent attention.

As a result, in October 1987, the Western Australian Government approved funding for an intensive two-year study into the ecology of the Albany harbours on the understanding that the study would provide long-term solutions to the environmental problems in the harbours.

This report presents a summary and recommendations of the Albany Harbours Environmental Study which was conducted over two years from 1988 to 1989. A brief report of the Study and recommendations is outlined in a companion document (EPA Bulletin 426). These two reports have been prepared not only for those responsible for making major management decisions but also for private individuals with an interest in the Albany harbours. These reports and recommendations, and the issues raised by public submissions will form the basis of an Environmental Protection Authority submission to Government.

Precis

Seagrass meadows provide food, shelter and a breeding ground for fish and many other animals and, in the past, have been at the base of the food web of the Albany harbours. Since 1962, when these seagrass meadows were considered to be in a pristine condition, about 90% of the meadows in Princess Royal Harbour and 80% in Oyster Harbour have been lost. In recent years the rate of seagrass loss in the harbours has accelerated due to a proliferation of macroalgae which shade and smother the seagrass meadows. The growth of macroalgae has been stimulated by excessive nutrient inputs to Princess Royal Harbour from industrial, rural and urban sources, and to Oyster Harbour from rural and urban sources.

Current information on the 'recovery' of seagrass meadows suggests that the luxuriant *Posidonia* meadows that once covered most of the Albany harbours will never return to their former state. However, once the large accumulations of macroalgae that presently occur in the harbours are removed and pollutant inputs are drastically reduced, conditions in the harbours are likely to improve sufficiently to allow the remaining seagrasses to flourish and other seagrass species and animals to colonise suitable bare areas of seabed.

If the recommendations in this report are implemented, seagrass decline in both waterbodies will slow down and eventually stop as the biological systems stabilize. In addition, pollutants such as faecal bacteria, solids, oils & greases and visible effluent slicks in the waters and along the shorelines of Princess Royal Harbour and King George Sound will be significantly reduced within two years. Furthermore, if the amount of heavy metals in the sediments of the western end of Princess Royal Harbour is significantly reduced, the re-opening of this part of the harbour to fishing is likely to occur earlier than if the removal of heavy metals from the sediment is left to natural processes.

If, on the other hand, the current pollutant loadings into these harbours continue, the bacteriological and aesthetic quality of Princess Royal Harbour and parts of King George Sound will decline further. In addition, most of the remaining seagrasses will be lost within five years in Princess Royal Harbour and within 5-10 years in Oyster Harbour and the general ecology of the harbours will continue to deteriorate.

Recommendations

The principal recommendations which resulted from the Albany Harbours Environmental Study are listed below. The recommendations are divided into two groups: (i) specific recommendations which, if implemented immediately, will not only retard the rate of seagrass decline but will also provide an immediate improvement in the general environmental quality of the Albany harbours and; (ii) general recommendations that provide guidelines for long-term environmental management strategies in the Albany region. Recommended Princess Royal Harbour effluent discharge criteria are outlined in Appendix 1.

Specific Recommendations

Recommendation 1

Immediate removal of the large accumulations of macroalgae in Princess Royal Harbour and Oyster Harbour. The rate of algal removal should be sufficient to remove these accumulations within two years.

Recommendation 2

Evaluation of removal of nutrient-rich sediments from the Albany harbours as an effective environmental management strategy be undertaken, as a matter of high priority, by the proposed Albany waterways management authority.

Recommendation 3

The four industries currently discharging directly into Princess Royal Harbour be directed to commence immediately, the formulation of a strategy, and to reduce, within two years, industrial pollutant loads currently entering Princess Royal Harbour. In the event of continued discharge to Princess Royal Harbour, as a minimum requirement, effluent quality from these industries is not to exceed Princess Royal Harbour effluent discharge criteria and pollutant loads are to be acceptable to the Environmental Protection Authority.

Recommendation 4

CSBP be directed to commence, immediately, the formulation of a strategy and to reduce, within two years, surface runoff nutrient loads into Princess Royal Harbour from its industrial estate to levels acceptable to the Environmental Protection Authority.

Recommendation 5

CSBP be directed to complete, within one year, a program to determine the current and likely future groundwater nutrient loads into Princess Royal Harbour from its industrial estate. Upon completion, CSBP be directed, if necessary, to implement a management plan that will reduce, within one further year, current and future groundwater nutrient loads into Princess Royal Harbour to levels acceptable to the Environmental Protection Authority.

Recommendation 6

The Water Authority of Western Australia commence immediately, the formulation of a strategy to reduce, within two years, pollutant loads in domestic wastewater effluent from the King Point outfall to levels acceptable to the Environmental Protection Authority. Alternatively, the Water Authority of Western Australia commence immediately, the formulation of a strategy to divert, within four years, the domestic wastewater currently discharged from the King Point outfall.

Recommendation 7

The Town and Shire of Albany be encouraged to complete, within one year, a program to determine the groundwater and surface runoff pollutant loads into the Albany harbours from urban point sources. Upon completion of this program, the Town and Shire of Albany, if necessary, be encouraged to implement a management plan that will reduce, within one further year, current and future groundwater and surface runoff pollutant loads from point sources to the Albany harbours to levels acceptable to the Environmental Protection Authority. As an incentive to local government to reduce pollution from urban sources, co-operative use of existing State Government resources such as the Chemistry Centre, the Department of Health and the Department of Agriculture be provided.

Recommendation 8

The Town and Shire of Albany be encouraged to develop a management plan to minimize pollution of the Albany harbours from urban diffuse sources. To promote community involvement, the Town and Shire of Albany be encouraged to conduct an education program related to minimising pollution from these sources.

Recommendation 9

The Western Australian Department of Agriculture continue, in consultation with farmers and other groups, to develop and promote the adoption of catchment management plans which will assist with the reduction of nutrient loads to target levels as determined by the Environmental Protection Authority. As an incentive to adopt more efficient fertilizer use, funding be provided for two years, for a free soil testing service targeted on sandy (low reactive iron) soils in the catchments of the Albany harbours.

Recommendation 10

The Western Australian Department of Agriculture evaluate current soil survey, land-use and other natural resource information to identify high phosphorus source areas (including point sources) within the catchments of Princess Royal Harbour and Oyster Harbour, and prepare a strategy for their management by June 1990.

Recommendation 11

Further investigations to refine initial estimates of the annual nutrient assimilative capacity of Oyster Harbour be undertaken as a matter of high priority by the proposed Albany waterways management authority.

Recommendation 12

CSBP be directed to undertake an extensive survey of the heavy metal concentrations in the sediments and biota of Princess Royal Harbour to assess the current contamination of the harbour and, if necessary, to formulate, within one year, a management plan to reduce the heavy metal contamination of Princess Royal Harbour to levels, and within a timeframe, acceptable to the Environmental Protection Authority.

General Recommendations

Recommendation 1

Annual total nutrient loading into Princess Royal Harbour and Oyster Harbour from all sources should not exceed the nutrient assimilative capacities of these waterbodies.

Recommendation 2

Future development proposals and management of industrial, urban and rural land-use in the catchments of the Albany harbours should have regard for the capacity of these waterways to assimilate pollutants, particularly nutrients.

Recommendation 3

A regional liaison structure be developed to ensure co-ordination of Government, technical and community involvement in the integrated management of the catchments and waterways of the Albany harbours.

Recommendation 4

A management presence be established to provide for future on-site management of the Albany harbours. An Albany Waterways Management Authority could be established under the Waterways Commission Act with direct local government and community involvement.

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Part I

Background Information

This part of the report provides background information relevant to the history of environmental problems which developed in Princess Royal Harbour and Oyster Harbour. There are three chapters in Part 1. Chapter 1 describes briefly the environmental changes in the harbours that prompted the study, and outlines the organisation and method of approach that was adopted. Chapter 2 describes the physical characteristics of the two harbours as well as their resources and uses. Chapter 3 identifies beneficial uses of the harbours and suggests water quality characteristics necessary for the protection of these uses.

Figure 1.1 Albany Harbours and adjacent areas.

Chapter 1

Introduction

The Albany region was the first area in Western Australia to be settled by Europeans. This settlement was based around the sheltered waters of Princess Royal Harbour and King George Sound which provided relatively safe, natural harbours (Figure 1.1). About 80 years ago agriculture-related industries were first established on the shores of Princess Royal Harbour. The rapid expansion of the population of Albany in the early 1950s led to the construction of a domestic wastewater treatment plant near King Point. Since then, primary treated domestic wastewater has been discharged to the ocean near the entrance to Princess Royal Harbour.

Currently, a fertilizer factory, a woollen mill, a fish processing factory, an abattoir and a vegetable processing factory are the main industries along the Albany foreshore and most routinely discharge their wastes into Princess Royal Harbour. Fertilizers, washed off the agricultural catchments of the Albany harbours, also enter these waterbodies via rivers, creeks and drains.

The input of pollutants from these sources over many years, was implicated in the gradual deterioration in the environmental 'health' of the harbours. The rapid decline of the seagrass meadows in the harbours over the past decade has raised widespread community concern over the long-term future of these waterbodies.

In recent times, the Albany region has experienced a substantial increase in tourism. This has been partly centred on the spectacular coastline around Albany and on Princess Royal Harbour and Oyster Harbour. The close proximity of the harbours to the town and their protected waters are ideally suited for water-based recreation. As the population of the Albany region continues to grow and tourism becomes an increasingly significant part of the local economy, it is inevitable that conflicts between industrial and recreational requirements will intensify.

This report summarizes a two-year investigation of the environmental problems of the Albany harbours, authorised by the Western Australian Government in October 1987. The study was co-ordinated by the Marine and Estuarine Branches of the Environmental Protection Authority (EPA) and by a Technical Advisory Group (TAG), comprising representatives from the EPA, Waterways Commission (WWC), the Department of Agriculture (DAg), and the Centre for Water Research of the University of Western Australia/Murdoch University (CWR). In addition to summarising results of the technical studies, the report presents a strategy for continued multipurpose use of the harbours.

The need for the study, its objectives and scope, and the method of approach are all described in this introductory chapter.

1.1 Need for study

The first documented scientific study of the Albany harbours was conducted by McKenzie (1962; 1964) who made surveys of the biological communities in Princess Royal Harbour and Oyster Harbour. At this time the harbours were considered to be in a 'pristine' condition. Concern for the water quality of Princess Royal Harbour dates back to the early seventies when WAIT-Aid Ltd undertook a survey of the waters of Princess Royal Harbour on behalf of the Albany Port Authority (Anonymous, 1975). In response to the recommendations made in this report the Department of Conservation and Environment (now the EPA) then commissioned a further survey of the waters of Princess Royal Harbour '... *to assess the extent of the contamination or deterioration of the main body of water in relation to the various trade wastes and other inputs*'.

The results of this survey indicated that some visual pollution of the harbour waters was occurring, although the long-term effects of waste discharge on the water quality of Princess Royal Harbour were unclear (Platell, 1978). In 1976 the Albany Waterways Management Advisory Committee (AWMAC) was established to ensure that the water quality of the Albany harbours remained high. In response to a request from AWMAC, the Department of Conservation and Environment in collaboration with the Botany Department of The University of Western Australia (UWA), undertook a water quality survey of Princess Royal Harbour between December 1978 and December 1979 (Atkins *et al.*, 1980). Although some areas of the harbour were found to be polluted by faecal bacteria, the overall nutrient status of the water was low and the harbour was considered to be sufficiently well flushed to cope with the nutrient loads at the time. This study recommended a series of actions that would be required to provide the necessary information base for effective future management of Princess Royal Harbour.

In 1983, a routine sample of fish, taken from the Perth metropolitan fish markets, was analysed by the Health Department and found to be contaminated by mercury. Subsequent investigations found that these fish had been caught in Princess Royal Harbour. An intensive survey of the sediments and biota in Princess Royal Harbour found that the western end of the harbour was extensively contaminated with lead and mercury (Jackson *et al.*, 1986). These findings led to the closure of this end of Princess Royal Harbour to fishing. The source of this pollution was identified as the CSBP fertilizer works, which discharged an effluent directly into the harbour via an outfall (Talbot *et al.*, 1987). By February 1984 the company had ceased discharging the effluent and the pipeline was removed in 1986. Since then the Department of Fisheries has continued to monitor the level of mercury in several species of fish and presently, the western end of Princess Royal Harbour remains closed to fishing.

In 1981 and 1984, the Department of Conservation and Environment funded surveys of the major marine plant communities in the Albany harbours. The latter survey reported extensive loss of seagrasses in both harbours and a considerable build-up of attached and unattached algae, usually a symptom of waterbodies that are severely polluted (Bastyan, 1986). In response to these findings, the EPA prepared an overview report on the current state of the environmental problems in the Albany harbours (Mills, 1987). In addition, Kirkman (1987) assessed the urgency of the situation by analysing the rate of decline in the seagrass meadows since 1962. Both studies considered the situation in the Albany harbours to be serious and requiring urgent attention.

As a result, the Western Australian Government approved funding for an intensive two-year investigation into the ecology of the Albany harbours on the understanding that the study would provide long-term solutions to the environmental problems in the harbours. This report presents the results, conclusions and recommendations of the Albany Harbours Environmental Study.

1.2 Objective and scope

The objectives of the Albany Harbours Environmental Study were as follows:

(i) to assess the biological status of Princess Royal Harbour and Oyster Harbour;

(ii) to determine the characteristics of industrial, domestic, urban and agricultural inputs to the Albany harbours;

(iii) to make an assessment of the causes of the decline of the seagrasses and;

(iv) to identify long-term solutions to the environmental problems in the Albany harbours.

The study's main focus was the environmental impact of man-made pressures upon the aquatic environment, particularly on the seagrass meadows. Seagrass meadows are important nursery areas for numerous species of fish and provide an excellent habitat for many other marine animals (Figure 1.2). When seagrasses are lost, the dependent animal populations are also severely depleted.

The unnaturally large accumulations of macroalgae (seaweed) in Princess Royal Harbour and the past discharge of wastes containing considerable quantities of plant nutrients suggested that nutrient enrichment was, indirectly, the cause of the decline of the seagrass meadows in Princess Royal Harbour. Prolonged reductions in light reaching the seagrass meadows due to shading and smothering by these algae, were implicated as the direct cause of seagrass decline.

The possibility that other wastes (eg fluorides, pesticides etc) were a major contributing factor in the loss of seagrass was considered to be less likely. As a result the studies were centred on the effects of nutrient enrichment on the plant communities in these waterbodies. Consideration of land-associated aspects was focussed on the catchments of Princess Royal Harbour and Oyster Harbour as sources of nutrients because of the intensive horticulture carried out in the former and the extensive agriculture in the latter.

Heavy metal contamination in several fish species in Princess Royal Harbour was monitored annually by the Department of Fisheries. The extent of the heavy metal problem had been determined several years before (Jackson *et al.*, 1986) and the main source of this pollution had been stopped by the time the study commenced (Talbot *et al.*, 1987).

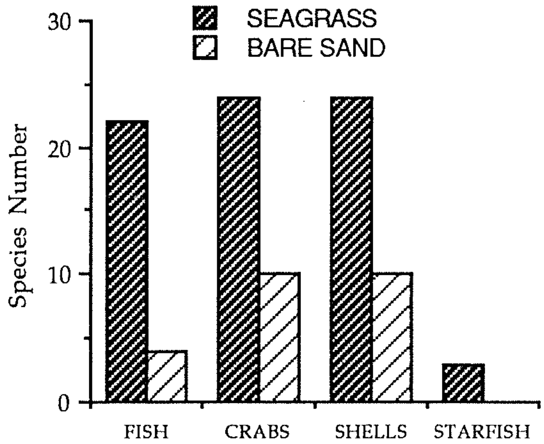

Figure 1.2 Comparison of animal diversity in seagrass meadows and adjacent bare sand in Princess Royal Harbour (adapted from Kirkman *et al.*, in preparation).

1.3 Definition of study area

The study area consists of Princess Royal Harbour and Oyster Harbour to the south and the north-east of the Albany township respectively, their rural and urban catchments and the western side of King George Sound (Figure 1.1).

1.4 Method of approach

The report on the water quality of Princess Royal Harbour by Atkins *et al.*,(1980) made a series of recommendations that, if implemented, would have provided a better understanding of the likely impacts of industrial discharges into these waters. Unfortunately, most of these recommendations were never implemented. A study by Bastyan (1986) of the distribution and abundance of seagrass meadows in the Albany harbours in 1984 indicated that a marked decline had occurred. The severity of the problem in the Albany harbours was outlined in this report and prompted the EPA to conduct an assessment of the overall situation in Princess Royal Harbour and Oyster Harbour (Mills, 1987). This report made a series of recommendations regarding further investigations which would enable selection and effective implementation of the most appropriate management strategies. These recommendations were, in part, a repeat of the earlier recommendations of Atkins *et al.*, (1980) and formed the initial basis of the study program.

As the study progressed it became apparent that additional information would be necessary to fulfil the study objectives and, as a result, several investigations were initiated in 1989. In addition, studies related to the feasibility of possible management options were also undertaken. A brief outline of each of the component studies is presented below. The detailed reports of these component studies are being published separately and provide the technical and scientific basis for the recommendations made in this report. These reports are listed with the other references cited in this report.

1.4.1 Survey of plant communities and nutrient pools.

The Centre for Water Research was contracted to undertake a survey of the distribution and abundance of the main plant communities in both harbours to enable comparisons with the earlier surveys of 1981 and 1984. Of particular concern was the continued decline in the *Posidonia* seagrass meadows in both harbours. Fixed transects were also established to monitor future changes to these communities. In addition, the major nutrient pools were determined in February 1988 to identify the fate of the nutrients entering the harbours (Hillman *et al.,* in preparation).

As a result of an exceptionally wet winter in 1988, the annual nutrient loading into Oyster Harbour increased dramatically in comparison to the low nutrient loads resulting from the 'dry' winter of 1987. The possibility that increased nutrient loads would stimulate rapid growth of the macroalgae in Oyster Harbour was raised. A further survey of macroalgal distribution and abundance was undertaken in February 1989 to determine the response of the plant communities in Oyster Harbour to this increased nutrient loading (Bastyan and McComb, in preparation).

1.4.2 Water Quality

The Centre for Water Research was contracted to undertake a survey of the physical, chemical and biological characteristics of the water column in the two harbours and at two control sites over healthy seagrass meadows in King George Sound (Hillman *et al.,* in preparation). This survey, from December 1987 to February 1989, was conducted on a monthly basis in summer and twice-monthly in winter. The water quality data collected in Princess Royal Harbour during this period allow comparisons to be made with the 1979 data of Atkins *et al.,* (1980).

1.4.3 Seagrass and Macroalgae Studies

The Centre for Water Research was contracted to undertake a survey of the seasonal changes in the biomass, productivity and epiphyte load of representative areas of seagrass meadows in Princess Royal Harbour, Oyster Harbour and King George Sound. This information enabled comparisons to be drawn between the degraded seagrass meadows in polluted water in the harbours and the healthy meadows in King George Sound.

A marine botanist from the Centre for Water Research, UWA was contracted to undertake, in collaboration with the Marine Impacts Branch of the EPA, a series of experiments on the effects of light and temperature on the photosynthesis and respiration of 'whole' seagrass plants, macroalgae and epiphytes (Masini *et al.,* in preparation). This study was designed to provide information on the minimum light requirements of these plants and the relative competitive ability, in relation to light, of seagrasses, macroalgae and epiphytes.

Further studies conducted by EPA in 1989 examined the effect of prolonged light reduction and algal smothering on a seagrass meadow in Princess Royal Harbour (Gordon *et al.,* in preparation). These studies provided information on the rate of decline and recovery of seagrass meadows 'stressed' by extended periods of reduced light availability.

1.4.4 Water Circulation

Water circulation patterns and related physical phenomena in the Albany harbours are the mechanisms by which wastewater and other pollutant inputs are transported, dispersed and diluted. The EPA conducted studies in both harbours.

Princess Royal Harbour is a marine embayment that is comparatively well mixed and bathymetrically less complex than Oyster Harbour which, because of the inflow of river water and solar heating is generally stratified in temperature and salinity with less dense (fresher and/or warmer) water on the surface and denser (saltier and/or colder) water underneath. Mathematical models of water circulation and pollutant transport in Princess Royal Harbour were developed, and the results compared with data collected from the harbour itself. These models were used to assess the rates of flushing of pollutants out of the harbour (Mills and D'Adamo, in preparation).

Collaborative studies with the Centre for Water Research, Department of Civil Engineering, UWA, examined the density structure of the water in Oyster Harbour under various meteorological conditions to identify the dominant hydrodynamic processes (D'Adamo, in preparation). This information is relevant to understanding the retention and flushing of nutrients in Oyster Harbour, and is critical to the long-term management of this waterbody.

1.4.5 Determination of Pollutant Inputs

Studies were undertaken by the EPA and the Department of Agriculture to determine the types and amounts of pollutants currently entering Princess Royal Harbour and Oyster Harbour.

Industrial discharges, urban runoff, agricultural inputs and domestic wastewater discharges were monitored to determine the characteristics of the effluents entering Princess Royal Harbour. Although CSBP has undertaken some degree of self-monitoring since the early 1980s, most of the industries discharging wastes into the harbour had not monitored their effluent discharges regularly. As a result, a program of self-monitoring by these industries was initiated, by the EPA, in 1989 to provide further information on their effluent discharge characteristics. This information, and estimates of the flushing characteristics of each discharge point, have been used to assess the relative contribution of each effluent to the pollution of Princess Royal Harbour (Deeley and Bott, in preparation).

Riverine inputs of nutrients to Oyster Harbour were determined in 1987 and 1988 for the King and Kalgan Rivers and other smaller creeks in the catchment of Oyster Harbour. In addition, nutrient inputs from other point and diffuse sources have been monitored (Bott and Pepper, in preparation).

An assessment of the history of pollutant discharges into both harbours was also made.

1.4.6 Feasibility Studies of Possible Management Options

The EPA conducted a study to determine the assimilative capacity of the Albany harbours (Gordon and Deeley, in preparation). The assimilative capacity is defined as the capacity of the receiving environment to absorb waste without causing long-term damage to the existing biological communities. This study estimated the annual total loading of nutrients that could be discharged into the harbours without a recurrence of the macroalgal blooms that caused the decline of the seagrass meadows in the past.

A marine botanist from the CSIRO was seconded to the EPA to prepare a report on the feasibility of seagrass meadow restoration. The various problems involved, such as transplanting seedlings and vegetative propagules, as well as the considerations regarding the site of restoration, are outlined in Kirkman (1989).

An engineer from the Waterways Commission prepared a report on the feasibility of harvesting macroalgae in the Albany harbours. As the main concentrations of macroalgae in the harbours are located between 1-3m depth, the harvesters would have to be designed specifically for these waterways. The harvesters currently in use in the Peel-Harvey Estuary near Mandurah have a depth limit of about 1m. Harvesting rates of different designs were estimated as well as capital and operational costs (Crawford, 1989).

The Albany Office of the Department of Agriculture conducted extensive surveys of the nutrient status of the soils in the catchments of the Albany harbours. The aim of this study was to examine fertilizer practices on local farms with the objective of optimising fertilizer applications, without a loss of productivity, and thereby reducing the amount of fertilizer lost in surface runoff from these catchments (Pepper and Prout, in preparation).

1.5 Study organisation

The Albany Harbours Environmental Study involved scientists and support staff from many different institutions including the Environmental Protection Authority, Waterways Commission, Department of Fisheries, Department of Agriculture and the Centre for Water Research of The University of Western Australia and Murdoch University. The Technical Advisory Group was established to oversee the technical programs and produce this summary report.

Chapter 2

Description, resources and uses of the Albany Harbours

This chapter contains brief descriptions of the Albany harbours and environs, their natural resources and uses. The first section describes the general physical characteristics of the Albany harbours, King George Sound and the adjacent land; the second section presents information on land-uses and related resources; and the third section outlines the water-orientated resources.

2.1 General physical characteristics

Princess Royal Harbour and Oyster Harbour are two natural, protected embayments which are connected to King George Sound through narrow channels. King George Sound is, itself, a partially sheltered embayment, protected from the full force of the Southern Ocean by Flinders Peninsula and Bald Head to the south and Michaelmas and Breaksea Islands to the south-east (Figure 1.1). On either side of King George Sound, Archean basement granites and gneisses, sometimes overlain by Pleistocene limestones, form prominent coastal cliffs (McKenzie, 1964). The cliffs are continually pounded by Southern Ocean swells and have been indented along major joints and planes of weakness. These indentations create spectacular features such as The Gap and the Natural Bridge which have become regional scenic tourist attractions.

Oyster Harbour is situated to the north-east of the Albany townsite and occupies an area of about 16km^2, about a third of which is less than 2m deep. The harbour is roughly rectangular in shape and approximately 5km long and 3km wide. It was formed by the drowning of a river valley during the Pleistocene era, approximately 130 million years ago. The King and Kalgan Rivers were once tributaries of this ancient river, the channel of which can be traced through Oyster Harbour and out to the 60m contour seaward of King George Sound (McKenzie, 1964). The King and Kalgan Rivers provide a significant freshwater input for Oyster Harbour, and as such, Oyster Harbour can be best described as an estuary.

Princess Royal Harbour is a roughly oval-shaped, almost land-locked bay, located to the south of the town of Albany. This harbour is approximately 8km long and 4km wide and orientated in a north-west south-east direction. Princess Royal Harbour occupies a total area of about 29km^2 and is comprised of a deep basin bordered by a shallow sand flat. Approximately half of the total area is less than 2m deep, and the shallow sand flats are most extensive off the western and southern shores. No major rivers discharge into Princess Royal Harbour. Sources of freshwater include drainage channels, local runoff and direct precipitation (Mills and Brady, 1985).

King George Sound is a large, semi-enclosed bay situated to the south-east of the Albany town-site. Although some protection from swell is obtained from islands and reefs to seaward and Flinders Peninsula to the south, King George Sound is considerably more exposed than either Oyster Harbour or Princess Royal Harbour. King George Sound occupies an area of about 110km^2, about half of which is between depths of 10 and 20m. Significant freshwater input is only known to occur via the two harbours and from direct rainfall; the contribution of groundwater discharge is unknown.

2.2 Land-uses and related resources

For convenience, this section is divided into segments covering land-uses, coastal flora and fauna, scenic and aesthetic values.

2.2.1 Land-uses

Land-use in the Albany region can be divided into residential, industrial and agricultural.

Residential: Residential development is mainly concentrated on the northern side of Princess Royal Harbour and on the eastern side of Oyster Harbour.

Industrial: The larger industries are mainly located on the northern and western sides of Princess Royal Harbour. However there are a total of 61 industries that are coded as 'manufacturing' by the Australian Bureau of Statistics in the Town of Albany, and they employed 843 people on June 30, 1988. The total income from manufacturing industry was $94M in the 1987/88 financial year.

Agricultural: Much of the catchments (about 85%) of the Robinson Estate and Marbellup-Elleker region to the west of Princess Royal Harbour is cleared for agriculture, mainly potato growing and beef farming. Clearing of the heavy soil vegetation along the banks of the King and Kalgan Rivers in the Oyster Harbour catchment commenced near the turn of the century, whereas clearing of the lighter sandy duplex soils of the catchment has largely occurred in the last 30 years (Mills, 1987). About 80% of these are now developed, and are used almost exclusively for sheep grazing. In the Lower Great Southern Statistical Division, of which Albany is the regional service centre, agricultural commodities were valued at $472M in the 1987-88 financial year (Australian Bureau of Statistics).

2.2.2 Flora and fauna

The coastal vegetation of the Albany region ranges from salt-pruned heath on the coastal cliffs to tall eucalypt forests bordering the more sheltered areas of King George Sound and the harbours. Plant life in the region is prolific due to the relatively consistent year-round rainfall and forests can be found in close proximity to the coast. Many species of fauna are native to the region. These include marsupials ranging from the large grey kangaroo and tammar wallaby to the pygmy possum and several small marsupial mice; colourful birds such as the western rosella, scarlet robin and red-eared firetail, and reptiles such as meullers snake, the little brown snake and black striped lizard (Hipkins and Associates, 1984).

2.2.3 Scenic and aesthetic values

Any assessment of scenic and aesthetic values must involve subjective and personal factors, but nevertheless they must rank high in importance when considering the relative value of an area. The town of Albany is elevated and offers outstanding views over Princess Royal Harbour and King George Sound. Many contrasting environments ranging from forest to pasture landscapes; from sheltered harbours to long sandy beaches and rugged cliffs, are all close at hand. With a little more effort, people can experience a whole range of underwater attractions. These include reefs with assortments of colourful plant and animal communities, and the waving seagrass meadows of the more sheltered areas.

2.3 Water-orientated resources and uses

The principal water-orientated resources and uses of the Albany harbours and King George Sound include fish production, shipping and related activities, recreation and effluent disposal.

2.3.1 Fish production

The extent of the amateur fishery in the Albany harbours is largely unknown. Herring, King George whiting, leatherjacket, trevally, garfish and squid are the species most sought after by amateurs in both the harbours and King George Sound. In King George Sound some of the larger reef fish, such as snapper and morwong, are also sought, while black bream are sometimes caught in the upper reaches of Oyster Harbour.

The professional fishing industry in the nearshore region of Albany is centred on a recently declared purse-seine fishery for pilchards in King George Sound. Pilchards (mulies) comprise approximately 97% (Table 2.1) of the total fish catch in Princess Royal Harbour and King George Sound and are used mainly for pet food and angling bait, however there is also an interest in canning them for human consumption.

2.3.2 Shipping and related activities

The natural harbour at Albany was the primary reason for the town's establishment. The port presently has three land-backed berths with a total length of 608m. Entrance to the harbour is via a 12.2m deep channel some 180m wide that extends

Species	1985/86	1986/87	1987/88
	(tonnes liveweight)		
Sea Mullet	1.4	1.4	2.1
Mulloway			0.1
Cobbler	10.7	7.1	7.6
Yelloweye Mullet	1.6	1.5	0.2
Whiting	5.4	2.4	2.1
Leatherjacket	17.8	15.8	18.0
Australian Salmon	4.7	1.1	0.2
Australian Herring	18.6	22.2	29.6
Garfish	2.1	1.9	2.5
Flathead	3.8	4.0	5.0
Pilchard	2788.0	3253.0	3476.4
Other Fish	15.1	13.7	9.1
Total fish	2869.2	3324.1	3552.9
Crabs	1.3	1.9	2.5
Other	2.4	1.8	4.5
Grand total	2872.9	3327.8	3559.9

Table 2.1 Annual fish production from King George Sound and Princess Royal Harbour combined (Australian Bureau of Statistics, 13.11.89).

from the wharf through the Princess Royal Harbour entrance channel and continues for about 2km into King George Sound. Excluding Fremantle, Albany was the busiest port in the southern half of the State in terms of gross tonnages and number of vessels during the early 1970s. Presently, the Port of Albany has about half of the shipping throughput of the ports of Bunbury and Geraldton. A total of 101 vessels, with a gross registered tonnage of 1 814 099 tonnes visited the port during the 1988/89 financial year. Total imports and exports through the Port of Albany during 1988/89 are summarized in Table 2.2.

2.3.3 Recreation

Opportunities exist for a wide range of recreational pursuits on and in the waters of the Albany harbours and King George Sound. The main recreational swimming areas in close proximity to the town of Albany are Middleton Beach and the more sheltered Ellen Cove. Facilities such as car parks, shops and picnic and barbeque areas are available close by. The harbours are utilised for activities such as sailing, windsurfing, sight-seeing, fishing and swimming, and provide sheltered conditions throughout the year. The clear waters of King George Sound provide excellent conditions for snorkeling and SCUBA diving, and a scuttled whale-chaser near Michaelmas Island in King George Sound provides an unusual underwater sight.

Type of Cargo	Total weight (tonnes)
Imports	
Rock phosphate	110 261
Petroleum products	75 848
Sulphur	25 567
Potash	9 668
DAP (fertilizer)	5 521
Other cargo	625
Total Imports	**227 490**
Exports	
Wheat	913 888
Barley	98 856
Oats	37 661
Lupins	10 186
Total Exports	**1 060 591**

Table 2.2 Imports and exports through the Port of Albany during 1988/89.

2.3.4 Tourism

The south-west coast of Western Australia between Walpole and Bremer Bay has been termed the 'Rainbow Coast' and is marketed as a tourist destination. Albany is the regional centre of the Rainbow Coast and in Albany alone, the value of tourism has been estimated to be about $40M per annum. To add to the amenity presently available to tourists and residents alike, a plan to redevelop the foreshore has been proposed. The redevelopment would utilise land currently occupied by Westrail and would be focussed around a marina to be built in the vicinity of the Albany Town jetty situated on the northern shore of Princess Royal Harbour. The proposed redevelopment would be extensive. The Great Southern Development Authority estimates the development would likely require up to $12M capital expenditure by State and local governments over the next three to five years and would probably attract in excess of $30M in private investment in the long-term.

2.3.5 Effluent disposal

The waters of Princess Royal Harbour are used to receive effluent from a number of industries that line the northern and western shorelines. These include factories that process potatoes and fish, an abattoir, a woollen mill and a fertilizer factory (see Figure 5.2).

The Southern Processors Pty Ltd factory converts potatoes into frozen chips. The effluent derived from the washing, peeling, chopping and blanching of potatoes is discharged into the intertidal margin of the harbour via an open culvert.

Metro Meats Pty Ltd kills up to 3700 sheep and 200 cattle per day from September to March. Effluent derived from the killing floor and stock holding yards is discharged just above the sea floor in about 5m of water some 30m offshore near the wharf.

Kailis and France Pty Ltd washes and freezes pilchards and salmon throughout the year. Effluent containing solids, oils and nutrients derived from fish slime and scales removed during washing is discharged one metre below the surface into 12m of water at the western edge of the wharf.

Albany Woollen Mills Pty Ltd dyes and spins wool and synthetic fibres to produce a wide range of carpet yarns throughout the year. Effluent is produced mainly from the dyeing house and is discharged into the intertidal margin of Princess Royal Harbour.

Surface runoff from the CSBP and Farmers Ltd Albany superphosphate works property, contains significant quantities of nitrogen and phosphorus. This runoff flows into the western end of Princess Royal Harbour via an agricultural drain.

Diammonium phosphate, a highly-concentrated, water-soluble nitrogen and phosphorus fertilizer is unloaded at the Albany wharf approximately once a year. Spillages sometimes occur during the unloading procedure and material can enter the harbour at these times.

The Water Authority of Western Australia (WAWA) discharges primary treated domestic wastewater into King George Sound about 30m from shore at King Point. This outfall is located near the mouth of Princess Royal Harbour (Figure 1.1). It has been estimated that about 20% of the annual outfall volume enters Princess Royal Harbour (Mills and D'Adamo, in preparation).

There are no direct industrial discharges into Oyster Harbour.

Chapter 3

Beneficial uses and water quality criteria

In general terms, waterbodies are natural resources which support a diversity of animal and plant life. In particular, the physical, biological and aesthetic qualities of sheltered embayments and estuaries are valuable community assets. The Albany harbours are used for a variety of purposes including fishing, conservation, recreation, transport and waste disposal. Some of these uses are clearly incompatible. For example, waste disposal may reduce the cleanliness and quality of waters to the extent that other recognised community uses (beneficial uses), such as those mentioned above, are impaired. To minimize conflict, and for the sustainable use of our environment, water quality criteria for marine and estuarine waters of Western Australia are set by the EPA (Anonymous, 1981).

Many of the terms, phrases and philosophies relating to beneficial uses and water quality criteria need to be defined at the outset to avoid misunderstanding. Section 3.1, therefore, gives definitions for the principal terms used in this chapter and in discussions of water quality management elsewhere in this report. Section 3.2 describes existing water pollution control practices in the Albany harbours. Section 3.3 describes present beneficial uses of the Albany harbours and the relationship between beneficial uses and various water quality parameters.

3.1 Definitions

It is useful at this stage to define the term *beneficial uses* and to distinguish between water quality *parameters, criteria, objectives* and *standards. Outfalls* and their associated *mixing zones* are also discussed.

3.1.1 Beneficial uses

A beneficial use is any use of the environment, or segment or element of the environment, that is conducive to public benefit, welfare, safety or health. A beneficial use will require protection from the detrimental effects of any direct or indirect alteration of the environment. Where conflicting uses exist, consideration of social, economic and scientific factors may be required to determine the uses to be protected.

3.1.2 Parameters

Parameters are specific physical, chemical or biological characteristics of wastewater or the receiving waters. For example, water clarity, temperature, biological oxygen demand, and concentrations of individual chemical elements are water quality parameters.

3.1.3 Criteria

Criteria are the general scientific yardsticks upon which a decision or judgement may be made concerning the ability of water of a given quality to support a designated beneficial use. Some constituents of discharges may only have localised effects while others may have far-reaching or even regional effects. In determining the allowable discharge of a given constituent, it would be necessary to consider the beneficial uses affected, or likely to be affected by the discharge and to consider the relevance of allowing a local mixing zone within which various parameters could dilute or otherwise be reduced to concentrations consistent with the criteria.

3.1.4 Objectives

Objectives represent the desirable and, possibly, the long-term aims or goals of a water quality management programme. Such objectives are often derived after consideration of water quality criteria in the light of economic, social and political factors.

3.1.5 Standards

Standards are current, legally-enforceable levels established by an authority. Standards are based upon the most relevant scientific knowledge available and will reflect both the beneficial use to be protected and a reasonable safety margin. Frequent changes in standards are inappropriate since they control the nature and type of wastewater treatment and disposal facilities provided. However, as additional knowledge is gained about the response of receiving waters to specific inputs, new criteria can be adopted and standards modified accordingly.

3.1.6 Outfalls and mixing zones

Outfalls are effluent discharge points and in waterbodies they are surrounded by a mixing zone where the concentration of pollutants decreases through dilution. Well-designed and sited outfalls promote rapid mixing of pollutants in small mixing zones and the minimum possible drift of undiluted effluent. Concentrations of various pollutants may be high within the mixing zones and this sometimes results in such areas being declared public exclusion zones.

Ideally, a receiving waterbody should assimilate diluted pollutants indefinitely with minor adverse impacts on the environmental or public health outside confined mixing zones. All too frequently however, outfalls have been situated in shallow, poorly flushed locations, often discharging at the surface of the receiving waterbody. Fresh water is less dense than marine water, and in calm conditions, effluents discharged at the surface may travel considerable distances under the action of wind and currents as buoyant plumes, before dilution can take place.

3.2 Existing water pollution control practices

3.2.1 Background information

One of the primary roles of the Environmental Protection Authority is to control pollution arising from the discharge of wastes. The Environmental Protection Act was amended in 1986, giving the EPA considerably more power to realise this objective. 'Pollution' in this sense refers to any direct or indirect alteration of the environment to its detriment or degradation.

3.2.2 Requirements for discharging into the environment.

A pollution control licence is required by any industry and is prescribed in regulations under the Environmental Protection Act of 1986. 'Prescribed premises' include those that cause pollution or are likely to cause pollution of any waters. Pollution control licences set conditions for effluent discharge and these vary according to discharge type, quality and quantity and also according to the characteristics of the receiving waterbody.

In general though, pollution control licences set effluent discharge limits and monitoring requirements. Effluent discharge limits are expressed as the maximum allowable concentration of each contaminant in the effluent stream, and/or as a total load of each contaminant per year. In some situations when information is not available to make an accurate assessment of the likely impact of a contaminant on the receiving ecosystem, a clause may be inserted which sets a particular discharge limit subject to no detrimental effects, resulting wholly or in part from that particular discharge, being observed in the receiving environment.

The EPA can revoke, suspend or change the conditions of the pollution control licence, at any time. Monitoring requirements are an integral component of the licences and are set to ensure that contaminant levels are not exceeded and all waste treatment equipment is operating efficiently. This also ensures that industry is aware of the extent of their contamination of the environment. Sampling frequency varies according to the parameter being measured and the timescale and severity of potential impacts. The EPA has the right to take its own samples to check the reliability of self-monitoring programs.

If for any reason an industry does not comply with the pollution control licence and causes or is likely to cause pollution, in addition to initiating prosecution procedures for a breach of the Environmental Protection Act, the EPA has the power to serve a Pollution Abatement Notice which requires the industry to prevent or abate discharges within a specified time. If an industry does not comply with a Pollution Abatement Notice and continues to cause pollution which may be seriously detrimental to the environment, the Minister for Environment may close the premises.

3.3 Beneficial uses

Waterbodies should conform to general aesthetic criteria regardless of the declaration of beneficial uses, unless otherwise specified. The general aesthetic criteria require that waters should be:

(i) Free from substances which will settle to form putrescent or otherwise objectionable sludge deposits.

(ii) Free from floating debris, oil, grease, scum, foam and other floating materials, in amounts sufficient to be unsightly or otherwise objectionable.

(iii) Free from materials which will produce colour, odour, turbidity, or other conditions to such a degree as to be unsightly or otherwise objectionable.

The present uses of the Albany harbours can be described by 9 of the 16 presently recognised beneficial uses (Anonymous, 1981). All of these uses do not occur in the same location and hence there is scope for zoning beneficial uses within particular waterbodies. For example, direct contact recreation (eg. swimming) may not be practical within the Albany Port Authority area which is used primarily for navigation and shipping. The current beneficial uses of Princess Royal Harbour, Oyster Harbour and King George Sound are briefly described below.

3.3.1 Direct-contact recreation

Swimming and boating activities are among the most important beneficial uses in many parts of the Albany harbours and King George Sound. Because these activities can involve complete immersion in seawater, water quality relating to public health is of primary importance.

3.3.2 Harvesting of aquatic life (excluding molluscs) for food

The waters of Princess Royal Harbour, Oyster Harbour and King George Sound are used by amateur and professional fishermen alike. These areas are highly productive and with proper management of inputs and other activities affecting growth and development of fish and their habitat these areas will remain highly productive, or improve in the long-term if habitat degradation can be stopped and reversed. The intensity of recreational fishing can be expected to increase in the future. Human health as well as the health of the various sea animals is of principal concern in considering applicable water quality criteria.

3.3.3 Harvesting of molluscs for food

In regard to this beneficial use human health is of principal concern in considering applicable water quality criteria. The levels of contaminants in water may be acceptable at any time but as contaminants (heavy metals in particular) tend to accumulate in sedentary, filter-feeding organisms such as molluscs, particular attention is focussed on levels found in the edible portions of these animals.

3.3.4 Passage of fish and other aquatic life

This beneficial use is concerned with waters used by fish and other aquatic life in their normal movements and migratory patterns.

3.3.5 Aquaculture of all forms

Water quality criteria for this form of beneficial use are related to the organism being cultured and whether it is edible or non-edible. For instance, if the cultured organism is fish then the criteria relating to 'harvesting of aquatic life (excluding molluscs) for food' would be used, whereas if molluscs were being cultured for food, then the criteria for 'harvesting of molluscs for food' would be applied.

3.3.6 Maintenance and preservation of aquatic ecosystems

An ecosystem comprises a physical and chemical environment interacting with a more or less stable community of organisms. The stability of an ecosystem depends on many inter-related factors such as sunlight, temperature, inorganic nutrients and wave energy. Three levels or classes of protection are recognised, and are summarized below:

Class 1 : represents maximum protection and allows no waste inputs whatsoever and no man-made changes within the surface or groundwater sheds, or the waterbody itself that will affect any part of the ecosystem.

Class 2 : offers a high level of protection such that any discharge or man-made change which occurs may be assimilated readily or tolerated by the system without any detectable effects on the biota or the structure of the ecosystem to which they belong.

Class 3 : affords a minimal level of protection, allowing discharge and disturbance that may lead to changes in the existing biota, but only to the point where the residing biota can still function as an ecosystem.

The EPA considers that the waters in most parts of the Albany harbours and King George Sound are important in terms of ecosystem maintenance. On this basis, Class 2 protection should be provided.

3.3.7 Maintenance and preservation of foreshores and banks.

The continued existence of certain physical features of waterbodies, such as banks and foreshores, may be directly dependent on the biological communities that live on or around them. For example the stability of subtidal seagrass banks relies on a cover of seagrass to absorb some of the wave energy that would otherwise mobilise the sediment. Similarly, rushes on the banks of rivers and estuaries prevent erosion by wave action from boats. The maintenance of aquatic vegetation depends on the quality of the surrounding waters. When these biological communities are degraded, artificial substitutes such groynes are rarely as successful as aquatic vegetation in protecting and maintaining submerged or intertidal banks.

3.3.8 Scientific and educational uses.

When a waterbody has been designated for a particular use, from a scientific and educational point of view, consideration should be given to designating a control area which resembles as closely as possible the area to be used. In this way, observed changes in water quality resulting from the specified use of that area can be separated from natural changes which may also be occurring. Scientific studies of a waterbody can provide much useful and necessary information to help determine:

(i) how aquatic ecosystems and water quality change naturally with time; ie to observe and monitor a changing baseline;

(ii) how a waterbody changes in response to a carefully managed programme of beneficial uses; ie to continually monitor changes resulting from a specific approved use and;

(iii) how the water quality changes as a result of the discontinuation of a particular use; eg the recovery from a specific form of pollution.

3.3.9 Navigation and shipping

Waters for navigation and shipping should provide for unobstructed passage of ships and boats. The physical and chemical properties of the water should be satisfactory for intake to engine rooms, motors and for other uses. Also water properties should afford reasonable protection of port facilities, installations and equipment, and not cause unpleasant or unsafe conditions for crew, manpower, passengers and the general public.

Part II

Summary of the studies

This part of the report consists of four chapters and presents brief overviews of the findings from specific technical and scientific investigations carried out during the study. The ecological investigations are summarized in Chapter 4. These studies were concerned mainly with quantifying the nutrient pools in the harbours and determining the past and present distributions and biomass of seagrass and algae and the responses of these plants to their environment. Chapter 5 examines the sources and amounts of pollutants entering the harbours while Chapter 6 describes hydrodynamic processes within the harbours and how these affect the dilution, dispersion and distribution of pollutants. Studies related to possible management options are summarized in Chapter 7.

Chapter 4

Ecological investigations

4.1 Survey of plant communities and nutrient pools in the Albany harbours

Extensive seagrass dieback in the Albany harbours was first reported in 1986 (Bastyan, 1986). Between 1962 and 1984, approximately 45% and 66% of the area of seagrass meadows that originally occurred in Oyster Harbour and Princess Royal Harbour, respectively, had been lost. Prolific growth of algae in both harbours, induced by an oversupply of nutrients, was thought to have smothered the seagrasses and reduced their light supply. This scenario has been documented in other Western Australian embayments and estuaries, notably Cockburn Sound (Cambridge, 1979) near Perth and the Peel-Harvey estuarine system near Mandurah (Hodgkin *et al.*, 1985).

4.1.1 Objectives and scope

The objectives of this study were:

(i) to map the distribution of seagrass, macroalgae and epiphytes in Princess Royal Harbour and Oyster Harbour.

This allowed comparisons to be made with past seagrass distributions in the harbours so that the current rate of seagrass decline could be assessed. It also provided information on the distribution and abundance of algae in both harbours.

(ii) to determine the size of nutrient pools in the water, sediments and plants in both harbours.

This study provided information on the likely origins and the fate of nutrients entering the harbours.

The study was carried out by the Centre for Water Research with assistance from the EPA. The summary information presented in this section was drawn from the Technical Series by Hillman *et al.*, (in preparation) and this report can be referred to for further details.

4.1.2 Distribution of benthic plants

Seagrass

The area of seagrass meadows decreased significantly in both harbours between 1981 and 1984 (Bastyan, 1986). Furthermore, surveys of fixed transects in 1984 and 1988 revealed a reduction in seagrass canopy density (leaves) along all of the transects surveyed in 1981, and in some cases a complete loss of canopy cover was recorded. Large accumulations of macroalgae were also recorded along these transects in the later surveys, suggesting that the decline and loss of the seagrasses was due to shading and smothering by these algae (Figure 4.1).

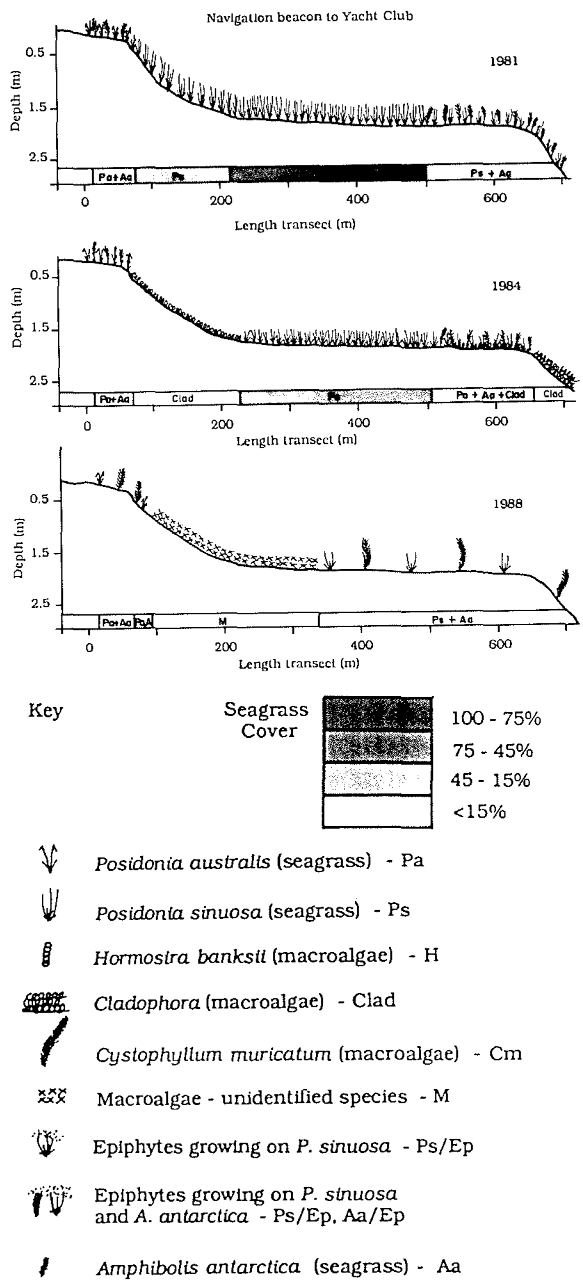

Figure 4.1 Decline in above-ground seagrass cover along a permanent transect in the south-western side of Princess Royal Harbour between 1981 and 1988 (adapted from Hillman *et al.*, in preparation).

Between 1984 and 1988, the total area of seagrass meadow in Princess Royal Harbour increased due to patchy regeneration of seagrasses in the deeper areas of the harbour. Seagrass biomass (a more meaningful index of seagrass meadow change), however, decreased in both harbours by about 50-60% during the same period (Figure 4.2).

The reduction in biomass was largely the result of thinning of the remaining dense seagrass meadows. Approximately 90% of these meadows (ie cover category 75-100%) were lost in Princess Royal

Harbour and 70% in Oyster Harbour. The increase in the lowest cover category (0-15%) in Princess Royal Harbour was the result of regeneration of plants in the deeper parts of the harbour which were classified as dead in the 1984 survey because, at that time, no live above-ground material was present.

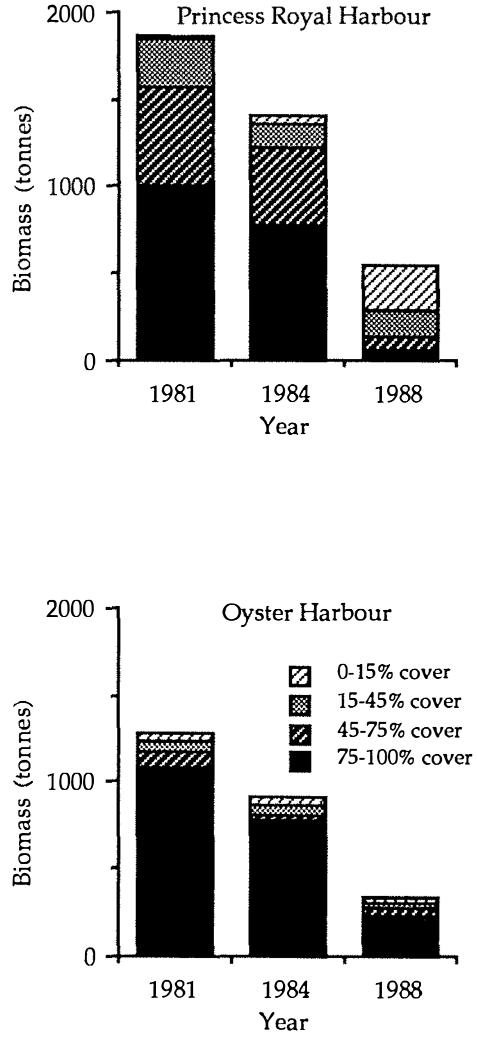

Figure 4.2 Decrease in seagrass biomass in Princess Royal Harbour and Oyster Harbour.

Macroalgae

Extensive accumulations of macroalgae, reaching densities exceeding 1000 g dry weight per square meter (m^{-2}) were present in depths of less than 5m in both harbours. In Princess Royal Harbour, the densest macroalgal beds were found in the shallows of the north-western and south-eastern ends of the harbour, although densities of 200-1000 g dry weight m^{-2} were present in the shallows throughout the harbour, except between the Albany Town jetty and Camp Quaranup.

Macroalgae were mainly confined to the middle and south-eastern corner of Oyster Harbour, although accumulations of greater than 1000 g dry weight m^{-2} were only present in the south-eastern corner of the harbour.

The accumulations of macroalgae in both harbours were not correlated with nutrient concentrations in the sediments or the water column, but occurred in shallow, relatively sheltered locations. These areas are likely to be more conducive to the growth of these plants and are also likely accumulation points for drift algae.

4.1.3 Nutrient pools

In February 1988, an intensive study was undertaken to determine the nutrient content of the water, sediments and plants. This study provided information on the relative size of each of the main nutrient stores in the two harbours. Each component of this study is discussed in more detail below.

Physical and chemical characteristics of the water column

The concentrations of water-borne nutrients in Oyster Harbour were equal to or higher than those in Princess Royal Harbour. Phytoplankton standing crops were low in both harbours at the time of this survey. Water clarity in Oyster Harbour was considerably lower in the northern part of the harbour, that is closer to the mouths of the rivers. This area of the harbour corresponds with past and present areas of dieback of the deeper seagrass meadows.

The King and Kalgan Rivers and, to a lesser extent, Yakamia Creek were all identified as major point sources of nutrients and total suspended solids to Oyster Harbour (Figure 4.3). Similarly, the WAWA King Point wastewater treatment plant, Metro Meats and the Robinson Estate Drain (which drains a catchment that includes CSBP fertilizer factory), were implicated as major point sources of nutrients into Princess Royal Harbour in this study (Figure 4.4).

Sediment characteristics

Sediment organic matter, water content, total phosphorus and total nitrogen concentrations were similar in both harbours. The highest concentrations of total phosphorus and total nitrogen in Princess Royal Harbour sediments were recorded in the dredged channel near the Albany Town jetty and at a shallow site near South Spit. In both cases, nutrients were probably associated with an accumulation of detrital material and fine sediment. The central area of the harbour was lowest in nutrients whilst intermediate nutrient concentrations were found in the sediments along the shallow margins.

The highest sediment nutrient concentrations in Oyster Harbour were associated with organic-rich sediments in the deeper portions of the harbour. Nutrient contents were correlated with sediment

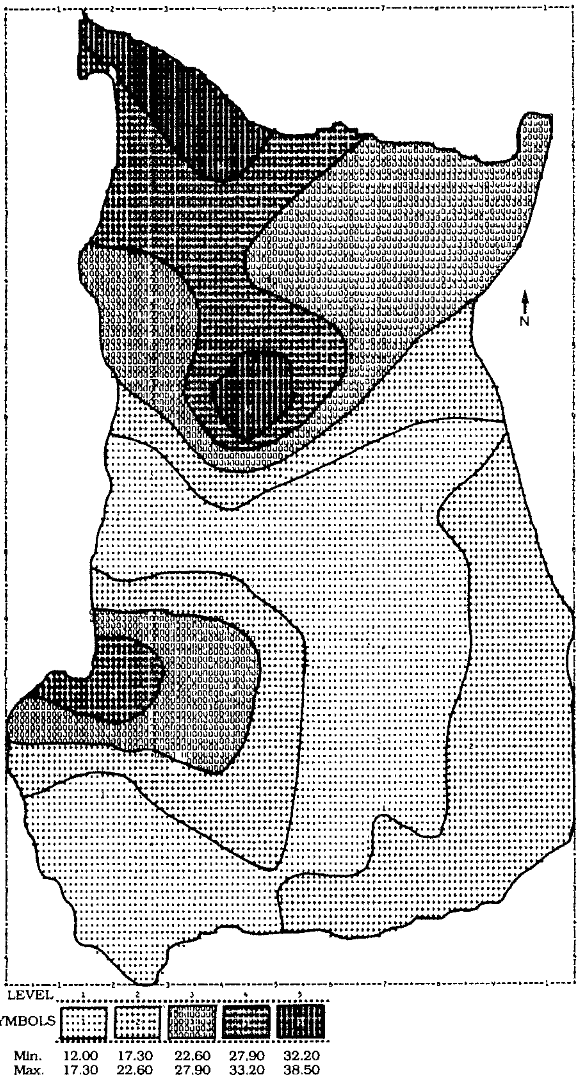

Figure 4.3 Distribution of organic phosphorus in the waters of Oyster Harbour in February 1988.

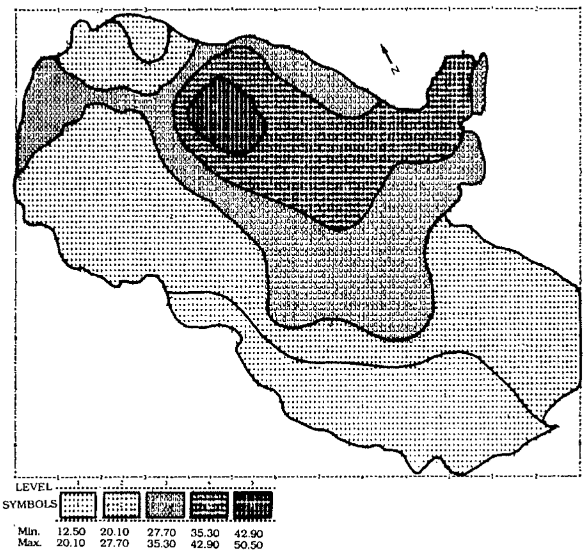

Figure 4.4 Distribution of organic phosphorus in the waters of Princess Royal Harbour in February 1988.

water and organic content, suggesting that a large proportion of nutrients are adsorbed onto organic material and fine sediments.

High concentrations of sediment nutrients did not coincide with past or present areas of seagrass decline in either harbour.

Seagrass and epiphyte biomass

By 1988, approximately 40% of the seagrass biomass that was present in each harbour in 1984, remained. The biomass of the 'healthiest' remaining stands of *Posidonia* in the two harbours were not significantly different and were approximately half of the leaf biomass, and less than a quarter of the below-ground biomass, of seagrass meadows in King George Sound.

Epiphyte load per square metre of seagrass meadow in Princess Royal Harbour was higher than in Oyster Harbour which, in turn, was higher than in King George Sound. Epiphyte levels recorded in this study were sufficiently high in Princess Royal Harbour to suggest that epiphytes, at the time of the survey, were a minor contributor to the seagrass dieback in the harbour. In contrast, however, epiphyte levels in Oyster Harbour were considered to be too low to be contributing to seagrass decline.

The contribution of epiphytes in the decline of the seagrass meadows in the Albany harbours in the past, however, should not be dismissed at this point as little is known of the temporal variability in the response of epiphytes to short-term and long-term fluctuations in nutrient loadings.

Seagrass and epiphyte nutrient concentrations

In general, tissue nitrogen and phosphorus concentrations in the leaves and rhizomes of *Posidonia australis* and *Posidonia sinuosa* were not significantly different between Princess Royal Harbour, Oyster Harbour and King George Sound. However, where elevated nutrient concentrations in seagrass tissues did occur, they were generally associated with nutrient-rich sediments.

Epiphyte nitrogen concentrations in both harbours were generally higher than epiphytes on seagrasses in King George Sound. However, although epiphyte phosphorus concentrations in Oyster Harbour and King George Sound were not significantly different, they were significantly higher than phosphorus concentrations in epiphytes from Princess Royal Harbour.

Macroalgal biomass and nutrient concentrations

Approximately 90% of the total macroalgal biomass in both harbours consisted of the green alga, *Cladophora* sp. Another green alga, *Enteromorpha* sp., accounted for a further 4% of the total macroalgal biomass in Princess Royal Harbour while a blue-green alga (*Lyngbya* sp) accounted for about 6% of the total biomass in Oyster Harbour.

The total biomass of macroalgae in Princess Royal Harbour was 11650 tonnes dry weight, or about 10 times greater than the 1197 tonnes recorded in Oyster Harbour. On a harbour-wide basis, the standing crop of macroalgae in Princess Royal Harbour (406 g dry weight m^{-2}) was about 5 times greater than in Oyster Harbour (77 g dry weight m^{-2}). By comparison, the biomass of macroalgae was about 13 times and 3.5 times higher than the above-ground seagrass biomass in Princess Royal Harbour and Oyster Harbour respectively. The high standing crop of macroalgae in Princess Royal Harbour is indicative of a highly eutrophic waterbody.

Tissue nutrient concentrations in macroalgae were comparable to values reported for similar species in the Peel-Harvey Estuary, again emphasising the eutrophic status of the Albany harbours. Nitrogen to phosphorus ratios were considerably higher in the macroalgae than in the epiphytes.

Size and distribution of nutrient pools

By far, the most substantial nutrient pool occurs in the sediments (Table 4.1).

	Princess Royal Harbour		Oyster Harbour	
	TN(%)	TP(%)	TN(%)	TP(%)
Water Column	0.8	2.1	2.4	2.2
Sediments	78.9	90.4	88.7	94.4
Seagrass	1.1	0.8	1.9	1.3
Epiphytes	0.1	0.1	0.2	0.2
Macroalgae	19.1	6.6	6.8	1.9
Total	100.0	100.0	100.0	100.0

Table 4.1 The relative contributions of the water, sediment and plants to the total nutrient pools in the Albany harbours. TN = total nitrogen, TP= total phosphorus.

The next largest pool is contained in the macroalgae, especially in Princess Royal Harbour (Figure 4.5). In oligotrophic (ie nutrient poor) ecosystems, the nutrient pool in the macroalgae and epiphytes combined, is usually smaller than the nutrient pool in the seagrasses.

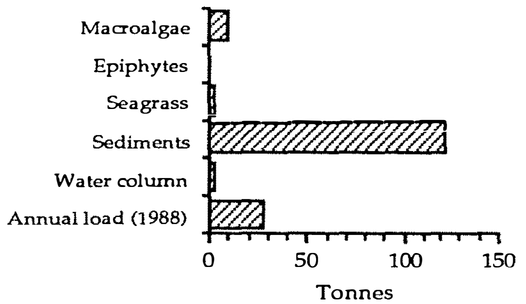

Figure 4.5 Major phosphorus pools in Princess Royal Harbour in 1988. Note the annual load of phosphorus into the harbour from industrial, domestic and community sources.

4.1.4 Conclusions

Forty-five percent and 66% of the areas originally covered by seagrass meadows in Oyster Harbour and Princess Royal Harbour, respectively, were lost between 1962 and 1984. By 1988, only 40% of the seagrass present in both harbours in 1984, remained. Thus, almost 90% of the seagrasses in Princess Royal Harbour and 80% in Oyster Harbour have been lost since 1962 when these seagrass meadows were considered to be in a pristine condition.

In recent years the rate of seagrass loss in the harbours has accelerated due to a proliferation of macroalgae which shade and smother the seagrass meadows. Light reduction is now considered the primary cause of the widespread loss and thinning of the seagrass meadows in both harbours.

The growth of macroalgae has been stimulated by excessive nutrient inputs to Princess Royal Harbour from industrial, rural and urban sources, and to Oyster Harbour from rural and urban sources.

Discharges from the WAWA outfall at King Point, the Metro Meats' abattoir outfall and the Robinson Estate Drain, which includes surface runoff and effluent from the licensed outlet of the CSBP fertilizer factory, were implicated as significant point sources of nutrients into Princess Royal Harbour at the time of this survey. Similarly, the King and Kalgan Rivers, and to a lesser extent Yakamia Creek, were identified as the main point sources for nutrients and suspended solids into Oyster Harbour.

Seagrass meadow density and epiphyte biomass in the Albany harbours was substantially lower and higher, respectively, than King George Sound. Although epiphyte loads were sufficiently high to reduce seagrass primary production, the epiphyte loads were not considered to be a major contributor to the decline of seagrasses in the Albany harbours at the time of the survey.

The largest nutrient store in the harbours is contained in the sediments. However, sediment nutrient concentrations were not linked to areas of seagrass degeneration, macroalgal accumulation or high epiphyte loads. Macroalgae contained the largest plant nutrient pool, and reached a biomass in excess of 1000 g dry weight m^{-2} in the shallow, south-eastern corners of both harbours.

Total macroalgal biomass was an order of magnitude higher in Princess Royal Harbour (about 11650 tonnes dry weight) than in Oyster Harbour (about 1200 tonnes dry weight).

4.2 The biomass and distribution of macroalgae in Oyster Harbour in late summer following a high-rainfall winter

A survey of macroalgal distribution and abundance in Oyster Harbour was conducted in February 1988. The large accumulations observed during this study are now considered to be the major cause of seagrass decline in the harbour. The proliferation of algae in Oyster Harbour has been linked to the excessive amounts of nutrients entering the harbour from surrounding rivers and creeks.

The 1988 survey was carried out after the driest winter for 16 years which resulted in the lowest flow of the Kalgan River since records began (see Figure 5.7). In contrast, the following winter was the wettest for 10 years, resulting in highest recorded flow of the Kalgan River. Nutrients are transported from the agricultural catchments to Oyster Harbour in surface runoff and annual loads are strongly correlated with river discharge (see Figure 5.8). The marked difference in riverine phosphorus load into Oyster Harbour in 1987 (about 3 tonnes) and 1988 (about 67 tonnes), provided a natural experiment to assess the short-term response of the algae in Oyster Harbour to this increased nutrient loading. To quantify this response a survey, identical to the 1988 study of macroalgae distribution and biomass, was undertaken in March 1989. The study was conducted by the Centre for Water Research, UWA and the Technical Report by Bastyan and McComb, (in preparation) can be referred to for further details.

4.2.1 Objectives and scope

The objectives of this study were:

(i) to determine the biomass (tonnes dry weight) and species composition of macroalgae at fixed sampling stations in Oyster Harbour and compare these with the same period in 1987 and;

(ii) to examine additional areas in Oyster Harbour for the presence of macroalgal accumulations.

4.2.2 Comparison of biomass and species composition of macroalgae in Oyster Harbour between 1988 and 1989

Macroalgal biomass and species composition in Oyster Harbour in March 1989 were not appreciably different to February 1988 despite considerable differences in nutrient loadings in these years. The total algal biomass estimated in Oyster Harbour in 1989 was about 1050 tonnes. This was slightly lower than the 1197 tonnes recorded in 1988. In both years, *Cladophora* sp. was the dominant alga, accounting for approximately 90% of the total biomass. Nitrogen fixing blue-green algae were also common and comprised about 6% of the total algal biomass in the harbour.

4.2.3 Changes in macroalgal distribution

In 1988 the area of highest algal biomass (>1 kg per m^2) occupied much of the south-eastern side of the harbour. In the 1989 survey these accumulations were markedly reduced. The shallow flats at the northern end of the harbour, which were essentially free of macroalgal accumulations in 1988, apart from small patches near the mouth of the King River, had considerable accumulations of the green alga, *Enteromorpha,* especially on the north Kalgan bank. These accumulations accounted for almost 120 tonnes dry weight and change the percentage contribution of this species, to the total biomass in the harbours, from about 1% to 7%. When these additional accumulations of algae recorded on the northern flats are included, the total macroalgal biomass in the harbour in March 1989 increased to approximately 1646 tonnes.

4.2.4 Conclusions

Total macroalgal biomass, determined from repeated surveys of fixed sampling sites in 1988 and 1989, did not increase after the high runoff (and high nutrient load) of winter, 1988. These results suggest that algal populations in Oyster Harbour do not respond significantly to marked changes in nutrient loading caused by major storm events over time scales in the order of 6 months. However, changes in the distribution of algal biomass were evident, with a decrease in the areas of highest macroalgal density recorded in 1988, and an increase in accumulations of algae on the shallow northern flats.

4.3 Water quality and seagrass biomass, productivity and epiphyte load in Princess Royal Harbour, Oyster Harbour and King George Sound

The results of a previous study, carried out during February 1988 (see section 4.1), provided information on the major nutrient pools and status of the seagrass and algal communities of the Albany harbours and King George Sound at one point in time. The physical, chemical and biological characteristics of a waterbody can show considerable temporal variation which is often linked to daily and seasonal changes in major environmental factors such as water temperature and light availability. Rainfall can also play an important role in altering the physical, chemical and biological characteristics of waterbodies with riverine input.

This study investigated the temporal variations in water quality and in seagrass biomass, productivity and epiphyte load in the Albany harbours and King George Sound from December 1987 to February 1989. The study was conducted by the Centre for Water Research with assistance from the EPA, Albany Town Council and Shire of Albany. A full report of this study can be found in the Technical Series by Hillman *et al.,* (in preparation).

4.3.1 Objectives and Scope

The general objectives of this study were:

(i) to provide data on the seasonal variations in physico-chemical characteristics of the water in the Albany harbours and King George Sound to allow a direct comparison to be made with data from an earlier study of Princess Royal Harbour carried out in 1979 (Atkins *et al.*, 1980);

(ii) to determine the seasonal patterns of seagrass growth, epiphyte loads and tissue nutrient concentrations of seagrasses and epiphytes. This information would help determine whether epiphyte loads significantly affected seagrass growth at certain times of the year and;

(iii) to estimate epiphyte productivity by determining seasonal changes in periphyton loads and to assess the use of periphyton as integrated indices of water quality.

A summary of the major findings of each of these investigations is presented below.

4.3.2 Water quality

There was little spatial variation in the physical, chemical and biological characteristics of the water column in either harbour under 'normal' conditions except in Oyster Harbour during large river-flow events (see Figure 6.2).

Physical Characteristics

The seasonal variation in salinity and temperature of the waters of Princess Royal Harbour and King George Sound in 1988 is shown in Figure 4.6.

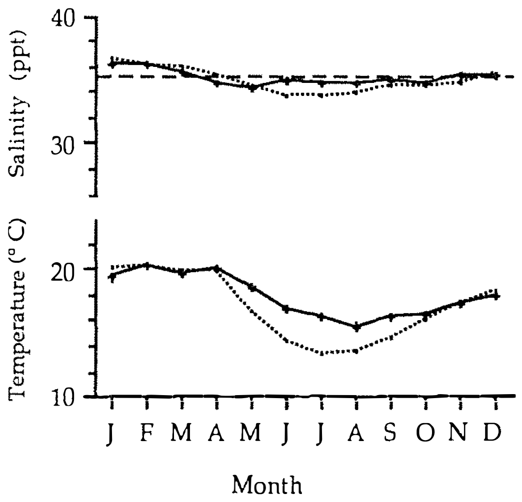

Figure 4.6 Seasonal fluctuations in salinity and temperature in Princess Royal Harbour and King George Sound during 1988, adapted from Hillman *et al.*, (in preparation).

··········· = Princess Royal Harbour;
——— = King George Sound,
– – – – = typical ocean salinity (35 ppt).

As a result of the longer residence times of water in the harbours than in King George Sound, the salinities of both harbours were higher than in the sound during summer due to evaporation, and lower than King George Sound in winter due to freshwater input. Salinities in Oyster Harbour dropped sharply several times during winter due to heavy rain in the catchment but rapidly returned to 'normal' after river flow ceased, indicating strong tidal flushing. Seasonal fluctuations in salinity were less pronounced in Princess Royal Harbour due to its small catchment and lack of riverine input of fresh water. Seasonal water temperature fluctuations in Princess Royal Harbour ranged from about 13-21° C and were slightly higher in summer and lower in winter than in King George Sound.

Mean dissolved oxygen concentrations were nearly always close to saturation. Water clarity was generally higher in King George Sound than both harbours and higher in Princess Royal Harbour than Oyster Harbour, especially during winter. A similar pattern was observed for total suspended solids concentrations in the three waterbodies. The organic fraction of the suspended solids load fell sharply in late June and remained low until mid-August in all three waterbodies.

Chemical Characteristics

Nitrate concentrations in King George Sound and in both harbours were generally similar, except during winter when concentrations in Oyster Harbour were substantially higher. Ammonium and organic nitrogen concentrations were highest in Oyster Harbour, with maximum values occurring during winter. These values were higher than Princess Royal Harbour, which were in turn higher than in King George Sound. Water column phosphorus concentrations were generally low and showed similar trends to those described for nitrogen. The data for Oyster Harbour suggest that riverine input of nutrients provide the major source of the nitrogen and phosphorus loads in the water column of this harbour.

Silicate concentrations were not significantly different between Princess Royal Harbour and King George Sound, but concentrations in Oyster Harbour were significantly higher than the other two waterbodies throughout the year.

Biological Characteristics

Chlorophyll *a* concentrations were very low in all three waterbodies but showed a slight increase during winter, presumably as a result of increased nutrient availability associated with runoff events.

N:P ratios

Nitrogen to phosphorus ratios in the water were generally below 30:1 suggesting that nitrogen rather than phosphorus availability may be limiting the growth of plants that are dependant on the water column for their nutrient requirements. This held true for all three waterbodies except in Oyster Harbour between March and May 1988 when ratios exceeding 200:1 indicated possible phosphorus limitation.

Comparison with 1978/79 water quality survey in Princess Royal Harbour

Mean monthly ammonium and phosphate concentrations in the 1988 survey were about four and five times lower respectively than during the 1978/79 study. Mean monthly organic phosphorus concentrations also tended to be lower in the 1988 survey, although annual means were not significantly different. Nitrate concentrations were not significantly different between the two surveys. Chlorophyll a concentrations have decreased significantly (2.5 times) since 1979 (Figure 4.7). In general, the water quality of Princess Royal Harbour has improved considerably since 1979.

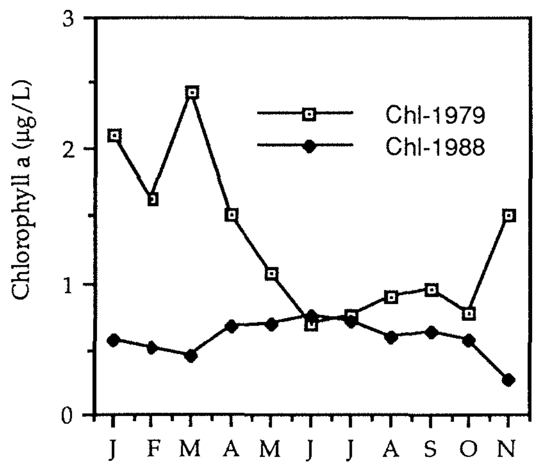

Figure 4.7 Comparison of chlorophyll a concentrations (a measure of phytoplankton abundance) in Princess Royal Harbour in 1979 and 1988.

Flood conditions

Salinity profiles measured during a winter flood in Oyster Harbour showed marked stratification of the water column with a plume of freshwater less than 0.5m thick flowing over denser, more marine water (eg. see Figure 6.2). Surface phosphate and nitrogen concentrations were much higher than in bottom waters and the majority of phosphate seemed to originate from the Kalgan River. In contrast, remineralization of organic matter at the sediment-water interface appears to be the primary ammonium-nitrogen source in Oyster Harbour.

The buoyancy of the freshwater layer suggests that the nutrients in this layer are likely to have minimal contact with the benthic plants in the deeper basins of Oyster Harbour and hence are unavailable for plant growth. An identical water quality survey about a week later indicated that this nutrient-rich freshwater layer was no longer present in the harbour.

4.3.3 Seagrass and epiphyte biomass

Seasonal changes in the biomass of the seagrasses *P. australis* and *P. sinuosa* were similar in all three waterbodies with maximum values occurring in summer and minimum in winter. The biomass of seagrass meadows in King George Sound declined less in winter and these meadows appeared to be healthier than the seagrass meadows in either harbour.

Maximum epiphyte loads in all three waterbodies occurred in either late winter/early spring or summer and did not exceed 25% of the seagrass leaf biomass. The highest epiphyte loads for both seagrass species occurred in Princess Royal Harbour, however epiphyte loads in Oyster Harbour may have been underestimated because a large proportion of the very fine diatomaceous scum coating the seagrass leaves was unavoidably lost during sampling.

4.3.4 Seagrass and epiphyte nutrient concentrations

Tissue nutrient concentrations were higher in *P. australis* than in *P. sinuosa*. Nitrogen content of *P. australis* showed little seasonal variation whereas *P. sinuosa* showed a winter minimum. The phosphorus concentrations of both seagrasses were highest in winter in all three waterbodies. This probably represents luxury uptake, as it occurs at the time of year when growth is lowest but phosphorus is most available. The tissue phosphorus content of seagrasses in King George Sound was significantly lower than in seagrasses in both harbours.

Epiphyte tissue nutrient concentrations were highest in Oyster Harbour but the time of year when tissue nutrient concentrations were highest was variable between harbours and between seagrass species. Like the host seagrass leaves, the tissue nutrient concentrations of epiphytes on *P. sinuosa* were higher than epiphytes on *P. australis*, which is consistent with the view that epiphytes obtain at least part of their nutrients directly from the seagrasses.

Generally, the nutrient concentrations of the seagrass leaves and the epiphytes indicated little difference between King George Sound and Princess Royal Harbour but suggest that Oyster Harbour was enriched compared to these other two waterbodies.

4.3.5 Seagrass productivity

The seasonal patterns of productivity of *P. australis* and *P. sinuosa* were similar, with maximum rates occurring in the spring/summer period that is characterised by high light intensities and long-days, and minimum rates in winter when days are short and light intensity is generally low. Leaf growth rates per shoot of *P. australis* were at least four times higher than for *P. sinuosa*. Due to the higher leaf and shoot density of seagrass meadows in King George Sound, seagrass growth rates, expressed on a unit area basis, were nearly two times higher in King George Sound than in the harbours.

Two crops of *P. australis* leaves were produced per year in King George Sound compared to 1.6 in the harbours. In contrast, crop turnover rates for *P. sinuosa* in Princess Royal Harbour were almost double those of Oyster Harbour and King George Sound. The high leaf turnover rates in Princess Royal Harbour may be indicative of stress as this response has been recorded in stressed seagrass meadows elsewhere.

In most instances, seagrass leaf growth rates were positively correlated with the amount of light received by the meadow. Exceptions occurred when macroalgal accumulations in spring blocked light reaching the *P. sinuosa* meadows in Princess Royal Harbour, and epiphyte accumulations shaded *P. australis* plants in Oyster Harbour.

4.3.6 Periphyton productivity

Periphyton production on artificial seagrass leaves made from plastic strips provides useful insights into the growth rates of epiphytes on seagrasses. The results revealed two distinct periods of maximum growth, one in spring and the other in autumn. This pattern was consistent in all three waterbodies. Periphyton loads measured on artificial seagrass kept in *P. australis* meadows in King George Sound and Princess Royal Harbour were similar, but were always less than half the loads that were measured in similar locations in Oyster Harbour. Higher periphyton loads at sites in *P. australis* meadows as opposed to sites in *P. sinuosa* meadows suggest that physico-chemical factors, rather than morphological factors, are likely to be the main cause of the differences in epiphyte biomass observed on actual seagrass leaves of the two species.

Reduction in available light to seagrass leaves due to the presence of epiphytes was estimated from relationships derived from studies of seagrasses and epiphytes in Cockburn Sound (Silberstein *et al.*, (1987). This relationship suggests that reductions of less than 25% were likely to be occurring in King George Sound and Princess Royal Harbour. Although light reduction by epiphytes to seagrasses in Oyster Harbour was usually less than 20%, occasionally epiphyte growth reached levels that could cause a 60-70% reduction in light to *P. australis* leaves and a 40% reduction in light to *P. sinuosa* leaves.

4.3.7 Conclusions

Mean nutrient and chlorophyll *a* concentrations in the waters of Oyster Harbour, were higher than either Princess Royal Harbour or King George Sound. In contrast, water clarity was lower.

The water quality of Princess Royal Harbour in 1988/89 had improved significantly since the survey conducted in 1978/79, and was similar to the water quality in King George Sound.

A high proportion of phosphorus entering Oyster Harbour is in a dissolved inorganic form. During floods a buoyant, nutrient-rich layer of freshwater flows over the top of the denser marine water of Oyster Harbour and out into King George Sound.

Seagrass leaf biomass reached a seasonal maximum in spring/summer at all sites. Seagrass biomass and shoot density was lower in the two harbours than in King George Sound. Stands of *P. sinuosa* in Princess Royal Harbour were particularly sparse.

Nutrient concentrations in seagrasses, epiphytes and periphyton indicated that Oyster Harbour was more nutrient enriched than Princess Royal Harbour and King George Sound.

Light was found to be the dominant factor affecting seagrass leaf growth in all three waterbodies. Maximum leaf production rates per shoot were highest in spring, but maximum rates per unit area of meadow occurred in summer. Production rates were less consistent in the harbours than in King George Sound indicating a reduced capacity to lay down below-ground storage reserves, creating an increased vulnerability to unfavourable conditions such as prolonged periods of low light levels.

Macroalgal smothering appears to be the major cause of seagrass decline in Princess Royal Harbour. In contrast, epiphytes are implicated as the main cause of seagrass decline in Oyster Harbour, apart from the south-east corner of the harbour where dense accumulations of macroalgae occur. This difference may be due to the better water clarity in Princess Royal Harbour favouring the proliferation of macroalgae, while the higher nutrient loading and relatively poor light conditions in Oyster Harbour may favour the growth of epiphytes.

4.4 Effects of light and temperature on the photosynthesis of seagrasses, epiphytes and macroalgae

Light is required by plants for photosynthesis and growth. The past decline of seagrass meadows in some Western Australian coastal waters and embayments has been linked to a reduction in light reaching the meadows, either through decreased water clarity or shading by epiphytic or unattached algae. Photosynthetic responses of plants to light can vary between species, and even between plants of the same species that are growing under different conditions. Changes in temperature also influences the photosynthetic response. These relationships are well known for many terrestrial plants but very little information is available on the light requirements of aquatic plants in Western Australia. In particular, little is known about the light requirements of the common marine seagrasses in Western Australia.

A laboratory technique for measuring the photosynthetic rate of 'whole seagrass plants' was developed for this study. This allowed the effects of light intensity and temperature on photosynthesis to be examined separately. These data provide the basis for a predictive model of seagrass photosynthesis (and growth) that would be expected in a meadow under a variety of conditions.

This study was carried out by the Centre for Water Research in collaboration with the EPA. This section summarizes the more detailed report on this study by Masini *et al.*, (in preparation).

4.4.1 Objectives and Scope

The primary objective of this study was to provide information relevant to the management of seagrass ecosystems. The scope of the study included the following tasks:

(i) to determine the photosynthetic response of intact shoots of the dominant seagrasses;

(ii) to determine the effect of temperature on the photosynthetic response of the dominant seagrass;

(iii) to determine the effect of 'light stress' removal on seagrass photosynthesis;

(iv) to determine the photosynthetic responses of the epiphytic and macroalgal communities and;

(v) to estimate the seasonal cycle of growth in seagrasses and macroalgae.

The results of these studies are outlined below.

4.4.2 The photosynthetic response of different seagrass species

For many plant species, the relationship between their metabolic rates (ie photosynthesis and respiration) and light intensity is qualitatively similar. In the dark or in very low light intensities, plants respire and produce carbon dioxide. As light intensifies, the photosynthetic rate (ie carbon fixation and oxygen production) increases proportionally, until a particular light level is reached after which the photosynthetic rate is constant (Figure 4.8).

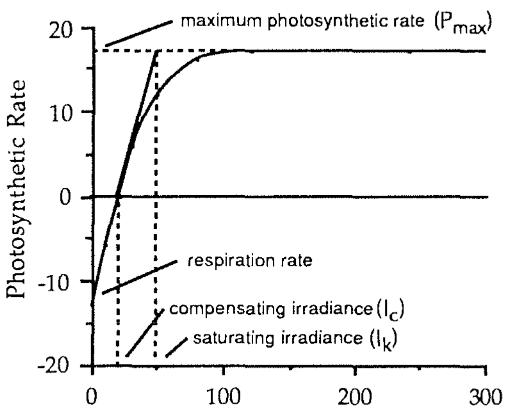

Figure 4.8 Plot of a typical photosynthesis versus irradiance curve (PI-curve) showing critical metabolic rates and light intensities.

Several metabolic parameters can be identified from these photosynthesis-irradiance curves (PI-curves). The metabolic factors of particular interest are the 'respiration rate' and 'maximum photosynthetic rate'. The relevant light parameters include the 'compensation point' (I_c), where oxygen consumption is balanced by oxygen production, and the 'saturation point' (I_k), which is the minimum light intensity which, theoretically, is required to saturate photosynthesis. An index of relative photosynthetic efficiency can be determined from the slope of the initial part of the PI-curve, adjusted for chlorophyll *a* content.

The most common seagrasses in the Albany harbours are *Posidonia australis, Posidonia sinuosa* and *Amphibolis antarctica*. The light requirements of these three seagrass species and the macroalgae and epiphytes that commonly occur in Princess Royal Harbour are shown in Table 4.2.

Species	I_c (μmol $m^{-2}s^{-1}$)	I_k
Seagrasses		
P. australis	25	92
A. antarctica	20	73
P. sinuosa	23	56
Macroalgae	22	122
Epiphytes	24	179

Table 4.2 Compensating (I_c) and saturating (I_k) irradiances for the dominant plants in Princess Royal Harbour.

Of the seagrass species examined, *P. australis* was found to have the highest light requirements (highest I_c and I_k; Table 4.2), that is, this species was the least efficient in using incoming sunlight. This was probably due to the relatively thick leaves and rhizomes of this species.

P. sinuosa has thinner leaves and rhizomes and had the lowest light requirement to saturate photosynthesis. Although this species was the most efficient at capturing light energy, it had the lowest maximum photosynthetic (ie growth) rate. The respiration rate of the leaves and rhizomes of both *Posidonia* species contributed approximately 70% and 30% respectively of the total respiration rate of the intact 'whole' plants. The third species, *A. antarctica,* has a totally different leaf and rhizome morphology to the *Posidonia* species (Figure 4.9) and has moderate light requirements and high photosynthetic rates.

Light attenuates rapidly through the canopy of *P. sinuosa*. For example, about 15% of sun-light reaching the top of the seagrass canopy penetrates to 0.1m while only about 5% reaches 0.2m into the canopy. The results of this study indicate that these seagrasses require about 1.5% of full summer sunlight (or about 30 $\mu mol\ m^{-2}s^{-1}$) at the level of the canopy, to balance oxygen consumption and production and about 15% (or about 300 $\mu mol\ m^{-2}s^{-1}$) to saturate photosynthesis, and therefore achieve maximum growth rates. The depths at which these light levels occur (on average) in Princess Royal Harbour correlates closely with the observed depth distribution of these seagrass species.

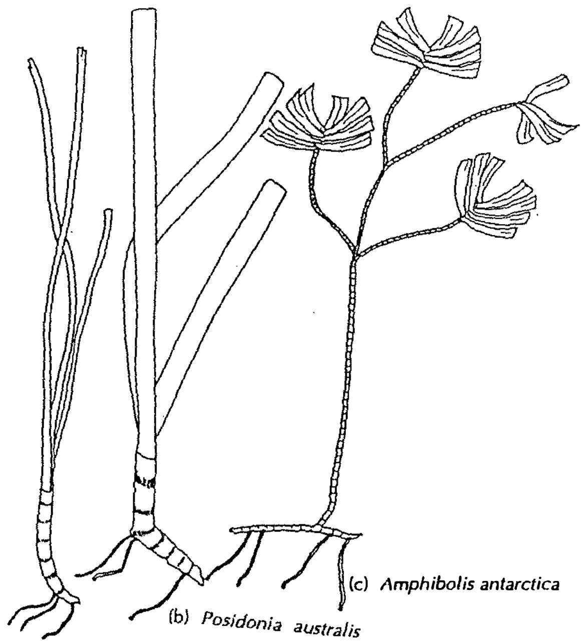

Figure 4.9 Typical morphologies of the major seagrass species found in the Albany harbours.

4.4.3 Temperature effects

The effect of temperature on photosynthesis was determined for *P. sinuosa* as this species is the most abundant seagrass in Princess Royal Harbour. Three experimental water temperatures were used (ie 13, 18 and 23° C) and represent the annual temperature range experienced in the harbour.

Respiration rates increased by about 25% between 13 and 18° C and by 44% between 18 and 23° C. The maximum gross photosynthetic rate also increased with temperature, approximately doubling between 13 and 18° C, but only increased a further 20% between 18 and 23° C. As a result the net photosynthetic rate (ie. the gross photosynthetic rate minus the respiration rate) approximately doubled between 13 and 18° C, but then decreased by about 20% between 18 and 23° C. These results indicate that the optimum temperature for the growth of *P. sinuosa* in Princess Royal Harbour is around 18° C, which is close to the mean annual temperature of the harbour waters.

4.4.4 Effect of epiphyte removal on photosynthesis of *P. sinuosa*

Seagrass leaves that are covered with epiphytes receive considerably less light than leaves with low epiphyte loads. Similarly, plants growing at the lower depth limit of their distribution receive less light than plants growing in shallow water. In both cases these plants are likely to be more prone to reductions in water clarity than plants that are growing in shallower water or have low epiphytic coverings on their leaves, unless there has been an alteration of their efficiency in capturing light, that is, unless they adapt to natural or induced low light intensities. An experiment was conducted to determine whether this is the case.

The photosynthetic response of highly epiphytised *P. sinuosa* plants collected from their current depth limit in Princess Royal Harbour (about 4m), was compared with plants with low epiphyte loads, collected from a depth of 2m. After removing the epiphytes, the photosynthetic responses of plants from these two sites were virtually identical. These results suggest that physiological adaptation to low light had not occurred in the heavily epiphytised plants collected from their depth limit and also that the photosynthetic rate of *P. sinuosa* in the harbour would return rapidly to 'normal rates' following the removal of the epiphytes.

4.4.5 Photosynthetic responses of epiphytes and macroalgae

When clear plastic strips, designed to mimic seagrass leaves, are left in a seagrass meadow they accumulate periphyton, which consists of a similar assemblages of plants and animals that form the epiphytes on seagrass leaves. The photosynthetic responses of 'epiphytes' grown on artificial seagrass for 115 days; naturally occurring epiphytes on seagrass leaves and composite samples of the macroalgal community in Princess Royal Harbour, were determined and compared with the photosynthetic responses of the seagrasses.

The average compensating light intensity of the algae were similar to those of the seagrasses, however saturating light intensities were about double those of seagrass (Table 4.2). The relative photosynthetic efficiency of the algae were high and the maximum photosynthetic rates were approximately double that of the seagrasses, partly explaining the rapid growth of these algae that has been observed in the field.

Interestingly, when light intensities were increased from half to approximately full summer sunlight, the maximum photosynthetic rates decreased by 10% to 25% suggesting that growth rates of macroalgae will be reduced at very high light intensities.

4.4.6 Seasonality of growth in seagrasses and macroalgae

P. sinuosa growth was modelled for each month using the relationships described earlier between photosynthesis, temperature and light. The model shows a tight coupling between growth and respiration over the annual cycle. A period of net growth occurs during the summer months when daylength is long and light levels are highest. However during winter the respiratory requirements of the seagrass outweigh potential production and net loss of energy (carbon) occurs over this period. These data suggest that the theoretical time required for a *P. sinuosa* plant to double its biomass (doubling time) is about 1.6 years.

When the same procedure is used to determine the potential growth of macroalgae, significantly higher growth rates are obtained. The doubling times of the macroalgal community can be as low as 12 days under ideal conditions. Unlike the seagrasses, the macroalgae appear not to consume more energy than is produced during winter. As a result, the comparative annual growth rate of macroalgae is about 25 times the growth rate of the seagrasses in Princess Royal Harbour.

4.4.7 Conclusions

The relative susceptibility of the three seagrass species examined to a reduction in available light is as follows:

P. australis > *P. sinuosa* > *A. antarctica*

Relative susceptibility to low-light conditions is dependent on the cause of the reduction, and the growth rate of the seagrass in question. If the light reduction is due to epiphytes, and epiphyte loads increase with time, the slow growth rate and leaf-turnover rates of *P. sinuosa* would allow large epiphyte loads to accumulate on its leaves, compared to a species with faster leaf turnover rates. It follows that each *P. sinuosa* leaf would receive less light than an equivalent leaf from the other species, thereby increasing its relative susceptibility.

The annual cycle of energy storage and usage, in the roots and rhizomes of seagrasses influences the seasonal effects of light on these plants. It appears that *P. sinuosa* depends on stored energy reserves for maintenance respiration and growth during winter. As a result, imposed light stress during the period when seagrasses are actively storing energy reserves (ie starch and sugars), could, potentially, threaten the survival of the meadow in the following winter when these reserves are needed. In contrast, imposed light reduction would have significantly less impact during periods of moderate temperatures (lower respiration) and long days, but only if average daily incident light is maintained above levels required for saturation of photosynthesis.

It appears that *P. sinuosa* growing under a reduced light climate (ie heavily epiphytised plants or those growing at their depth limit) in Princess Royal Harbour have not adapted their photosynthetic efficiency to the low-light conditions and therefore these plants are immediately able to resume normal photosynthetic rates when re-exposed to normal light levels. As stored energy reserves are likely to be important in the annual growth cycle of *P. sinuosa*, the ability to recover from stress is also likely to change throughout the year and be related to the duration of the light stress.

Seagrass growth is tied to a yearly cycle where carbon produced by the plants is used by the plants, with little, if any surplus energy available to provide a buffer against prolonged periods of even slightly adverse conditions. These findings highlight the need to maintain a light climate that will optimise photosynthetic rates. Prolonged periods of even slight light reduction, either through decreased water clarity, epiphyte loading, or macroalgal smothering are likely to result in reductions in meadow leaf-density, and ultimately total loss of the meadow.

4.5 Effects of imposed light reduction on seagrass meadows in Princess Royal Harbour

The extensive loss of healthy seagrass meadows in Cockburn Sound from the 1950s onwards was associated with enrichment of the waters with nutrients and consequent lowered water quality and excessive growth of algae (Anonymous, 1979). Similar problems are now apparent in Princess Royal and Oyster harbours, where there has been clear diminution of the once extensive healthy seagrass meadows since the late 1970s (Bastyan, 1986; Mills, 1987) and this decline has been linked to the addition of pollutants, including nutrients, to these waterways. This has, once again, focussed attention on the need to better understand the impact of stresses imposed on seagrasses in their natural environment.

Like their land counterparts, seagrasses are flowering plants which require sunlight, obtaining their food through the process of photosynthesis. Any lowering of the light available for this process therefore will have a direct bearing on the successful functioning of these plants.

This section presents a summary of a field investigation to examine the nature and significance of changes introduced to a seagrass meadow in Princess Royal Harbour by prolonged and continuous reduction in light imposed on the leaf canopy. The work was undertaken by staff of the EPA as a contribution to understanding the role of stresses on these communities and to complement the work described on seagrasses in preceding sections of this report. The information presented here draws on the findings of a supporting Technical Series report by Gordon *et al.*, (in preparation).

4.5.1 Objectives and scope

Little is known of the sequence and time-scales involved in the decline of Western Australian seagrasses under the influence of long-term light reduction. The objectives of the work were therefore:

(i) To determine the nature of, and time-scale involved in, changes to the structure and productivity of a seagrass meadow under long-term *in situ* light reduction and;

(ii) To determine the extent to which the seagrasses can recover from this stress.

A seagrass meadow consisting of a single species, *Posidonia sinuosa,* was selected for the study. It was located in waters of 3-4m depth, some 50m offshore from Camp Quaranup, on the north-eastern shore of Princess Royal Harbour (Figure 1.1), where relatively healthy seagrasses still occur. The seafloor here is generally flat and the meadow has a low infestation of macroalgae compared with similar meadows in other parts of the harbour.

4.5.2 Measuring the effects of light reduction

The approach used to examine the effects of light reduction on seagrasses was to place shadecloth covered screens approximately 0.2m above the canopy of the seagrass meadow (Plate 7). These screens reduced incoming light by 80%, 88% and 99% of that normally available to the underlying meadows. The seagrasses under these screens were subsequently monitored over several months and the changes in their structural features (leaf density, shoot density, biomass, leaf length and leaf width) and productivity (rates of production of new leaf material) were measured and compared with identical measurements made on adjacent unshaded meadows.

The study comprised two phases: a treatment phase, where the screens were deployed continuously for 5 months, from mid-January 1989 to mid-June 1989, and a recovery phase, starting from mid-June 1989 and extending through to the end of the year, when the screens were removed to return light levels to that of the neighbouring unshaded seagrasses. At the start of the recovery phase, leaves remaining in both the unshaded and shaded meadows were clipped back to ground level and the meadows subsequently monitored from this new baseline.

4.5.3 Sequence and time-scale of seagrass decline

Seagrass meadows grow in a fashion somewhat akin to terrestrial grasses, via a horizontally spreading network of rhizomes running just under the surface of the seafloor and colonizing suitable sites. These rhizomes give rise, along their length, to shoots, which bear the leaves. These grow to form the photosynthetic canopy of the seagrass meadow. With this particular species of *Posidonia* usually one, two, and sometimes three leaves will sprout from the same shoot, the leaves being initiated from an active meristem at their bases, close to the seafloor.

In situ shading of the seagrass meadow caused thinning of the leaf canopy, particularly in the most severely light-stressed plots. There was little initial difference in leaf densities of unshaded meadows and those given the least degree of shading until 1-2 months after the start of shading when there was clear thinning of the meadow, the extent being proportional to the severity of light reduction imposed. After 104 days the mean density of leaves was reduced to between 54% and 71% that of the unshaded meadows (Figure 4.10).

The density of shoots also decreased under long-term shading although the changes were less marked than for leaf density. The variation in shoot density in the unshaded meadow was considerably higher than in the shaded meadows. Unshaded meadows and meadows with the least light reduction (80%) showed no statistical difference in shoot density over the period of shading. In contrast, the mean density of leaf-bearing shoots with the highest light reduction was significantly less than the unshaded meadow. For example the mean shoot density was reduced by about 60% after 104 days (Figure 4.9).

Shading also reduced the lengths, but not the widths, of the leaves in the canopy, and also impaired their growth rates. The extent to which leaf productivity was reduced was proportional to the severity of the light reduction and was enhanced the longer the duration of shading. For example, leaf production of shaded seagrasses was reduced to 10-27% that of unshaded meadows within the first 15 days of shading, to 20-60% that of corresponding unshaded meadows within 42 days, and to 67-83% that of unshaded meadows within 100 days of the start of shading.

Recovery of seagrasses previously shaded for several months was initially rapid and also inversely proportional to the severity of the previous light stress imposed. Best recovery of the leaf canopy was achieved in the previously unshaded plots and the poorest recovery in plots which had been subjected to the greatest light reduction. For example, 35 days after the screens were lifted, leaf density of seagrasses previously subjected to the most and the least light reduction returned to 42% and 76%, respectively, that of the corresponding previously unshaded meadows. After 96 days the corresponding figures were 39% and 59%, indicating that the coupling between the plants' history of light stress and the degree to which they recovered was being maintained for several months after the removal of the stress.

One hundred and sixty days after the shadecloth was removed, the meadow had recovered to similar levels to that found in the control (previously unshaded) meadow. For example, mean leaf density of seagrasses previously given 88% reduction had returned to values measured in the unshaded meadows (controls), while those previously given 99% light reduction had returned to 92% of the controls.

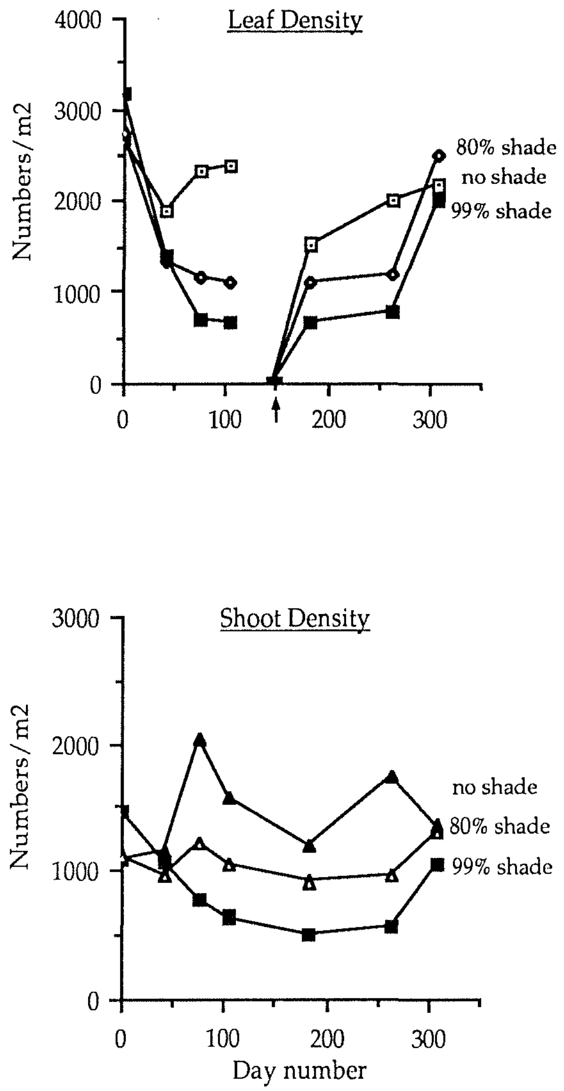

Figure 4.10 Changes in the density of leaves and leaf-bearing shoots in a *P. sinuosa* seagrass meadow in Princess Royal Harbour subjected to shading of the leaf canopy for 5 months. The figure shows changes in the unshaded meadow, and in meadows given light reductions of 80% and 99%. The canopy was clipped back to ground-level and the shading removed after 148 days (indicated with an arrow) and the re-growth of the canopy subsequently monitored.

Similar responses were seen with densities of leaf-bearing shoots in this recovery phase. The reduction in density which had occurred under shading at a given light level was maintained for several weeks after the screens were lifted but eventually approached that of the unshaded meadows. For example, mean shoot densities of meadows previously subjected to the most and the least light reduction were 33% and 54%, respectively, that of the corresponding unshaded meadows 96 days after the screens were lifted. This increased to 78% and 98%, respectively, that of the unshaded meadows 160 days after the screens were lifted (Figure 4.10).

The results suggest that the meadows have a high potential for recovery from severe attenuation of light in the overlying water, even where this is coupled with the loss of the entire leaf canopy. It is important to recognize, however, that the structural features of the previously shaded meadows do not return to those of the unshaded meadows for several months after the stress is removed. The data suggest that the effect of the level of light stress imposed here (5 months) was reversible, at least in terms of structure of the meadow and in terms of the timescale of the experiment.

4.5.4 Smothering of seagrasses by free-living macroalgae

The nutrient enrichment of the harbours is now clearly expressed in excessive growth of macroalgae, which are predominantly free-living and cover extensive portions of the floor of both harbours, storing and recycling nutrients, and reducing the light available to the seagrasses. In some locations these algae form a dense mat on the seafloor, effectively smothering healthy seagrass meadows.

A smaller, but related, field study was undertaken in conjunction with the shading experiment described above, to examine the impact of free-living macroalgae on the underlying meadow.

Several small plots were randomly marked out in the same seagrass meadow and isolated from their surrounds by enclosing the seagrasses in open mesh wire cages. A known quantity of macroalgae, collected from the surrounding meadow, was then introduced into the cages, thus eliminating light from the underlying seagrass meadow. The algae were imprisoned in this fashion for nearly 5 months and the underlying seagrasses monitored at intervals to detect gross changes in the meadows.

Smothering of the seagrasses resulted in rapid reduction in leaf numbers and leaf length and a reduction in shoot density compared with the untreated meadow. After 104 days the mean density of leaves was reduced by nearly 79% that of unshaded seagrasses, leaf lengths were reduced by over 50% and density of leaf-bearing shoots reduced by over 83% that of the untreated meadow. There was little change in leaf widths. The extent of thinning of the meadow under the impact of overlying macroalgae was similar to that produced by shading of the entire canopy, suggesting that the macroalgae primarily impact on the underlying seagrasses through reducing their light availability rather than in imparting mechanical stresses on the plants.

4.5.5 Clearing of macroalgae from seagrass meadows

An identical set of cages to those described above was placed in the seagrass meadow and the algae cleared from within. These cleared meadows were periodically compared with the surrounding uncleared meadow to determine whether there were any benefits of removing algae on the productivity and structural features of the seagrass meadows.

There was no obvious improvement in the structural features of the meadow with clearing but rather a thinning of the canopy accompanied by a reduction in leaf length and shoot numbers. After 104 days the density of leaves was reduced to nearly 29% that of the corresponding uncleared meadow. Similarly, leaf lengths and leaf-bearing shoot numbers were reduced to 67% and 18%, respectively, that of the surrounding uncleared meadow. There was evidence, initially, of faster leaf growth in the cleared meadow, compared with the uncleared meadow. This difference was reduced in subsequent measurements later in the year although there was an overall lowering of productivity towards winter.

4.5.6 Conclusions

Reducing the incoming light normally available to the seagrasses by between 80% and 99% for over 140 days resulted in a rapid thinning of the leaf canopy, accompanied by reduced length of leaves and reduced density of shoots. The effects were most obvious where light reduction was most severe.

Shading of the leaf canopy also reduced the rate at which new leaves were formed. Differences in leaf productivity between unshaded and shaded meadows became larger the longer the duration of shading.

There was a high initial recovery of the leaf canopy following continuous and severe light reduction for 5 months, although the previously shaded meadows remained consistently thinner and did not recover to the extent of the unshaded meadows, for several months after the stress was removed. For three months following removal of the stress the extent of recovery was proportional to the severity of the previous light stress imposed.

The results of this study provide evidence that these seagrasses have a high tolerance to attenuation of light in the overlying water. Removal of the leaf canopy following 5 months with light reduced up to 99% that normally experienced by the meadow did not signal the death of the meadow. The findings suggest that periods of reduced light in Princess Royal Harbour, for example through the influence of dense phytoplankton blooms or resuspension of sediments can be expected to lead to some thinning of the meadow and a lowering of productivity.

Responses to *in situ* shading did not indicate that these plants can adapt to low-light levels or to conditions which reduce self-shading. There was no increase in mean leaf length or in leaf productivity as the meadow thinned under the impact of reduced light availability. Leaf productivity and leaf density were both reduced the longer the duration of shading. These findings are consistent with laboratory studies on plants from the same meadow, which indicated that there was no short-term adaptation to reduced light (Masini *et al.*, in preparation).

Addition of free-living macroalgae to the seagrass meadow reduced the density of intact leaves and leaf bearing shoots. The extent of this reduction was similar to that observed with the most severe shading (99%) of the leaf canopy over the same time interval, suggesting that the addition of macroalgae to the meadow had most impact through reducing light than through imposing mechanical stresses on the plants.

Although cleared meadows displayed an overall thinning of the leaf canopy, leaf productivity was actually greater than in the uncleared plots. This difference was more obvious in summer than in winter.

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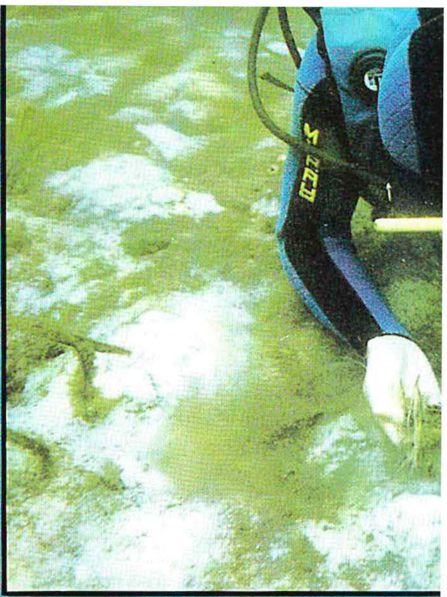

Ecosystems such as Albany's harbours are complex, inter-dependent associations of plants and animals, often in delicate balance with each other and their environment.

When this balance is upset by human activities, the changes are usually detrimental, subtle and unnoticed.

These changes become obvious only when the ecosystem is in an advanced state of decline. Although the symptoms of deterioration are clear, the causes are rarely obvious.

Determining the causes of decline usually require extensive scientific investigation.

The remedy to this type of problem extends beyond purely scientific solutions and involves commitment by the whole community to recognise the importance of an environmentally sustainable lifestyle.

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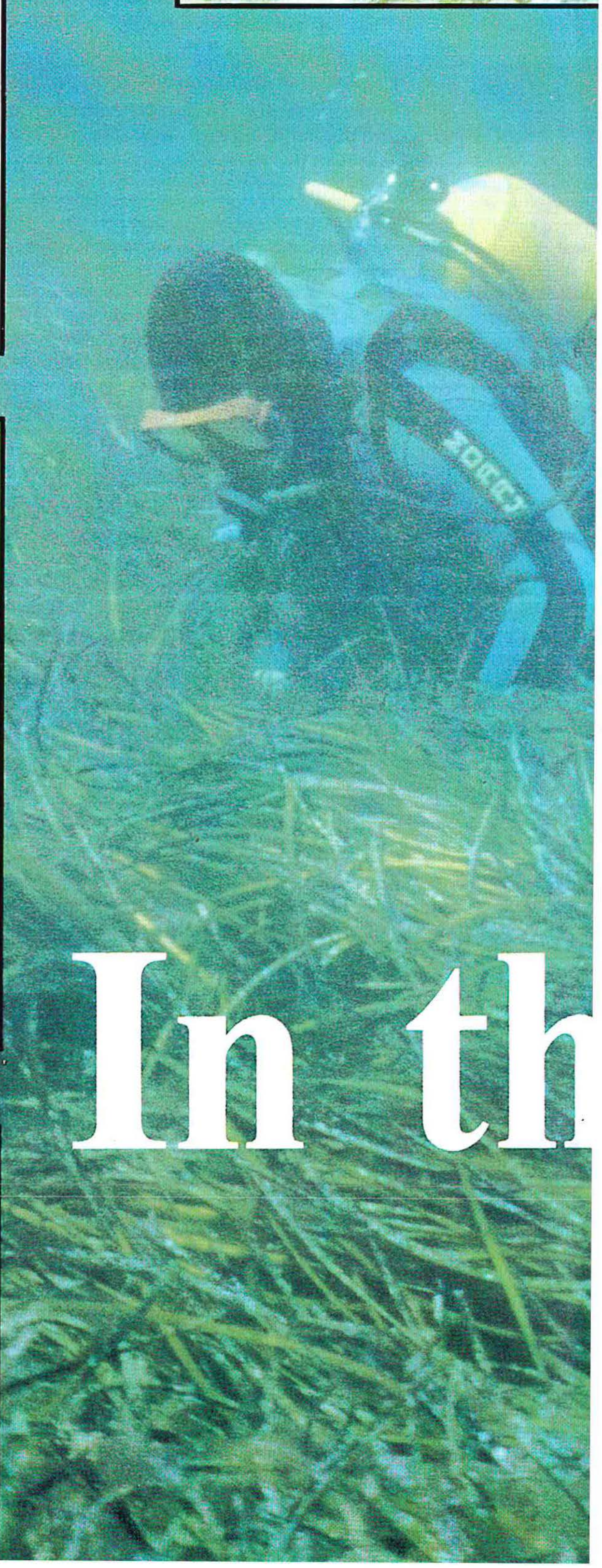

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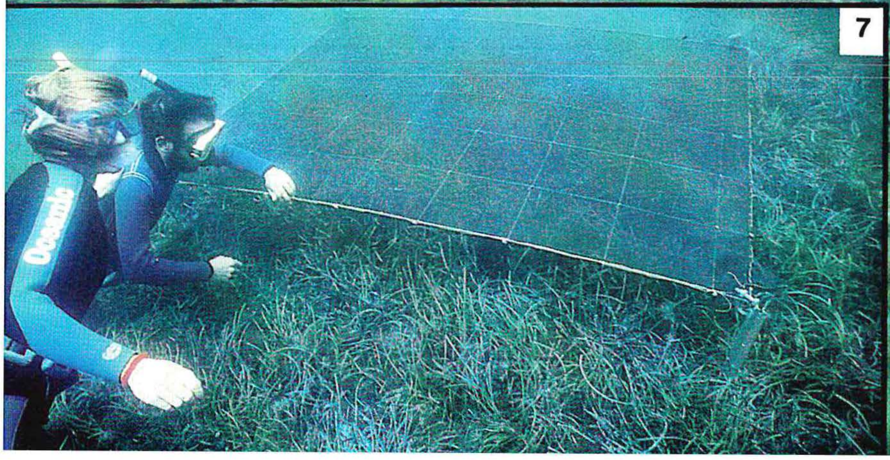

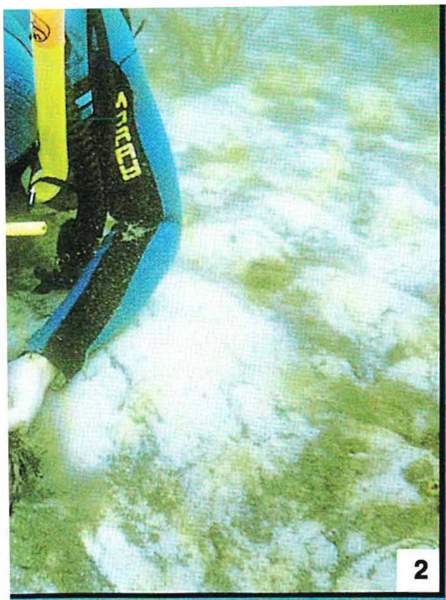

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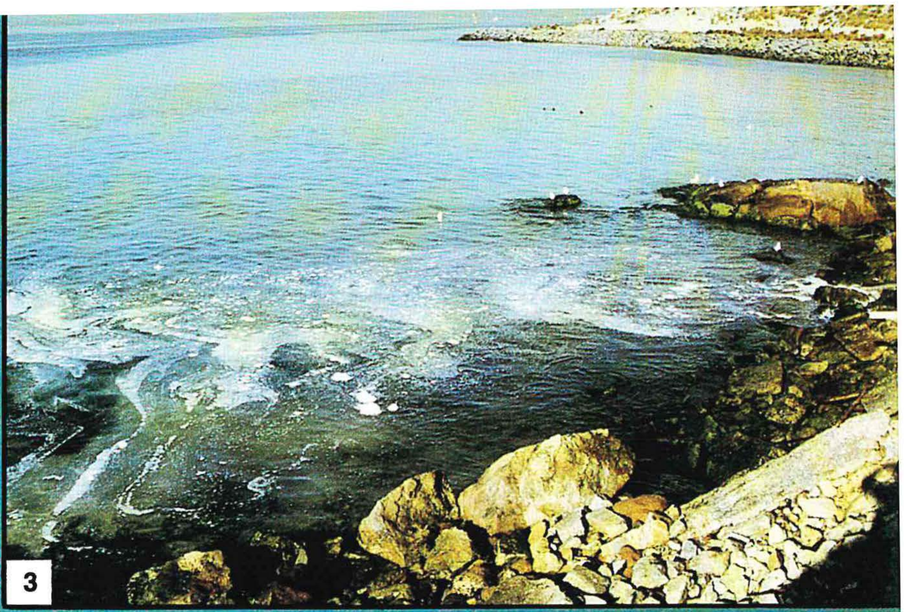

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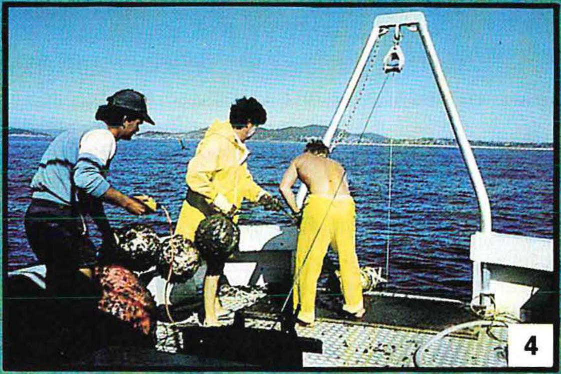

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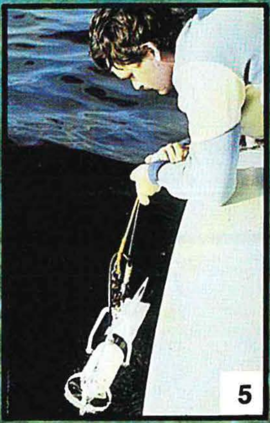

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e field

1. Water on the move: a surface winter flow into King George Sound.
2. A sign of trouble: when seagrass meadows die, they may take centuries to return.
3. Waste at work: the visible side of shore-based discharge into Princess Royal Harbour.
4. Science at work: environmental problems warrant intensive studies.
5. Looking for clues: the direct measurement of water currents in the harbours.
6. Covering all angles: a fixed-light recorder attached to a buoy in Princess Royal Harbour.
7. Experiments in the field: seagrass is shaded to gauge its reaction to light stress.
8. Simulating nature: plastic seagrass strips are used to measure algal growth.

Chapter 5

Urban, Industrial and Agricultural Inputs

5.1 Heavy metal contamination in Princess Royal Harbour

In 1983, fish contaminated with mercury were identified following analyses of routine samples collected from the Perth metropolitan fish markets. These fish were subsequently found to have been caught in Princess Royal Harbour. An extensive survey in Princess Royal Harbour determined that the sediments and biota in the western end of the harbour were contaminated with lead and mercury (Jackson et al., 1986). The main source of this pollution was identified as coming from the effluent discharged by the CSBP fertiliser works (Talbot et al., 1987). As a result of these findings the company ceased discharging the effluent in February 1984 and the pipeline was removed in 1986.

The finding of mercury contaminated fish above the health limit led to the closure, in March 1984, of the western portion of the harbour to the taking of all fish, crustaceans and molluscs. Since then, the Department of Fisheries has continued to monitor the level of mercury in several species of fish and presently, the western end of Princess Royal Harbour remains closed to fishing.

The major findings of the heavy metal studies that led to the identification of the problem, and the follow-up monitoring program on the existing state of mercury contamination in the harbour, are outlined below.

5.1.2 Objectives and Scope

The studies referred to above were concerned with determining the extent of heavy metal contamination of Princess Royal Harbour.

The aims were to identify;

(i) the sources of lead and mercury pollution ;

(ii) the extent of the contamination and;

(iii) the factors controlling the distribution of lead and mercury.

5.1.3 Sources of lead and mercury pollution

The CSBP superphosphate plant has operated on the western shore of Princess Royal Harbour since 1954. The effluent from this plant was found to be the source of the mercury and lead contamination (Jackson *et al.*, 1986). Mercury is present in rock phosphate in trace amounts and is present in effluents produced during the manufacture of superphosphate. Lead is also produced during the production of sulphuric acid used in the manufacturing process. Initially, both contaminants entered the harbour via a drain. Later on, the effluents were discharged directly into Princess Royal Harbour through pipe outlets. Once this contamination was identified, the inputs of heavy metals to Princess Royal Harbour ceased, through on-site treatment and recycling of industrial effluents and stormwater from the CSBP plant, and cessation of direct effluent discharge.

5.1.4 Extent of the pollution

An estimated 900 kg of mercury was discharged from the fertilizer plant prior to the cessation of discharge in 1984, and the majority of this is thought to have entered Princess Royal Harbour. The quantity of lead that entered Princess Royal Harbour however, is unknown.

Surveys of lead and mercury levels revealed that accumulation occurred in sediments in the western end of the harbour, principally near the CSBP drain and outfall pipes. Sediments with a high organic fraction contained considerably more methyl mercury than sediments with lower organic contents.

High levels of lead were also found in cockles and mussels, both filter-feeding organisms that are known to accumulate heavy metals in their tissues. However, the main problem identified was the high concentrations of the highly toxic 'methyl mercury' in edible fish species. As a result, subsequent research was aimed primarily at addressing this problem.

Studies conducted by the Department of Fisheries revealed that of the 15 species of fish analysed, 11 species were found to exceed the health standard. Fish containing the highest levels of methyl mercury probably feed in areas of the harbour in the vicinity of the former outfall, which trap fine, organic-rich sediments and therefore contain the highest levels of total and methyl mercury. As a result of these findings, the western end of Princess Royal Harbour was closed to fishing in March 1984.

Since 1984, mercury concentrations in the major fish species in the harbour have been monitored annually by the Department of Fisheries. Results from the latest survey conducted in August 1989 are not yet available. Mercury concentrations in many of the species that were analysed have generally decreased between 1985-1988, however this trend was only statistically significant for cobbler and King George whiting (Figure 5.1).

In 1988, some species were at or below the health limit, however others such as the flathead and brown-spotted wrasse remained well in excess of this level. For the ban on fishing to be lifted, levels of mercury would need to be consistently below 0.5 mg kg^{-1}, the National Health and Medical Research Council (NH&MRC) health limit.

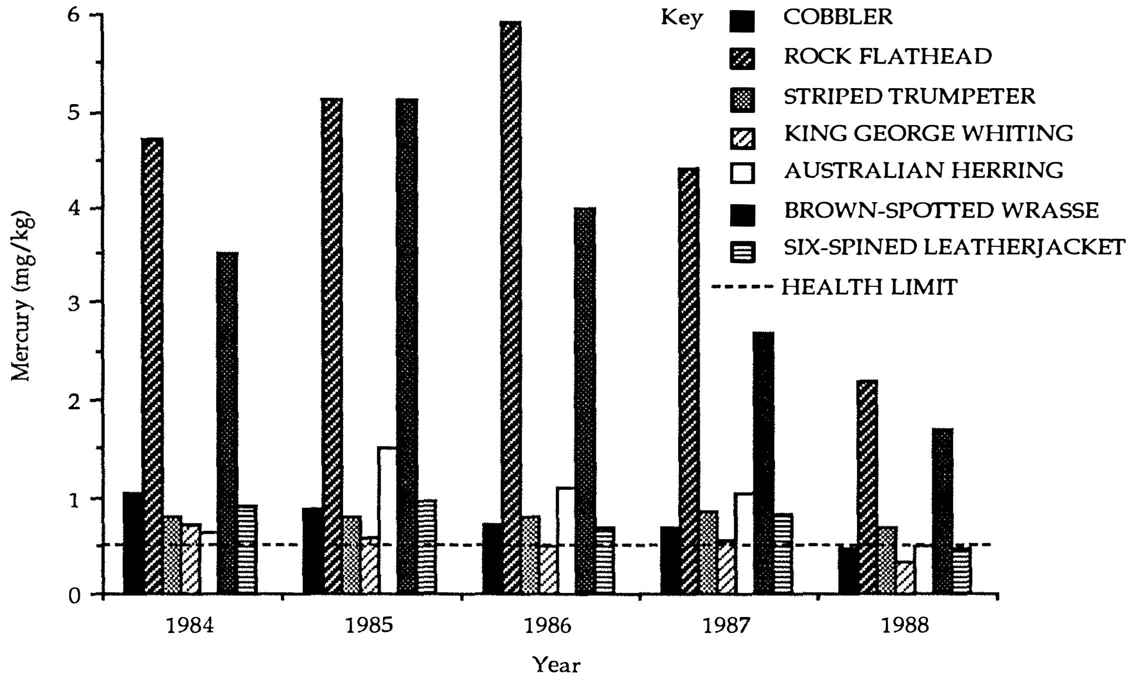


Figure 5.1 Mean mercury levels in fish from the western end of Princess Royal Harbour. Information supplied by the Department of Fisheries.

A limited survey of mercury levels in the sediments of Princess Royal Harbour in 1989, in the vicinity of the former CSBP outfalls suggested that mercury levels in these sediments have not decreased significantly since the discharge from CSBP stopped in 1984. Studies elsewhere have shown that, after the cessation of mercury input to an area, the levels of mercury in fish tend to decrease after about 5 years. Recent studies have shown that mercury levels in water throughout the harbour are very low. It is likely that natural water-borne export of mercury from the harbour is very slow and that it will take at least several decades to achieve a substantial reduction in the total amount of mercury in the harbour by natural processes. However, removal of these organic-rich sediments may reduce this problem.

5.2 Industrial effluent and drainage into Princess Royal Harbour

Industries located on the northern and western sides of Princess Royal Harbour have discharged their wastes directly into the harbour for several decades. Fertilizer, washed from the agricultural lands to the west and carried by creeks and drains, has also entered the harbour for many years. Some of the domestic wastewater discharged into King George Sound, near the entrance to Princess Royal Harbour, is swept into the harbour by incoming tides. Furthermore, because of the steep topography and shallow topsoil surrounding the Albany township, most of the urban runoff flows rapidly into the harbour, further adding to the pollution.

These inputs contain pollutants such as bacteria, heavy metals, pesticides and especially the plant nutrients nitrogen (N) and phosphorus (P). Several different types of environmental problems have developed over the years as a result of the gradual buildup of contaminants in Princess Royal Harbour. For example an oversupply of nutrients has led to excessive algal accumulations which, in turn, caused the seagrasses to decline. Lead and mercury have accumulated in the sediments, contaminating the fish and other animals that live in the western end of the harbour to levels exceeding the National Health and Medical Research Council (NH&MRC) health limits. High levels of faecal bacteria have made swimming unsafe in parts of the harbour and pungent odours, grease slicks and solids floating on the water surface are unpleasant and unsightly, and lower the amenity value of Princess Royal Harbour.

The last inventory of pollutant loads into Princess Royal Harbour was made in 1979 by Atkins *et al.*, (1980). This section outlines an inventory of more recent pollutant loads that was undertaken in 1988 and 1989. The study was carried out by the Environmental Protection Authority, with assistance from officers of other State and local government authorities, and summarizes the more detailed information on recent pollutant loads into Princess Royal Harbour contained in a technical report by Deeley and Bott (in preparation).

5.2.1 Objectives and Scope

The major objective of this study was to determine the current and historical inputs of pollutants to

Princess Royal Harbour. The relative significance of each source of pollution was assessed and appropriate management measures evaluated. Information on pollutant loads into the harbour was obtained from a number of sources including;

- analyses of samples of runoff and effluents collected by the EPA in 1988 and 1989;
- results from industry self-monitoring programs in 1989;
- estimates of groundwater inputs;
- previously published information on effluent and drainage inputs (Atkins *et al.*, 1980; Mills, 1987) and;
- unpublished consultancy reports.

Samples of effluent and runoff were analysed for a number of parameters including; physical properties (pH, suspended solids, total soluble salts), oxygen demand (BOD_5, COD), oil & grease, nutrients (N and P), heavy metals (cadmium, copper, zinc, lead, chromium, arsenic, mercury), and pesticides (organophosphates and organochlorines).

After recording high levels of faecal bacteria in water samples from Princess Royal Harbour in 1979, Atkins *et al.*, (1980) recommended that faecal bacterial populations in the harbour be monitored regularly. Results of these surveys, conducted by Town of Albany health surveyors from 1982 to 1988, are also included in this summary.

5.2.2 Sources of pollutant inflow to Princess Royal Harbour

Inputs are grouped under four general headings; urban drainage, rural drainage, industrial and domestic effluents and groundwater inputs.

Urban Runoff

Urban drainage includes inputs from 18 drains which collect runoff from a catchment of about 235 hectares within the Town of Albany. Drainage volume and nutrient loads have been estimated from limited sampling and from similar information gathered elsewhere (Bayley *et al.*, 1989).

Urban runoff contained significant quantities of nitrogen and phosphorus, presumably derived from garden fertilizers and the decomposition of organic matter. It was also found to contain significant bacterial loads and low concentrations of heavy metals and pesticides.

Rural Drainage

Input of nutrients to Princess Royal Harbour from rural runoff occurs mainly via the upper Robinson Estate drain which drains rural land to the west of Princess Royal Harbour (Figure 5.2). The contribution of smaller drains (Princess Road North and South, Lime Burner's Creek, etc) were considered to be minor. Some allowance for nutrient inputs from rural land to the south-west of the harbour was made in estimates of the groundwater inputs.

Industrial and Domestic Effluents

The main industrial and domestic discharges to Princess Royal Harbour are shown in Figure 5.2. The agricultural-based industries which produce effluents entering the harbour include a vegetable processor, an abattoir killing sheep and cattle, a fish freezing works, a fertilizer manufacturing plant and a woollen mill. Because of the considerable daily and seasonal variation in the pattern of discharge and in the quality and quantity of the effluents entering the harbour, the estimates presented below should be considered as preliminary.

Effluents were sampled by the EPA during two intensive 24 hour periods in 1988. Results from industry self-monitoring programs during 1989 are also included. Effluents were sampled from:

(i) The WAWA King Point wastewater treatment plant outfall;

(ii) Southern Processors' potato processing stream;

(iii) Metro Meats' abattoir effluent;

(iv) Kailis and France's fish processing effluent and;

(v) Albany Woollen Mills' effluent.

Estimates were also made of the quantity of diammonium phosphate spilt into the harbour during unloading at the Albany wharf, and is included in this section. The total nitrogen and phosphorus loads from the Munster Hill Drain, which includes the licensed outlet of the CSBP Superphosphate Works and runoff from the CSBP property was estimated as the difference between the loads measured in the Upper Robinson Estate Drain and the loads measured below the confluence of the Munster Hill Drain and the Upper Robinson Estate Drain.

King Point wastewater treatment plant

The WAWA King Point wastewater treatment plant is a primary sewage treatment plant which, up until recently, discharged at the shoreline for 24 hours a day, 365 days a year. A preliminary estimate of the proportion of this effluent that enters Princess Royal Harbour was about 40% of the discharge volume (Mills *et al.*, 1987). Recent calculations estimate that in the order of 20% of the discharge volume is more realistic (Mills and D'Adamo, in preparation) and this estimate is used here. The shoreline outfall was extended in 1989 to discharge about 30m offshore in

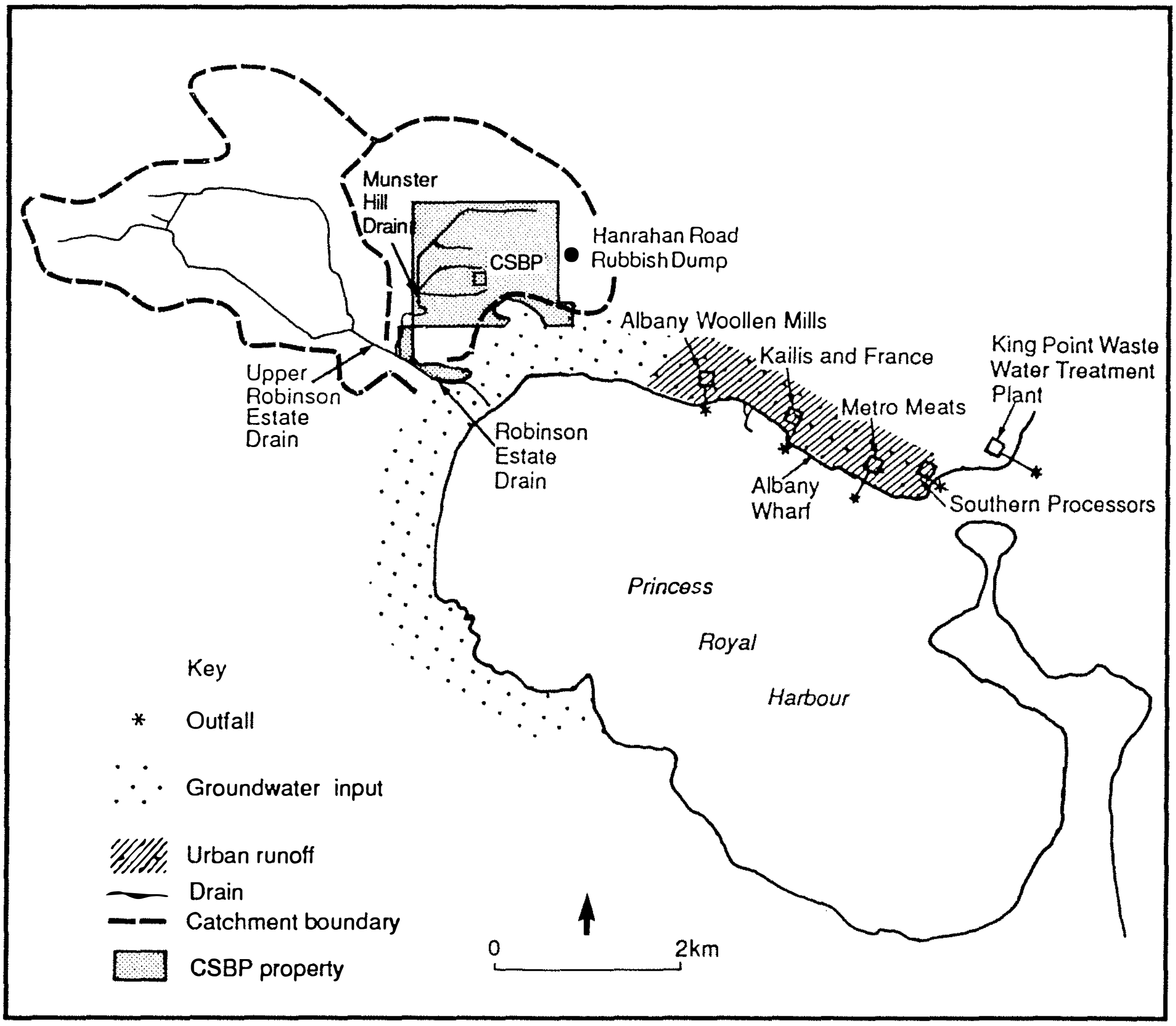


Figure 5.2 Location of the major sources of contaminants in Princess Royal Harbour.

a water depth of 10m and, although it may not significantly reduce the input of nutrients to Princess Royal Harbour, the bacterial concentrations at the sea surface are likely to be significantly reduced as a result of improved initial dilution.

Southern Processors Pty Ltd

The Southern Processors factory converts potatoes into frozen chips for around three months of the year in late summer. The effluent is derived from the washing, peeling, chopping and blanching of potatoes. This effluent was found to contain very high phosphorus concentrations. Effluent derived from the washing and freezing of peas, beans, corn and other vegetables is considered to be of little environmental consequence. The potato processing effluent is discharged at the shoreline via an open culvert.

Metro Meats Pty Ltd

Metro Meats kills up to 3700 sheep and 200 cattle per day from September to March. The abattoir effluent is derived from the killing floor and stock holding yards. The outfall discharges on the sea-floor in about 5m of water, some 30m offshore, just south of the wharf.

Kailis & France Pty Ltd

Kailis & France wash and freeze pilchards and salmon throughout the year. Effluent volume is relatively small but does contain solids, oils and nutrients derived from fish slime and scales removed during washing. This effluent is discharged one metre below the surface into 12m of water at the western edge of the wharf.

Albany Woollen Mills Pty Ltd

Albany Woollen Mills dye and spin wool and synthetic fibres to produce a wide range of carpet yarns throughout the year. Effluent is produced mainly from the dyeing house and is discharged through a shoreline outfall.

Albany Wharf

A range of fertilizer materials including rock phosphates, elemental sulphur, potassium chloride (muriate of potash) and diammonium phosphate (DAP) are unloaded at the Albany wharf. Spillages of these materials into the harbour are undesirable, but only the spillage of DAP is considered to be ecologically significant because DAP is a highly concentrated, water soluble nitrogen and phosphorus fertilizer. There is usually only a single shipment of this material unloaded annually. Rock phosphates and elemental sulphur are insoluble in sea water. Potassium chloride is of little ecological consequence because of the abundance of both potassium and chloride ions in sea water.

Groundwater Inputs

Groundwater inputs of pollutants, particularly nutrients, to Princess Royal Harbour originate from a number of sources (Figure 5.2). These include nutrients from rural land to the south-west and west of the harbour, the Hanrahan Road rubbish tip, CSBP's industrial estate, and from the urban areas around the northern part of the harbour. Septic tanks also contribute significant amounts of nitrogen and phosphorus to the soil, but the current load of nutrients entering the harbour from this source is not accurately known. Septic tanks in close proximity to the harbour are not an appropriate method of waste disposal in the long-term, because, as the surrounding soil becomes increasingly saturated with nutrients, less are retained and therefore more enter the harbour via the groundwater.

5.2.3 Magnitude of pollutant inputs to Princess Royal Harbour

This section summarizes the pollutant inputs to Princess Royal Harbour under the following headings; effluent and drainage volumes, bacterial loading, solids, biochemical oxygen demand (BOD), oil and grease loadings and nutrient inputs. Some indication of the historical loadings into Princess Royal Harbour can be gained from previous investigations and from extrapolation of the 1988 data. Estimates for inputs for 1980 are considered typical for loadings in the 1970s to mid-1980s.

Effluent and drainage volumes

There is considerable yearly variation in the volume of runoff entering the harbour caused by variations in both the quantity and pattern of rainfall, and by variations in the moisture status of catchment soils.

The volume of industrial effluents discharged into Princess Royal Harbour annually is around 380 megalitres, or 0.4% of the average harbour volume. By comparison, around 6140 megalitres of urban and rural runoff enters the harbour annually which is about 7% of the harbour volume.

Bacterial loading

Pathogenic bacteria such as forms of *Salmonella* and *Shigella*, which cause gastroenteritis and dysentery in humans, are often associated with faecal material from warm-blooded animals. The presence of these organisms in water samples are a threat to human health. Faecal coliforms and faecal streptococci are also present in the gut of all warm-blooded animals. An indication of water pollution from faecal matter can be gained from the number of these organisms in water samples. Faecal bacteria die-off rapidly in fresh and marine water and large numbers in water samples indicate recent inputs of faecal material. Sample results are quoted in terms of the number of organisms per 100ml of sample. Faecal bacterial counts of less than 50 per 100ml are considered satisfactory for direct contact recreation whereas consistent counts above 200 per 100ml indicate a distinct health risk and warrant a sanitary survey. Counts above 1000 indicate serious faecal pollution, while counts above 2000 indicate objectionable water that is heavily polluted.

In 1979 the bacteriological quality of some areas of Princess Royal Harbour and King George Sound was considered to be poor (Atkins *et al.,* 1980). Occasional high faecal coliform levels at Middleton Beach and frequent isolations of *Salmonella* serotypes in waters associated with some of the outfalls were described.

The bacterial condition of the Albany waterways has been monitored regularly following the 1979 recommendations made by Atkins *et al.*, (1980). Water samples were taken from within the mixing zones of the various effluent plumes, and also from Ellen Cove, at the western end of Middleton beach, on 35 occasions from 1982 to 1988. The results of these surveys show the percentage of these water samples with faecal bacterial counts greater than 200 organisms per 100ml, and the percentage of samples in which *Salmonella* serotypes were isolated (Table 5.1).

Site	% above 200/100ml faecal coliforms	% above 200/100ml faecal strepts	% of samples with salmonella
Pt King WWTP	100	100	39
Southern Processors	46	51	8
Metro Meats	52	50	24
Kailis & France	14	23	5
Woollen Mills	71	17	6
Robinson Estate Drain	56	47	3
Ellen Cove	27	3	0

Table 5.1 The relative frequency that water samples collected from within the mixing zones of various industrial outfalls exceeded 200 faecal coliforms per 100mls during the period 1982 to 1988. Results of samples collected from Robinson Estate drain and from Ellen Cove are also included. Data provided by the Town of Albany.

Bacterial contamination levels in Princess Royal Harbour and King George Sound in 1988 were similar to levels reported by Atkins *et al.* (1980). Nearshore mixing zones associated with both the WAWA King Point wastewater treatment plant outfall (prior to the pipeline extension) and the current Metro Meats outfall, were found to be heavily polluted with faecal bacteria. Bacterial counts greater than 100,000 organisms per 100mls were recorded on 100% and 30% of occasions respectively. *Salmonella* serotypes were detected on 39% and 24% of occasions for waters associated with the Water Authority outfall and the Metro Meats outfall. Water within the mixing zones of these two outfalls are grossly polluted with bacteria, and these areas constitute a serious health risk.

The submarine extension to the King Point wastewater treatment plant outfall was completed recently and is likely to have caused a significant change in effluent dilution and plume dynamics. The outfall now discharges on the sea floor in 10m of water some 30m offshore. At least a ten-fold improvement in the initial dilution of the effluent stream will have reduced bacterial concentrations at the sea surface and the likelihood of unacceptable levels of bacteria reaching Middleton Beach. Future monitoring will reveal the degree of improvement gained from this change.

Solids, BOD and oil and grease loadings

Solids entering the harbour are derived from a number of sources including animal and plant fragments and soil particles. Solids may vary in particle size, density and in their rates of decomposition. Most of the industries discharging into the harbour have some installation or equipment for the removal of solids from their effluent stream, but still over 1000 tonnes of solids entered the harbour in 1988 (Figure 5.3).

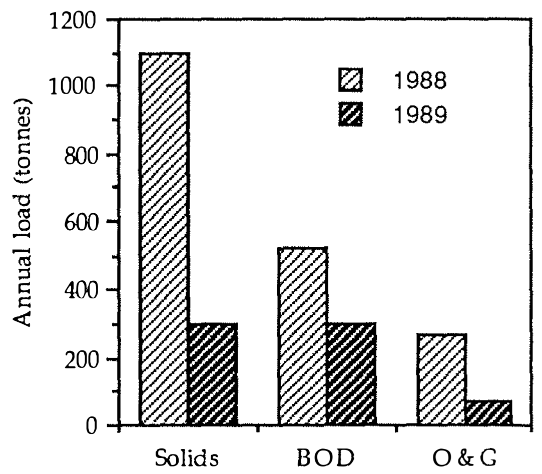


Figure 5.3 Annual loads of solids, biochemical oxygen demand (BOD) and oils and greases (O&G) entering Princess Royal Harbour in 1988 and 1989. (loads for 1989 are based on actual loadings to August and projected loadings for the rest of the year).

Biochemical oxygen demand (BOD) is the amount of oxygen that will be consumed from harbour waters during the breakdown of a substance. Low levels of oxygen in water resulting from the decomposition of organic material in effluents with high BODs, can result in the death of aquatic animals from oxygen starvation. Microbial activity and the oxidation of the larger molecules are responsible for this oxygen consumption. The relative decomposition rates of different organic materials in effluents varies considerably. For example, starches derived from potato processing have a very high oxygen demand, but they are broken down relatively quickly (usually within hours). However larger lumps of animal remains may take several days to fully decompose.

The total BOD of effluent discharged into Princess Royal Harbour in 1989 was in excess of 500 tonnes (Figure 5.2). This is equivalent to the oxygen normally contained in 18 hectares of water a metre deep. The organic material generating the BOD is discharged mainly over the summer months when water temperatures are relatively high and, as a result, some localized deoxygenation events may occur in the mixing zones of the outfalls of Metro Meats and Southern Processors.

Oils & greases are mainly associated with waste streams derived from the processing of animal products including sheep, cattle, fish and wool. Metro Meats screens effluent to remove large solids and has a small, dissolved air flotation unit, downstream of these screens, to remove some of the smaller floatable fatty particles. However, because the effluent is heated, some oils and greases are dissolved and bypass the separation units designed for their removal. These materials solidify when mixed with cooler harbour waters and float to the surface. Oils and greases also slowly build up in the effluent pipeline and when they become dislodged, large pieces of fat and grease enter the harbour. In total, approximately 250 tonnes of oils and greases were discharged to Princess Royal Harbour in 1988 (Figure 5.3).

Solids, BOD and oils & grease loads for 1989 (Figure 5.3) are based on actual loadings to August and projected loadings for the rest of the year. Because of improved management practices implemented in 1989, there has been a considerable reduction in the concentration of these pollutants entering Princess Royal Harbour. This has largely been brought about by significantly improved solids and fat recovery by several of the industries, particularly Metro Meats.

Nutrient inputs

Nutrients (nitrogen and phosphorus) enter the harbour from a number of sources. Leaching of applied fertilizers and atmospheric nitrogen fixed by leguminous pastures, and the movement of nutrients bound to inorganic and organic soil particles are the main sources of nitrogen and phosphorus in surface water runoff. Industrial effluents entering Princess Royal Harbour also contain significant concentrations of nutrients. Groundwater may contain significant concentrations of pollutants, including nutrients, derived from agricultural fertilizers, rubbish tip and septic tank leachates.

Estimates of the total nutrient inputs to Princess Royal Harbour for 1980, 1988 and 1989 are shown in Figure 5.4.

The total nitrogen inputs increased from 51 to 66 tonnes between 1980 and 1988. The nitrogen load in 1989 is estimated to be around 70 tonnes. In contrast, phosphorus loads have decreased markedly since the early 1980s (Figure 5.4). Total phosphorus inputs to the harbour dropped from around 43 tonnes in 1980 to 28.7 tonnes in 1988. Further decreases are anticipated in 1989 with an estimated load of around 20 tonnes being discharged to Princess Royal Harbour. In the early 1980s rural runoff and groundwater from the western end of the harbour contributed around 80% of the total P entering the harbour. Much of this input was probably derived from fertilizer washed from CSBP's superphosphate works.

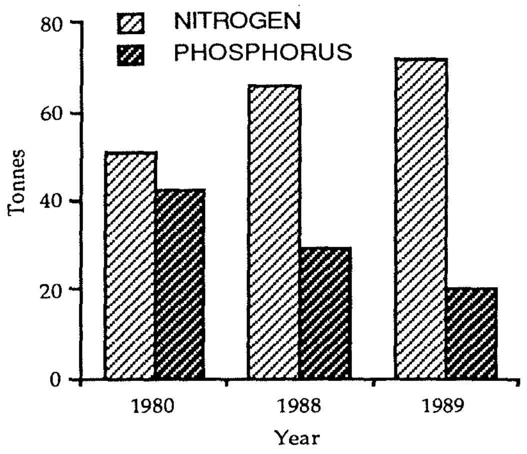


Figure 5.4 Total input of nitrogen and phosphorus to Princess Royal Harbour in 1980, 1988 and 1989. (Loads for 1989 are based on actual loadings to August and projected loadings for the rest of the year).

The survey of nutrient loadings into Princess Royal Harbour in 1988 identified three input types. Pollutants enter the harbour by direct discharge via outfalls, in surface runoff and through the groundwater. Nutrient inputs from direct discharges and surface runoff were measured accurately but groundwater inputs were particularly difficult to estimate due to limited data being available and, as such, the results should be treated with some caution. Nevertheless these estimates provide some idea of the relative nutrient contributions from these sources.

Nitrogen

The input of nitrogen to Princess Royal Harbour in 1988 from all major known sources is shown in Figure 5.5.

In 1988, 54% of the N input was derived from industry and 31% from rural sources including rural groundwater. Community sources, including domestic wastewater, contributed about 15 %. The largest single industrial contributor of nitrogen to the harbour in 1988 was Metro Meats. The industrial N input also included 10 tonnes of runoff that was discharged into Princess Royal Harbour from the Munster Hill drain, the majority of which was runoff from CSBP's industrial estate, and around 3 tonnes via the groundwater from the same source. Rural inputs of nitrogen contributed over 20 tonnes of nitrogen to the harbour in 1988, the majority entering in surface runoff.

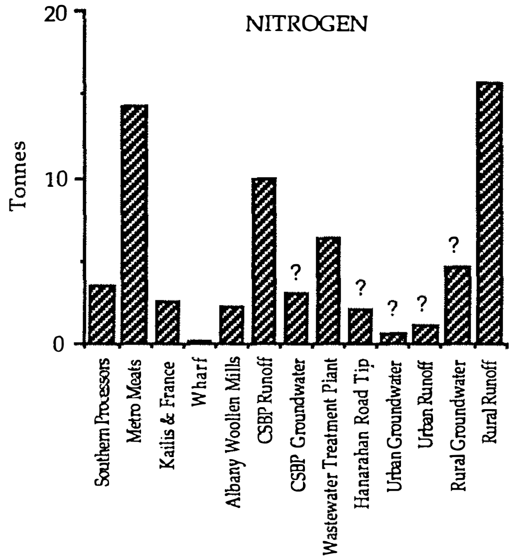


Figure 5.5 Inputs of nitrogen to Princess Royal Harbour in 1988. (?= estimates)

Phosphorus

Phosphorus loads into Princess Royal Harbour in 1988 from the major known sources are shown in Figure 5.6.

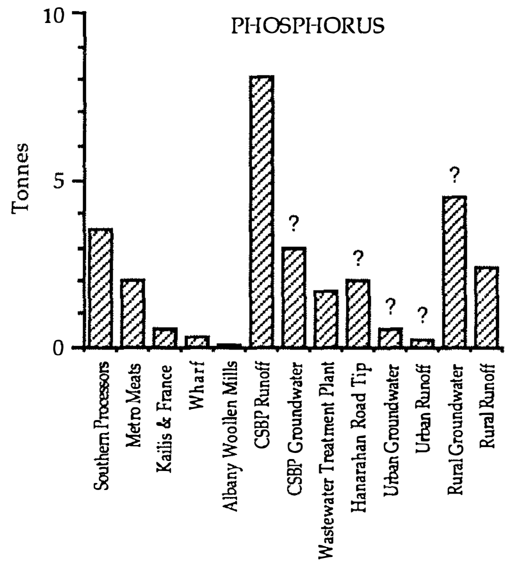


Figure 5.6 Inputs of phosphorus to Princess Royal Harbour in 1988. (?= estimates)

In 1988 industrial, rural and community sources (including domestic wastewater) contributed 61, 24 and 15% respectively of the total phosphorus input to Princess Royal Harbour. Of the industrial inputs, CSBP was the main contributor, with about 8 tonnes of P being discharged in runoff from CSBP's industrial estate via the Munster Hill drain, and an estimated 3 tonnes through the groundwater from the same source. Other major industrial sources of P included Southern Processors (3.5 tonnes) and Metro Meats (2.0 tonnes). Rural sources contributed about 7 tonnes of P in total with 2.4 tonnes entering as surface runoff. Domestic wastewater contributed 1.6 tonnes and the estimate of P input to Princess Royal Harbour from the Hanrahan Road rubbish tip was about 2 tonnes.

The load of phosphorus into Princess Royal Harbour in 1989 was estimated to be about 20 tonnes (Figure 5.4), a significant decrease from the 28.7 tonnes of 1988. This reduction, not yet verified by EPA monitoring, was mainly due to less P leaving CSBP's industrial estate in surface runoff, and was largely the result of improved management practices during the preparation and handling of fertilizers around the works area and from diverting a large proportion of surface runoff through lime-dosing ponds. There has also been a significant reduction in the amount of DAP spilled during fertilizer unloading at the wharf.

Pesticides and heavy metals

Samples of urban and rural runoff and various industrial effluents were analysed for heavy metals and pesticides in 1988. There was considerable variation in the concentrations of various heavy metals and pesticides found in these waste streams and, in some instances, elevated concentrations were recorded. Since then, the Albany Woollen Mills has ceased using chrome-black dye and a zinc-based bleaching agent, substantially reducing the minor loading of these metals into the harbour.

Heavy metals in urban runoff originate from lead in vehicle exhausts, trace metals in rubber tyres, organic matter to which they are attached and as dust fallout. Analyses of urban runoff indicated elevated concentrations of metals in the York Street drain during initial drainflows after the first major rains in 1988.

Elevated concentrations of dieldrin and other organochlorine pesticides were present in initial urban drain flows and in some industrial effluents. Concentrations of these compounds in the effluent streams were well below human health criteria but occasionally exceeded the criteria recommended for the maintenance of aquatic life (Anonymous, 1981). However, on entering the harbour, these pollutants would be diluted to concentrations well below this level. The elevated pesticide concentrations in urban runoff are likely to have leached from residues in garden soil treated with pesticides (historical garden usage) or from disposal of waste pesticide into urban drains. Surface applications of organochlorine pesticides are now banned in Western Australia.

Instances of elevated concentrations of various organochlorine pesticides also occurred in the effluents of the Albany Woollen Mills and Southern Processors. The Woollen Mills now ensures that organochlorine pesticides are not used for mothproofing wool imported from countries where these pesticides are still in common use. The residual organochlorine pesticides in Southern Processors effluent are associated with soil washed from potatoes and, as these chemicals are now banned for agricultural use, a gradual decrease in background soil pesticide levels will occur.

Preliminary tests were also carried out to assess whether pesticides had entered the food chain. Shellfish accumulate organochlorine pesticides in fatty tissues when exposed to these chemicals, thus providing an indication of recent water quality history. Mussels were collected from within the mixing zones of both Albany Woollen Mills' and Southern Processors' effluents, that is, where the potential for contamination was the highest. The levels of organochlorine pesticides in the mussel tissues from these locations were well below human health criteria on all occasions indicating a low level of contamination of these species.

The current loadings of heavy metals and pesticides into Princess Royal Harbour are very low and are not considered to be environmentally significant.

5.2.4 Implications for management

This section discusses some of the management options available for reducing pollutant loads into Princess Royal Harbour.

Industries

Continued discharge into Princess Royal Harbour is only viable if there is a significant improvement in the quality of all effluents in order to achieve acceptable long-term pollutant loads.

On-site effluent management involving relatively low-cost, low-technology pond-based treatment is not considered appropriate for industries discharging directly into the harbour because of the lack of available land for effluent ponds, and because of the likelihood of increased odour generation associated with these ponds. This is particularly relevant to industries like Metro Meats which produce organic-rich effluents with high solids, BODs and oils & greases which would require extensive areas of effluent ponds.

CSBP is currently reviewing management practices, with the intention of further reducing the volume and nutrient content of runoff leaving CSBP's superphosphate works. For example, conversion of existing on-site pastures to some form of tree plantation may result in a reduction in the volume and nutrient content of surface runoff leaving the site.

In the long-term, if new treatment technologies that do not require large amounts of space are not practicable, some form of total or partial diversion of the effluents away from the harbour will be necessary.

Urban runoff

Although the current input of pollutants from urban runoff is relatively small compared to the total pollutant loading into Princess Royal Harbour, the relative contribution from this source will increase in importance as other inputs are reduced. Local authorities should investigate ways of reducing the volume, and improving the quality of urban runoff by intercepting existing inputs and by educational programs to promote improved usage of these pollutants. Managed detention ponds, for example, are highly successful at reducing the concentrations of solids, nutrients, metals and pesticides in urban runoff.

Rural runoff

Catchment management options such as soil nutrient testing to optimise fertilizer application rates, and tree plantations currently being implemented in the Peel-Harvey and Oyster Harbour catchments may be appropriate for the rural catchments drained by the Upper Robinson Estate drain and those areas to the south of Princess Royal Harbour.

Groundwater

Increased monitoring of the leachates leaving the Hanrahan Road tip site is required before management plans to reduce pollutant loads from this source can be formulated. The location of the tip may not be appropriate given the current degraded state of the harbour and the likely movement of leachates from the site through time as soil adsorption (binding) capacity becomes exhausted. The movement of nutrients from septic tanks in close proximity to the harbour is not considered to be significant to date, but this form of domestic effluent disposal close to the harbour is not acceptable in the long-term because of likely exhaustion of soil nutrient adsorption capacities.

In summary, industrial wastes currently entering Princess Royal Harbour are largely non-toxic, but are biologically active because of their nutrient loads and high levels of organic material. Nutrient loads entering the harbour in surface runoff have been reduced considerably in recent times, largely as a result of reductions in surface runoff from CSBP's industrial estate. Reductions in the nutrients washed off agricultural lands in the catchment of Princess Royal Harbour are necessary to significantly reduce this source of pollutants. Groundwater nutrient inputs to the harbour is not well quantified. Extensive groundwater surveys are required before management strategies can be formulated and implemented to reduce these inputs.

5.3 Phosphorus and nitrogen loads into Oyster Harbour

Phosphorus and nitrogen are essential for plant growth, both in terrestrial and aquatic environments. An over supply of nutrients in an aquatic environment can cause excessive plant growth (eutrophication) that may lead to beach fouling, obnoxious odours, smothering and loss of bottom-dwelling plants, deoxygenation of the water column, fish deaths and human health risks. These symptoms are becoming all too common in the estuaries and waterways of the south-west of Western Australia (Table 5.2), and are primarily caused by the leaching of phosphorus from farm applications of phosphatic fertilizers (superphosphate) and point sources of nutrients (eg. piggeries, dairies, abattoirs, sheepholding yards, cattle feedlots, poultry farms, industries).

Estuary	Symptoms of nutrient enrichment
Peel Inlet	Excessive macroalgal growth with limited green and blue-green algal blooms.
Harvey Estuary	Dense green and blue-green algal blooms.
Princess Royal Harbour	Excessive macroalgal growth with losses of seagrass.
Oyster Harbour	Excessive macroalgal and epiphytic growth with losses of seagrasses.
Pallinup Estuary	Excessive green algal blooms and associated fish deaths due to deoxygenation
Wilson Inlet	Excessive seagrass and epiphytic algal growth.
Leschenault Inlet	Excessive macroalgal growth
Swan Estuary	Excessive macroalgal growth, limited microalgal blooms.
Vasse Lagoon	Green and blue-green algal blooms and fish deaths caused by deoxygenation of the water
Wonnerup Lagoon	Green and blue-green algal blooms.

Table 5.2 Summary of the trophic symptoms of some south-west Western Australian estuaries.

Phosphorus, not nitrogen, is regarded as the critical element limiting plant growth in Western Australian estuaries. This is because nitrogen-fixing blue-green algae have the ability to assimilate atmospheric nitrogen for growth and, therefore, are not limited by insufficient water column concentrations of nitrogen. Potential management options must therefore address the sources of phosphorus inputs to Oyster Harbour.

To achieve this objective an investigation was initiated to:

(i) determine the load of nutrients to Oyster Harbour, in order to assess the trophic status of the waterbody;

(ii) determine the relative contributions of the various land uses within the catchment of Oyster Harbour to the total nutrient load and;

(iii) provide information in order to formulate management strategies to reduce nutrient losses from the catchment of Oyster Harbour.

5.3.1 Riverine flow and concentration monitoring

Records of gauged flows exist for the Kalgan River (see Figure 7.1) for the period 1976-1988. The other rivers and creeks draining into Oyster Harbour have only been gauged for the duration of this investigation (1987-1988). As a result, total phosphorus and nitrogen loads into Oyster Harbour from riverine input are only available for this period. Flow monitoring of the Kalgan River began in 1976. In the two years of this study, the minimum (1987) and maximum (1988) runoff years were recorded (Figure 5.7). This has provided some insight into the variation in the annual nutrient loads into Oyster Harbour.

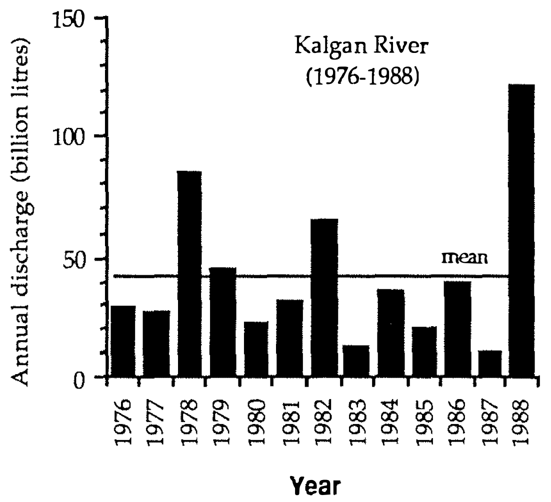


Figure 5.7 Long-term discharge for the Kalgan River (Note: 1987 and 1988 are the lowest and highest flow years on record).

5.3.2 Riverine nutrient inputs

The large variation between the 1987 and 1988 annual streamflows are reflected in the corresponding nutrient loads into Oyster Harbour for this period (Figure 5.8). For example, in 1987 less than 5 tonnes of total phosphorus entered Oyster Harbour whereas in 1988, the phosphorus loading was about 70 tonnes. These data are consistent with the general relationship that exists between annual discharge volume and annual total phosphorus load for the large riverine systems of the south-west of Western Australia and suggest that mean annual phosphorus loading to Oyster Harbour is approximately 30 tonnes. The mean annual nitrogen load is approximately 330 tonnes.

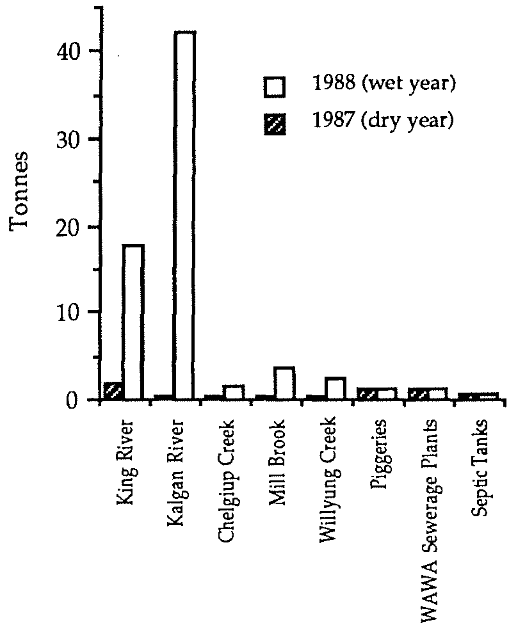


Figure 5.8 Comparison of annual phosphorus load for Oyster Harbour in a below average rainfall (dry) year (1987) and an above average rainfall (wet) year (1988).

Annual nutrient loads into Oyster Harbour are highly variable, mainly as a result of the influence of the Kalgan River. Under most conditions the Kalgan River has low mean nutrient concentrations (e.g. about 0.05 mg/L for phosphorus). However, under certain flood conditions, the nutrient concentrations can escalate to extremely high levels (Figure 5.9).

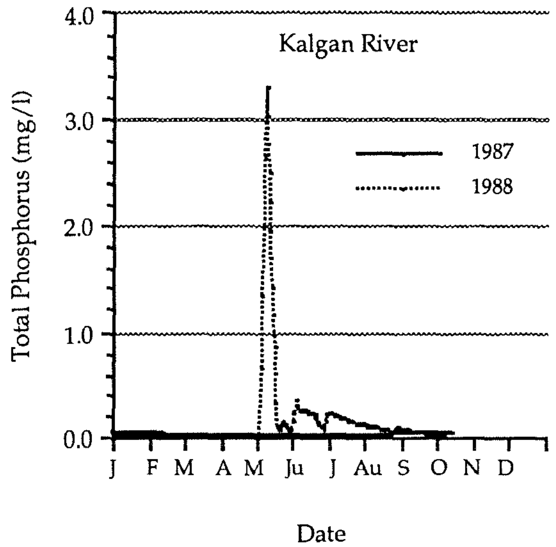


Figure 5.9 Abrupt change in the phosphorus concentration of the Kalgan River due to the break of winter ('first flush' effect).

This is the result of runoff from the large inland portion of the Kalgan catchment and the associated first flush of nutrients, characteristic of the break of winter. Such an event was observed on May 4-6 1988. Although the runoff from this period was only 5% of the annual Kalgan River discharge, 42% of the total phosphorus annual load from this river in 1988 was discharged into Oyster Harbour during this period (Figure 5.10). In contrast, a second, larger flood that occurred from June 25-29 (about a 1 in 30-year flood), yielded 22% of the annual Kalgan River discharge but only 11% of the total annual phosphorus load into Oyster Harbour. These events emphasize the significance the first flush has on the total annual phosphorus load to the harbour.

Large volumes of inland runoff did not occur in the catchment of the Kalgan River in 1987 (the driest year on record) and as a result, a discernible first flush did not occur (Figure 5.9). This partly explains the markedly reduced nutrient loads in that year.

In contrast to the highly variable flow of the Kalgan River, the King River, and the smaller tributaries, provide a more consistent input of freshwater to Oyster Harbour, due primarily to their smaller catchment size and the higher and more reliable annual rainfall that occurs close to the coast.

The optimum molecular N:P ratio for plant growth is in the range 9:1 to 15:1. Oyster Harbour receives an adequate and reasonably constant N:P input ratio of about 11:1. In addition to the ratio of nitrogen to phosphorus, plants also require the nutrients to be in sufficient concentration for growth to occur. Flushing, both riverine and tidal, affects the nutrient concentrations in the water column and is the key element to understanding the trophic status of Oyster Harbour (D'Adamo, in preparation).

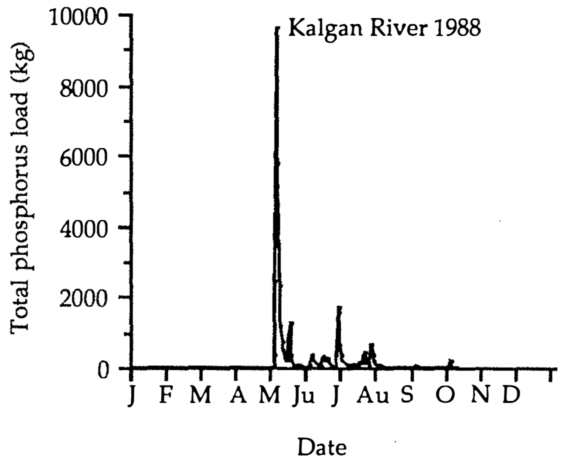
5.3.4 Urban sources of phosphorus and nitrogen

The urban nutrient input to Oyster Harbour from septic tanks, represents a relatively minor proportion of the total annual nutrient load except in years of low rainfall when river discharge is low (Figure 5.8).

The current ecological impact of nutrient loadings into Oyster Harbour from septic-tank leachate is unknown. However, additional use of septic tanks in close proximity to the harbour is likely to exacerbate the problem of nutrient enrichment as the phosphorus adsorption capacity of the soils become exhausted.

5.3.5 Point sources of nutrients

Dairies and piggeries are currently being assessed in more detail as potential nutrient pollution sources. Early indications suggest that these sources contribute only relatively minor amounts to the total nutrient load currently entering Oyster Harbour (Figure 5.8).



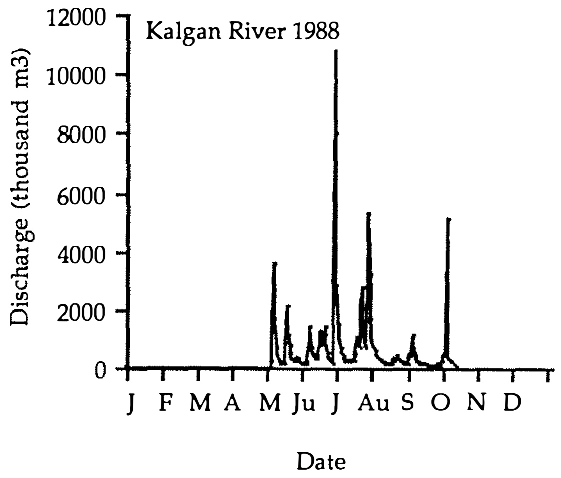


Figure 5.10 Relationship between the timing of phosphorus loads and river discharge.

5.3.6 Past nutrient loads

From the relationship between river discharge and nutrient loading (Figure 5.11), the exceptionally severe flood of January 1982 (about a 1 in 90-year event) is likely to have discharged high quantities of nutrients into the harbour and possibly had a considerable influence on the current trophic status of Oyster Harbour.

The phosphorus nutrient load from this event has been estimated conservatively at about 17 tonnes (based on the 1988 annual flow weighted mean total phosphorus concentration[1]). Although this is not a large amount on an annual basis, the tonnage is unusual for January (mean phosphorus loading in January between 1976-1988, excluding 1982, is estimated at 100 kg). In addition, most of the phosphorus was discharged into the harbour over three days and at a time of the year when aquatic plant productivity is high, thereby facilitating uptake of nutrients from the water column and retention within the harbour.

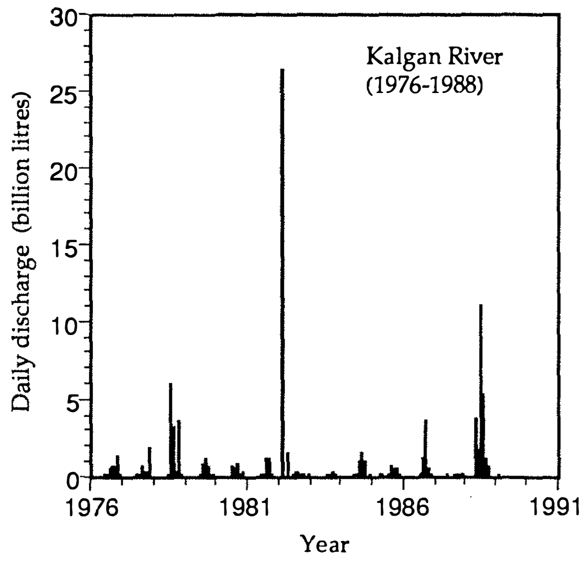


Figure 5.11 Past discharge rates of the Kalgan River. Note the severe flood of January 1982.

5.3.7 Conclusions and Summary

The findings of this study are summarized as follows:

- Under average-to-high runoff conditions the major nutrient inputs to Oyster Harbour are riverine in origin, and stem from the broad-scale use of phosphatic fertilizers and leguminous pastures within the catchment.

- The majority of the phosphorus load into Oyster Harbour is carried by runoff associated with the break of the season ('first flush'). About 40% of the total annual phosphorus load entered the harbour by this mechanism in 1988.

- About 85% of the total phosphorus load and 50% of the total nitrogen load into Oyster Harbour is soluble and in a form readily available for plant growth.

- The total nitrogen and total phosphorus loads into Oyster Harbour are in the ratio of about 11:1, a suitable ratio to stimulate aquatic plant growth.

- Urban nutrient sources such as septic tanks and WAWA package treatment plants are considered to contribute a significant proportion of the annual nutrient load into Oyster Harbour in below average rainfall years. However, the effect of these sources of pollution on the trophic status of Oyster Harbour is poorly understood.

[1] The actual tonnage is expected to be higher than 17 tonnes since the nutrient concentrations from cyclonic summer runoff is usually elevated above the seasonal average. The tonnage may well be about 150 tonnes, based on the total phosphorus concentrations observed during the June 26th 1988 flood (3.3 mg/l).

Chapter 6

Water Circulation

6.1 Princess Royal Harbour

Princess Royal Harbour is a large (28.8 km^2), almost land-locked marine embayment (see Figure 1.1), linked to King George Sound and the Southern Ocean by a narrow, navigable opening. The harbour comprises a deep basin, bordered by an extensive, shallow margin off its south-west shore. Its surrounding drainage catchment area is small, and freshwater inputs from urban and agricultural drainage are minor (by comparison with nearby Oyster Harbour).

The harbour has an established port, and is also used for fishing, recreation, and as a receiving body for agricultural and urban runoff, and for industrial wastes. Pollutant wastes entering Princess Royal Harbour have resulted in a problem of widespread loss of seagrass meadows, in toxic metal contamination of the harbour's food chain, and in objectionable visual and bacterial pollution in the vicinity of some effluent outfalls.

To manage the pollution problems of Princess Royal Harbour, it is necessary to understand its hydrodynamics. How rapidly are pollutants mixed down through the water column after release? How extensively do they spread around the harbour? How efficiently does incoming sea water mix with and replace harbour water? How readily are wastes flushed from the harbour?

A study program was initiated to address these questions, and a summary of the major findings is presented below. Further details will be available in the Technical Report by Mills and D'Adamo (in preparation).

6.1.1 Objectives and scope

The objectives of this study were:

(i) to characterise water circulation and mixing within, and immediately outside Princess Royal Harbour;

(ii) to estimate water exchange between Princess Royal Harbour and King George Sound, and;

(iii) to use this knowledge to understand the dispersion and flushing of pollutant materials released into these waters.

The study included the following tasks:

- field measurement of the movement and density-layering of water within and outside Princess Royal Harbour, under a range of tidal and wind conditions. Free-moving drogues were tracked for periods of 6 to 36 hours to gauge the speed and patterns of water movement. Vertical profiles of salinity and temperature were measured and used in conjunction with other data (Hillman *et al.*, 1989; Atkins *et al.*, 1980) to determine the density layering of the water;

- computer simulation of water circulation patterns in Princess Royal Harbour, induced by wind and tidal forcing and;

- computer simulation of pollutant transport within, and flushing from Princess Royal Harbour.

6.1.2 Water circulation and mixing within, and immediately outside Princess Royal Harbour

Primary forces driving water movement

Tide and wind are the primary forces driving water movement in Princess Royal Harbour.

The Bureau of Meteorology has analysed surface wind speed and direction, observations having been taken twice daily (0900 and 1500h) at the Albany airport for 19 years.

Prevailing wind direction varies throughout the year. From December to the end of March, winds are generally easterly in the morning, swinging to south-easterly in the afternoon. From April to August, the winds typically move from north-westerly in the morning to westerly in the afternoon. From September to November, morning westerlies typically give way to afternoon south-westerlies.

Moderate wind speeds are experienced throughout the year, typically about 3-5ms^{-1} in the morning, and increasing to typical speeds of 5-7ms^{-1} in the afternoon. Autumn is the season with the weakest winds and most frequent calms. High wind speeds (greater than 12.5ms^{-1} or 25 knots) may occur, but only for a small proportion of the total time. These high-speed winds are often from the south-west. Wind speeds may be higher at the coast than at the airport.

The astronomical tide at Albany displays diurnal (daily) and semi-diurnal (twice daily) variations in water level, the former being stronger. The tidal range rarely exceeds 1.1m, and varies with periods of approximately 14 days. Water levels are also influenced by the passage of weather systems.

Princess Royal Harbour is linked by a relatively short, narrow channel to King George Sound and the ocean. Sea-level variations of periods longer than a few hours are readily transmitted into Princess Royal Harbour, and the water-level ranges within and outside the harbour are virtually identical.

Water Structure in Princess Royal Harbour

Freshwater inputs to Princess Royal Harbour are low. The catchment areas draining into Princess Royal Harbour are only about three times the area of Princess Royal Harbour itself. Salinity and temperature data, from this study, and from others (Atkins *et al.*, 1980; Hillman *et al.*, in preparation) indicate that the waters in the main basin of Princess Royal Harbour are near marine salinity, and generally either well-mixed vertically or very weakly stratified. Theory indicates that for a waterbody of the size and weak stratification generally exhibited by Princess Royal Harbour, moderate winds are able to induce vertical mixing over most of the harbour area within several hours. Near-shore salinity depressions of several parts per thousand have been recorded on the very shallow western margin in winter, during periods of maximum freshwater runoff (Atkins *et al.*, 1980). Under these conditions, horizontal density differences may be important in driving water exchange between the shallows and the basin.

Wind-driven circulation in Princess Royal Harbour

The action of wind on the harbour is important in forcing horizontal water movement. Wind-driven currents vary with depth. Surface water generally moves downwind at about 3% of the windspeed. Floating material and slicks are influenced by this movement. Below the surface, water circulates about Princess Royal Harbour as horizontal gyres, which are controlled by the speed and direction of the wind, and the alignment and depth of the harbour. These gyres (or circulating current patterns) have a downwind component in shallow water and an upwind component in deeper water. The non-uniform, but relatively simple bathymetry, and the alignment of Princess Royal Harbour with prevailing wind directions, favours the generation of wind-driven currents.

Steady west-to-north winds generate a major anti-clockwise circulation gyre which covers much of the harbour. East-to-south winds generate predominantly clockwise circulation. Under south-west winds, two major gyres are established (one clockwise in the north-west end of Princess Royal Harbour, and the other anticlockwise in the south-east end of the harbour). For winds swinging within these respective direction ranges, the water movements will generally be consistent and cumulative. For winds swinging between these direction ranges, currents may be decelerated or reversed, and net circulation limited.

Tidal-induced circulation

The water volume stored in Princess Royal Harbour at mean water level is about 90 million m^3. Water volumes of up to 30 million m^3 may enter or leave Princess Royal Harbour within 8-16 hours on rising or falling tides, respectively. The water passes through the narrow Princess Royal Harbour channel with current speeds up to $0.5 ms^{-1}$, much greater than the average tidal current speeds across Princess Royal Harbour and King George Sound. The momentum imparted to the water as it flows through this channel is an important factor in determining water exchange between Princess Royal Harbour and King George Sound.

In the absence of winds, and during mean-to-spring flood tides, water from King George Sound is drawn in radially from a distance of up to 1.5km outside the entrance channel, passes rapidly through the channel, initially shedding vortices into the harbour, and then jets narrowly (under its own momentum) a distance of up to 2.5km directly across Princess Royal Harbour, prior to undergoing clockwise circulation during a directional reversal on the ebb tide. This promotes significant horizontal mixing over that area of Princess Royal Harbour where water depths are greater than 5m. Elsewhere in the harbour, tidal current speeds are very low, except across the shallow sandy sill at the outer edge of the western margin.

Likewise, on the ebb tide, water in Princess Royal Harbour converges radially toward the entrance channel from a distance of up to 1.8km, accelerates through the channel, and then passes into King George Sound. Early in the ebb tide, the flow fans out broadly into King George Sound. As the water level falls more rapidly, outward-directed momentum increases, and vortices (typically 500-1000m across) are shed into King George Sound on both sides of the channel axis (but more consistently and intensely on the north side). In particular, such vortices have been observed adjacent to the King Point wastewater treatment plant outfall. Subsequently a narrow tidal jet streams out of the entrance channel, across King George Sound, for a distance of at least 2-3km. This body of water continues to move across King George Sound for several hours after low water, while water closer to the entrance channel again starts to converge on the harbour.

Some of the water which formed side vortices in King George Sound on the ebb tide remains sufficiently close to the harbour channel to re-enter Princess Royal Harbour on the subsequent flood tide. Since these vortices have been observed to form in the vicinity of the King Point wastewater treatment plant outfall, it is likely some of the effluent from this outfall enters Princess Royal Harbour.

The tidal rise and fall of water levels within and outside Princess Royal Harbour are very similar. Hence, a widening or deepening of the existing entrance channel would not result in an increase of flow through the channel (because the tidal capacity of the harbour would remain unchanged), and the speed of water flowing through the channel would decrease. This may adversely affect the penetration of the jet flow on either side of the entrance channel, and the net amount of exchange between these two waterbodies.

Circulation under combined wind and tidal conditions

It takes only very moderate winds to modify the purely tidal circulation pattern within Princess Royal Harbour. For example, under north-to-west winds, the tidal jet streaming into the harbour on the flood tide is deflected to the right (along the length of the wharf area) as it becomes entrained into the anticlockwise wind-driven circulation (Figure 6.1a). A portion of this newly introduced water penetrates so far into Princess Royal Harbour that it is retained there during the subsequent ebb tide; water leaving the harbour is derived predominantly from the southern side of the entrance (Figure 6.1b). For east-to-south winds, the flooding tidal jet is diverted southward, and much of the ebbing water is derived from in front of the wharf. The combined influence of wind and tide on the water movements is of great importance to the flushing of the harbour.

Likewise wind-driven circulation in King George Sound can modify the tidal jet flows emanating from Princess Royal Harbour into the sound. From field measurements it appears that south-west to south-south-east, or north-north-west to north-east winds are the most efficient in driving water circulation in the western portion of King George Sound. These directions are approximately parallel to the general coastal alignment of this part of the sound. South-west to south-south-east winds induce marked water flow to the north (3-4km excursions observed), through Middleton Bay. North-north-west to north-east winds induce a southward flow of water.

Fate of Effluents

The dispersion of effluent discharged to Princess Royal Harbour is determined by its characteristics (eg buoyant, dissolved, settling) and its dilution and transport by the harbour waters.

Buoyant pollutant materials (eg fat, oil, grease) remain at or near the water surface and are affected by water movement at that level. Such materials generally move downwind at about 3% of the wind speed, unless caught in strong tidal currents, for example in the entrance channel on peak flood or ebb tides.

Dissolved or fine particulate pollutants in suspension are more uniformly distributed throughout the water depth, reflecting the ability of the wind to mix the water vertically. The movement of these dissolved and suspended materials is predominantly influenced by the tidal currents and the wind-driven horizontal gyres. For example, in deep water, off the wharf area, floatable matter is driven in a south-east direction (downwind) under strong north-west winds, and much of the dissolved and suspended matter at greater depth is transported to the north-west as part of the return flow in an anticlockwise gyre.

Much of the dissolved/suspended effluent discharged to Princess Royal Harbour emanates from industrial outfalls on the northern shore or the Robinson Estate drain to the north-west of the harbour. In winter, under north-west to west winds, these materials tend to be transported about the harbour in an anticlockwise direction, moving about the south-west side of the harbour, prior to circulating back toward the harbour entrance. In summer, under east to south-east winds, these materials move clockwise along the northern shore.

Flushing times for Princess Royal Harbour

The flushing time for Princess Royal Harbour can be considered in terms of a mass of dissolved/suspended material dumped into Princess Royal Harbour at a given time, and defined as the time required for 90% of this material to be lost from the harbour through flushing processes. For this purpose it is assumed that material is influenced only by hydrodynamic processes.

A pollutant-transport model was employed to understand time scales for flushing dissolved/suspended pollutants from Princess Royal Harbour.

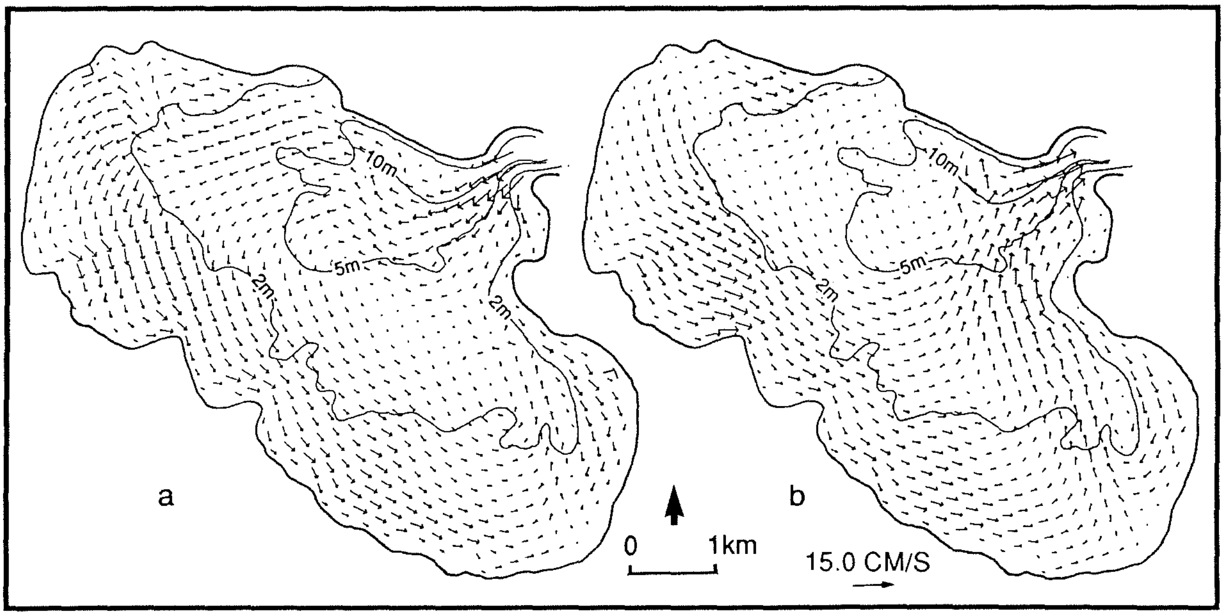


Figure 6.1 Computer-simulated circulation patterns in Princess Royal Harbour for a wind of approximately 7-8ms^{-1} (15 knots) from the north west. Water current speeds and directions are shown by the lengths and directions of the arrows.
a) flood tide; b) ebb tide.

This computer model simulates the mean movement and spreading of pollutant clouds in Princess Royal Harbour as they are influenced by water circulation and the dispersion processes. The model also accounts for loss of pollutant from near the harbour mouth, due to flushing on the ebb tide.

The computer simulations were run for simplified conditions of constant wind and a repeating tidal range of 1m, yielding 90% flushing times of about 10 days. However, in reality: (a) winds are variable in direction and speed, and the resultant water circulation in Princess Royal Harbour less coherent than for constant wind; (b) tidal range varies, and is usually less than 1m, and (c) on each flood tide there is some re-entry of water and material which left the harbour on the previous ebb tide. Because of these factors, a typical 90% flushing time of about 20 days is estimated.

Mixing, circulation, nutrient exposure to plants and algae mobility

The waters of Princess Royal Harbour are frequently well-mixed vertically by the action of wind. This suggests that dissolved and suspended nutrients introduced to the water column are also well-mixed vertically, and that these nutrients frequently contact the benthic plant and animal communities.

Bottom wave orbital speeds were calculated to assess the importance of these motions to resuspension of sediments and mobilisation of benthic algae. For typical moderate winds ($7ms^{-1}$) and maximum wind fetch, the wave orbital velocity at the bottom (BOV) in water depths of 2.8m is small ($0.04ms^{-1}$), and unlikely to be able to mobilise benthic algae. However, for gale force winds ($20ms^{-1}$), the BOV increases dramatically ($0.38ms^{-1}$), and creates conditions that are probably energetic enough to move benthic algae. For the same range of wind conditions, and in a water depth of 4.0m, the BOVs are considerably reduced ($0.01ms^{-1}$ and $0.23ms^{-1}$, respectively). It is possible that wind speeds, and bottom orbital velocities are rarely strong enough to mobilise macroalgae at depths of 4m or more and that the processes of algal decay outstrip the processes of accumulation, whereas accumulation can be much more active at shallower depths.

It should also be noted that some of the strongest winds come from the south-west, and drive circulation patterns in Princess Royal Harbour which favour movement of suspended benthic algae towards the north-west and south-east ends of the Princess Royal Harbour basin, where the heaviest algal accumulations have been observed (see Section 4.1.2). These current speeds are typically in the order of $0.16ms^{-1}$.

Role of Seagrass

Water movement is retarded within seagrass meadows, therefore providing a depositional environment for fine organic particles. Nevertheless, even in very shallow water, appreciable currents can still be generated at the level of the seagrass canopy, and above fully-submerged meadows.

6.1.3 Conclusions

Mixing and transport

The waters of Princess Royal Harbour are frequently well-mixed vertically by the action of wind. Dissolved or suspended pollutants become well-mixed vertically within about 1km of the discharge point. The pollutants therefore have frequent contact with the bottom-dwelling plants and animals.

Horizontal circulation induced by wind (and to a lesser extent tide and density forces) promotes broad horizontal mixing of effluents throughout Princess Royal Harbour.

The transport of dissolved/suspended materials is mainly influenced by wind-driven circulation gyres (downwind in shallow water and upwind in deeper water), and by tidal currents closer to the mouth. Floatable material or surface slicks move downwind, except when caught in strong tidal currents, for example, in the entrance channel.

Current speeds and wave-induced water speeds at the harbour bottom are generally weak in locations where the benthic algae are observed to accumulate.

Seagrass meadows provide resistance to flow, and dissipate wave energy, providing a depositional environment, although water movement at the canopy may be significant.

Exchange and flushing

The combined water movements within Princess Royal Harbour due to wind and tide promote net water exchange between Princess Royal Harbour and King George Sound.

The time required to flush discharged pollutant from Princess Royal Harbour varies with location of the discharge and season. A typical 90% materials flushing time for Princess Royal Harbour is about 20 days.

Widening or deepening the existing entrance channel, or opening a new one, would not necessarily lead to greater flushing. Tidal range internal and external to Princess Royal Harbour is virtually identical; these measures would lessen the extent of the tidal jetting into Princess Royal Harbour and King George Sound, and possibly reduce the flushing.

Deepening (dredging) the harbour in areas of heaviest benthic algae accumulation (presently 2-5m depth) may also result in reduced flushing. A harbour with more uniform bathymetry would lead to a reduction in the strength of the wind-driven circulation, a weakening of horizontal mixing in the harbour, and possibly a reduction in the flushing capacity of the harbour.

The King Point treated sewage outfall is located within the influence of intake of water from King George Sound to Princess Royal Harbour on flood tide, for mean-to-spring tide ranges.

6.2 Oyster Harbour

Although seagrass loss is the major ecological problem in Princess Royal Harbour and Oyster Harbour, some of the mechanisms that have resulted in these losses appear to be quite different (Chapter 4). The harbours are physically dissimilar, mainly due to the difference in freshwater inputs. Substantial amounts of freshwater are discharged into Oyster Harbour, principally from the King and Kalgan Rivers, and as such Oyster Harbour is an estuary. In contrast, Princess Royal Harbour receives only minor freshwater inputs and is a marine embayment.

Freshwater is less dense than salt water and is therefore more buoyant. When freshwater flows into saltier water, a generally stable vertical grading, or stratification, of salinity exists through the water column with a surface layer of fresh water overlying a layer of saltier water. Stratification is a common physical characteristic of estuaries like Oyster Harbour. In contrast, Princess Royal Harbour, a marine embayment, receives only a comparatively small volume of freshwater and as a result the salinity of the water is always essentially marine (approximately 35 parts per thousand). The potential for stratification, therefore, is weaker and thus the system is generally well-mixed vertically.

This section of the report outlines the results of a study which was conducted in Oyster Harbour to determine the manner in which water circulates and mixes within the harbour. The characteristics of the exchange processes between Oyster Harbour and King George Sound were also investigated. These processes are important in understanding why the biological communities in Princess Royal Harbour and Oyster Harbour respond differently to similar long-term nutrient loadings.

The study was undertaken by the EPA, in collaboration with the Centre for Water Research, and the Australian Surveying and Land Information Group. Historical information of the water structure, local meteorology, river flows and current patterns were complemented by intensive field surveys conducted for this study. The complete details and results of the study are contained in an EPA Technical Series by D'Adamo (in preparation).

6.2.1 Objectives and Scope

The study had the following overall aims:

(i) to determine the extent and seasonality of stratification in Oyster Harbour;

(ii) to quantify the mixing potential of streamflow, tides, atmospheric heating and cooling, and winds in Oyster Harbour;

(iii) to determine internal circulation patterns in Oyster Harbour and;

(iv) to determine exchange characteristics between Oyster Harbour and King George Sound.

Most of the riverine discharge into Oyster Harbour occurs in winter. Other important mixing processes such as solar heating and cooling also display seasonal differences. Because of this seasonality, the circulation of Oyster Harbour in summer and winter is discussed separately.

6.2.2 Winter

Most of the leaching of nutrients and their subsequent transport into Oyster Harbour in surface water runoff occurs in response to the first major winter rains (see Figure 5.10). Hence, vertical mixing during this period will act as a primary control on nutrient availability and biotic uptake of a large proportion of Oyster Harbour's annual nutrient load.

During 'floods', buoyant river discharge flows over the denser marine water causing the harbour to be "capped" by a plume of outflowing brackish water less than 1m thick (Figure 6.2). The surface water flows rapidly over the marine water, the two waterbodies remain separated and the mixed layer between them is generally not greater than about 0.3m thick. For flood events of this type, the buoyant plume takes approximately 5 to 20 hours to traverse Oyster Harbour, a distance of approximately 5km. Opposing wind and tidal currents can extend this traverse time, depending on their strength and relative direction, by up to about 15 hours. Once through the mouth the surface plume propagates out into King George Sound as a buoyant frontal jet. Foam or slick lines in King George Sound mark the leading edge of this feature (Plate 1).

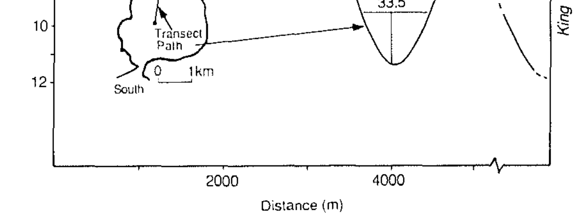


Figure 6.2 North-south cross-sectional contour plot of salinity stratification (in parts per thousand, ppt) during a common winter flood event on 20 July 1988.

In winter, winds are the dominant factor controlling the mixing of waters in Oyster Harbour. The potential of winds to break down a typical stratification event that occurs during these 'flood' flows is presented in Figure 6.3. Little wind mixing is caused by winds of less than $5ms^{-1}$. However, as winds become stronger and rise above $5ms^{-1}$, the rate of vertical mixing increases. For example, winds of approximately $10ms^{-1}$ could mix the buoyant flood plume to a depth of about 12m in just 15 hours.

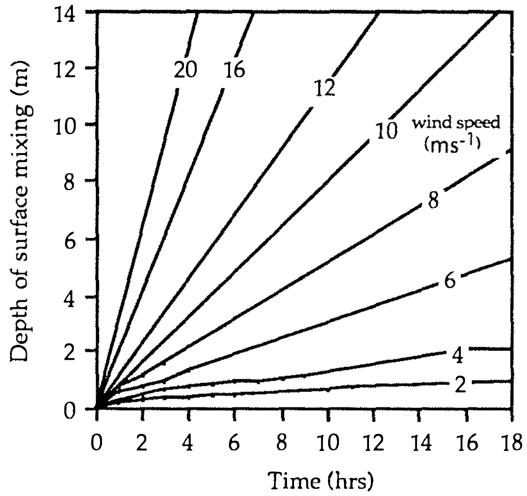


Figure 6.3 Theoretical curves of the depth of wind mixing down from the water surface, during 'flood' river flows into Oyster Harbour as a function of time for a wide range of wind speeds (ms^{-1}) blowing in the longest harbour direction.

Stronger winds are commonly associated with rainfall but subside in intensity as the event passes the region. Peak river discharge rates arrive at Oyster Harbour between 12 and 48 hours after heavy rainfall. Hence, the likelihood of strong winds persisting during the period of peak discharge is low. Furthermore, winds following rainfall periods sometimes blow from the northern quadrant and enhance the speed of the buoyant flow towards the mouth, thus reducing the surface plume's residence time and hence the time for winds to mix the plume down through the water column. These data indicate that complete vertical mixing of nutrient-rich flood waters after heavy rainfall events is likely to be infrequent.

Some areas around the periphery of Oyster Harbour are sheltered from winds and hence mix more slowly than the more exposed central regions. Consequently, wind mixing will be spatially patchy causing horizontal density gradients between adjacent regions which will then drive density currents of light waters at the surface over deeper, denser waters flowing in the opposite direction. This would occur rapidly when density differences between adjacent waterbodies is high and is an effective mechanism for redistributing water masses around Oyster Harbour, after a wind-mixing event.

LANDSAT satellite imagery, provided by the Department of Land Administration (Remote Sensing Application Centre) reveals the spatial variability of surface water temperatures that occur in Oyster Harbour. At night harbour waters cool, especially over the peripheral shallows. As a result temperature differences form between the shallows and the deeper central area of the harbour. This leads to density differences which could generate density-driven currents of up to .03-.05ms^{-1} between these two areas of the harbour.

6.2.3 Summer

Although river discharges into Oyster Harbour are generally low in summer, sufficient water flows in to provide a source of freshwater that stratifies Oyster Harbour. Marine water also intrudes into the harbour as a bottom front and is overlain by a surface front of this resident, less saline harbour water. This structure, is called a "salt-wedge".

The temperature structure of the water in Oyster Harbour closely parallels the salinity structure and together these parameters combine to produce a similarly structured density stratification. A typical example of the summer salinity structure of Oyster Harbour is presented in Figure 6.4.

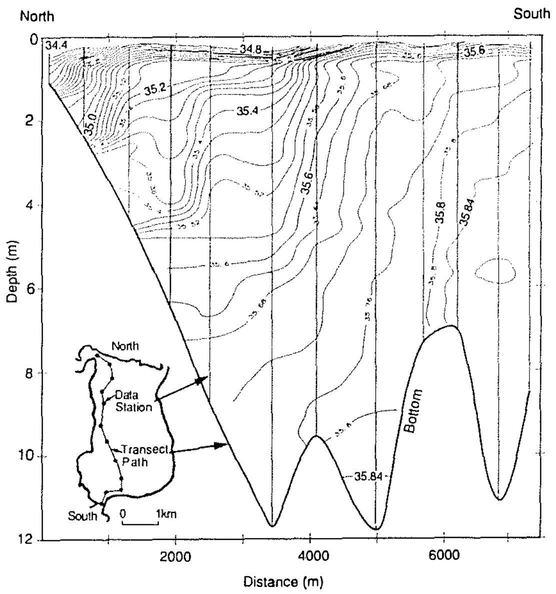


Figure 6.4 North-south cross-sectional contour plot of salinity stratification (in parts per thousand, ppt) during summer (February, 1988) showing a salt-wedge structure.

Tides, atmospheric heating and cooling, winds and density currents are also important to circulation and mixing in the harbour during summer and these are discussed in more detail below.

Tide and wind currents

Salinity and temperature measurements, in conjunction with the tracking of drifter drogues, revealed the cyclic nature of the salt-wedge dynamics in the lower harbour and entrance channel. The salt-wedge penetrated and retreated, through the harbour mouth, by up to 3km during respective spring flood or ebb tides. Mixing of waters by this process is minimal, except in the entrance channel where vertical mixing due to boundary turbulence can be vigorous, occurring up to 8m off the seabed.

The strongest tidal currents in Oyster Harbour, apart from near the entrance, occur in the deeper central basins of the harbour. Flows in the shallows are typically weaker and dominated more by wind rather than by tides. Wind-driven surface currents of .03-.05ms^{-1} have been recorded during wind events of 3-5ms^{-1}.

These results suggest that marine water from King George Sound does not generally penetrate into the upper part of Oyster Harbour by the action of tidal forcing alone.

Atmospheric heating and cooling

The temperature of the water in Oyster Harbour also fluctuates in response to diurnal heating and cooling, particularly in the shallows. As a result of this differential heating and cooling, the shallow waters around the periphery of the harbour become much warmer during the day and cooler at night than the waters of the deeper central basins. Consequently during the day, warmer, less dense water will tend to flow out to the central regions as surface currents while cooler more dense water in the deeper basins will flow into the shallows as bottom currents. These processes may reverse at night-time. The magnitude of these processes alone indicates that density currents could drive waters from the peripheral shallows into the central regions of the harbour in approximately 12 hours. While the circulation of Oyster Harbour is influenced by these density currents it is also influenced by the effects of wind and tide. Hence, the overall current patterns result from the combined effect of these three factors.

Wind mixing

A wide range of wind speeds and directions can occur in Oyster Harbour during summer, ranging from calms of less than 5ms^{-1} to sea-breezes and storms of greater than 10ms^{-1}.

During typically stratified summer conditions (such as in Figure 6.4), winds greater than about 5ms^{-1} will quickly begin to mix harbour waters. When winds reach 10ms^{-1} or more, complete mixing to the bottom can occur in 5 to 10 hours. Mixing will generally be strongest in the more exposed central regions of the harbour and weakest around the periphery and northern reaches because of sheltering by the surrounding hills. This differential mixing of harbour waters was observed in February 1989 during a strong storm when wind speeds exceeded 10ms^{-1} (Figure 6.5). Thus in summer, the waters of Oyster Harbour are well-mixed by strong sea-breezes and occasional storms.

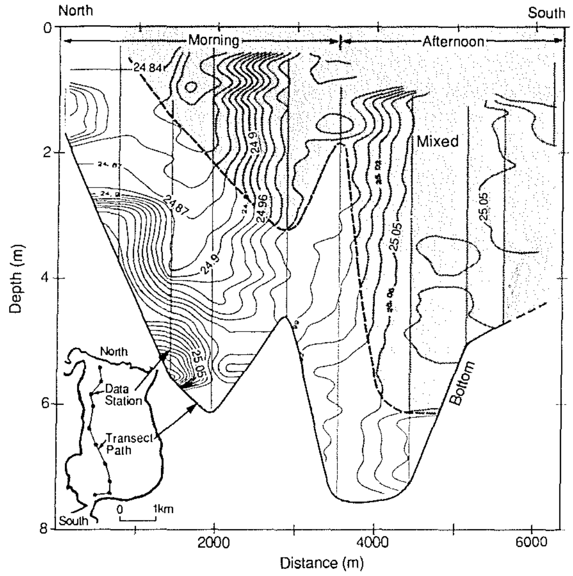


Figure 6.5 North-south cross-sectional contour plot of the density stratification (in kg per cubic metre above freshwater density) during a summer storm on 13 February 1989 where wind speeds exceeded 10ms^{-1}. The vertical density lines indicate a well-mixed region, highlighted by the shading.

Following a mixing event the waters of the harbour are generally vertically well-mixed but remain horizontally stratified. The more saline, denser waters reside in the half of the harbour closest to the harbour entrance. This water quickly slumps underneath the fresher, more buoyant waters of the upper half of the harbour closest to the river mouths. This density driven exchange can cause a re-forming of vertical stratification in the harbour within 5 to 10 hours after complete mixing. Tidal, wind and density currents, as described in the above sections, will then reassert their influence and dominate the circulation patterns once again.

Tidal trapping

Water can be trapped in interior embayments and side-arms of estuaries for extended periods of time. This occasionally occurs in the south-west corner of Oyster Harbour, just west of Green Island. Drifter paths in this region of the harbour indicate that rotating currents, or eddies, sometimes occur. However, little evidence of similar water entrapment was observed for the remainder of the harbour.

Groundwater

Groundwater enters the ocean and coastal embayments as sub-surface discharges along shorelines. Hence, groundwater could influence Oyster Harbour's ecological problems by adding freshwater which would facilitate the establishment of stratification in the harbour and hence influence circulation and flushing of pollutants. In addition, groundwater that has traversed subterranean areas with high pollutant loads (such as from septic tanks) can carry significant quantities of polluting materials to the waterbody in which it discharges.

Whilst these processes may be important, no quantitative information on groundwater inputs into Oyster Harbour were identified during this study and are not considered further.

Density currents and flushing

The above discussion indicates that water densities, current speed and direction, and mixing in Oyster Harbour are spatially heterogeneous. Mean salinity and temperature differences have also been shown to occur between Oyster Harbour and King George Sound. These differences result in density gradients between patches of water within Oyster Harbour and also between the harbour and King George Sound. Hence, there will be a tendency for density currents to transport water in the following manner:

(i) at night colder, heavier water will flow out from the shallows into the central harbour as bottom density currents;

(ii) during a sunny day warmer, lighter waters will flow out from the shallows as surface density currents into the central harbour and;

(iii) waters in the northern half of Oyster Harbour, that have been diluted with river discharges, will flow out into the lower harbour as surface density currents.

All of these three mechanisms could drive water from the periphery to the centre of the harbour in less than 12 hours. Furthermore, light winds (ie $<5 ms^{-1}$) will influence these transport patterns by imposing downwind surface current patterns. Once into the more exposed regions of the harbour, these introduced waters can be readily mixed to the bottom by stronger winds of $10ms^{-1}$ or more and then be transported into King George Sound by ebb tidal flows.

It is evident that flushing of waters to King George Sound during summer is a difficult process to model either conceptually or analytically. By assuming complete inner-harbour mixing of every flood inflow volume, an average flushing time of the order of 10 days is calculated. This would be the time taken for about 90% of the harbour's water to be replaced by sea-water from King George Sound by tidal flushing alone, assuming a typical maximum daily tidal range of approximately 0.3 to 1.2m.

However, the stratified nature of Oyster Harbour confirms that the assumption of a continually mixed harbour is not valid. The eventual flushing of water and pollutants from Oyster Harbour is strongly influenced by processes induced by density differences. The residual horizontal stratification of salinity and temperature between the Oyster Harbour and King George Sound would drive surface water masses of less than 1m thickness towards the mouth. It is estimated that this could drive water from the upper harbour out into King George Sound within 2 days during summer conditions. However, under certain conditions of wind and tide, water could reside in the shallow corners of the harbour for considerably longer. The deepest waters of the upper and lower basins within Oyster Harbour will have the longest residence times and could range from about 10 to 20 days.

6.2.4 Conclusions

Winter: River discharge traverses Oyster Harbour in times of less than about 2 days as a fresh-to-brackish surface layer of less than 1m thickness, and typically undergoes little mixing. Winds of $7ms^{-1}$ or more and occurring for more than 5 hours are required to appreciably mix this layer.

Once through Oyster Harbour the river discharge ejects well out into King George Sound as a surface buoyant front and this is an effective mechanism for nutrient export from the harbour.

Summer: The estuary is salt-wedge in nature, being generally vertically stratified in salinity, temperature and density.

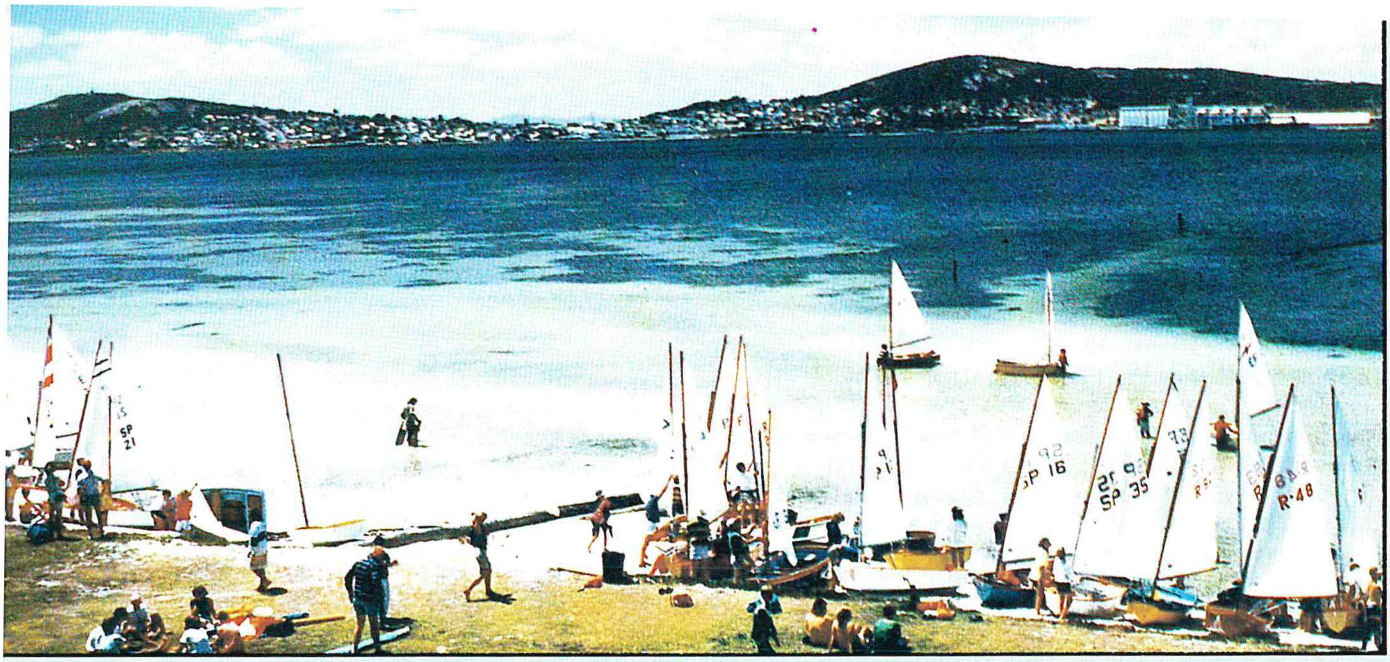
Wind mixing will be vigorous during sea-breezes or storms when winds are greater than about $5ms^{-1}$. Mixing to the seabed will be attained within 5 to 10 hours when winds are greater than about $10ms^{-1}$. This mixing is typically spatially variable, being most vigorous in the central area of the harbour. Light winds ($<5ms^{-1}$) are less efficient at mixing the water vertically but produce downwind drift currents at the surface.

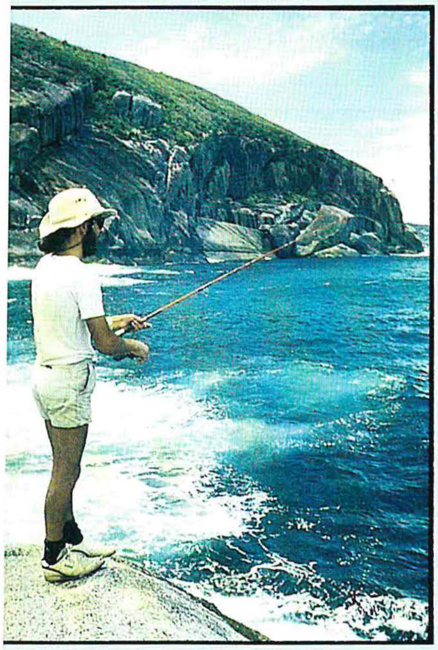
Freshwater inputs, solar heating, night cooling and patchy wind mixing result in the setting up of density gradients within the inner harbour. These can drive surface exchange between the peripheral shallower regions of the harbour and the central deeper basins.

Tidal currents can eject water from the central lower harbour out into King George Sound during ebb tides.

Density driven exchange between the harbour and the ocean is an important flushing mechanism.

Under average conditions surface waters reside in the harbour for 2 days or less, whereas bottom waters reside in the harbour for about 10 to 20 days.





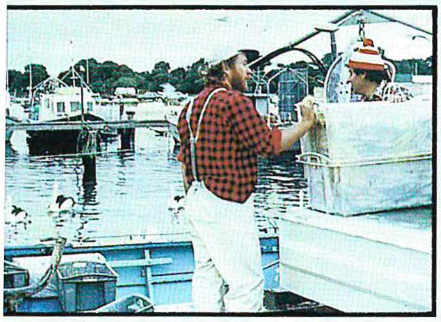
An environment worth protecting

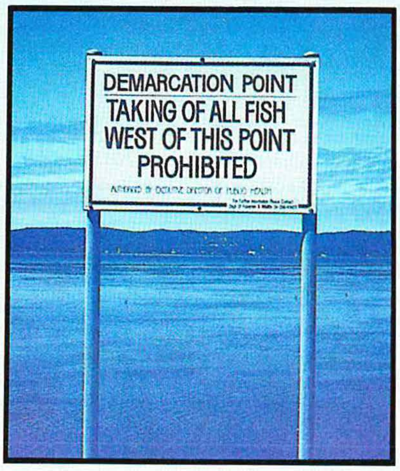
Albany's harbour environment has many different and, sometimes, conflicting uses.

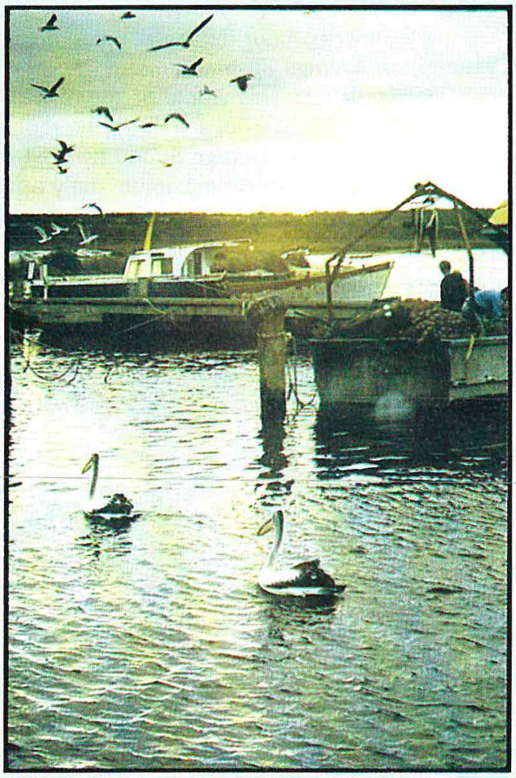
From recreational boating and fishing to industry and agriculture, the harbours have been used to sustain a unique lifestyle.

In the past, a lack of understanding of the capacity of the harbours to assimilate waste has resulted in a deterioration of their environmental quality and a reduction of some of their uses.

With careful management, based on a thorough understanding of how these ecosystems function, all uses of the harbours can be maintained with maximum benefit to the whole community.







Chapter 7

Studies related to management options

7.1 Defining the assimilative threshold for nutrients

This section presents information on the extent to which Princess Royal Harbour is now enriched with nitrogen (N) and phosphorus (P). In addition, initial estimates of the loadings of N and P which can be assimilated in both Princess Royal Harbour and Oyster Harbour without leading to further detrimental changes in the aquatic communities of these waterbodies have been made.

Any attempt to calculate the quantities of excess nutrients in a complex, interactive natural system, or to estimate assimilative capacity of that system, must, at this stage, necessarily be crude. The best approach, given the lack of much of the necessary information on the processes involved, is to determine the role of N and P in regulating excessive growth of free-living macroalgae, which are, in turn, having detrimental effects on seagrasses.

Nutrient enrichment of both Princess Royal and Oyster Harbours has greatly stimulated growth of large populations of free-living macroalgae, leading to shading and smothering of the once healthy seagrass meadows in these waterbodies. In Princess Royal Harbour this has arisen through long-term discharge of industrial wastes from industries located along the shoreline of the harbour in conjunction with nutrient inputs in surface runoff and groundwater from urban and agricultural sources. In Oyster Harbour nutrient inputs originate primarily from rural sources.

The information used to estimate the extent of nutrient enrichment was obtained from the results of investigations on the water quality and nutrient status of the harbours in February 1988 (see Section 4.1) and from information on the nature and quantity of nutrients entering Princess Royal Harbour from industrial, urban and rural sources (see Section 5.2).

The nutrient pools in sediments, plants and water (see Section 4.1) have been re-assessed and apportioned according to the different marine habitats now present in Princess Royal Harbour. Thus there are minor discrepancies between total quantities of N and P presented here and those described earlier. The information which follows draws on the contents of a supporting technical report (Gordon and Deeley, in preparation).

What are the existing nutrient levels in Princess Royal Harbour and where do they occur?

Princess Royal Harbour can be arbitrarily divided into four broad categories based on benthic community type:

(i) bare sediments make up 40%, or about 1200ha, of the harbour area. These include; coarse, siliceous sands along the shallow, marginal shelves; silty muds, high in organic matter, in the deep (> 6m) portion of the harbour; and sandy muds occupying the remainder;

(ii) sediments now overlain by a blanket of free-living macroalgae cover 17%, or about 490ha, of the harbour area;

(iii) seagrass meadows infested (and smothered) to different degrees with free-living macroalgae and also supporting epiphytic (attached) algae (35%, or 1050ha, of the harbour area) and;

(iv) healthy seagrass meadow supporting epiphytic algae, but with only minor quantities of macroalgae (8%, or 240ha, of the harbour area).

When the four categories of habitat are combined, most nutrients were found to have accumulated in the sediments and in the macroalgae.

Of the 1200 tonnes of N and 107 tonnes of P now in the system, the superficial sediments (20mm) contain nearly 1000 tonnes of N and 100 tonnes of P while the macroalgae contain nearly 190 tonnes of N and 8 tonnes of P.

What were the nutrient levels in Princess Royal Harbour before it was polluted?

There are no data available on the quantities of N and P associated with the marine habitats in this harbour in its original (pristine) condition.

The presence of intact, dead seagrass rhizome mats in the sediments of most of the harbour suggests that it was originally dominated by seagrass meadows. Comparisons with other unpolluted seagrass ecosystems in Western Australia, indicate that the seagrass meadows in Princess Royal Harbour were unlikely to ever have contained significant amounts of macroalgae.

Information on the N and P content of seagrasses, epiphytes and overlying water from pristine seagrass meadows in adjacent King George Sound, in conjunction with data on the nutrient content of sediments in other seagrass ecosystems in Western Australia suggest that about 830 tonnes of N and 70 tonnes of P were present in Princess Royal Harbour before it was subjected to pollution.

What is the estimated excess of N and P present in Princess Royal Harbour?

Based on the difference between the sizes of the nutrient pools in the harbour in 1988 and those estimated for the harbour in its pristine condition, the current excess of N and P in the system is estimated to be about 370 tonnes of N and 38 tonnes of P.

Of the total nutrient excess in the harbour, the macroalgae contain over 50% of the N and nearly 20% of the P. Of the remaining nutrient excess, most is associated with the deep basin sediments (>6m).

How does the estimated nutrient enrichment of Princess Royal Harbour compare with quantities of N and P entering the harbour from external sources?

External nutrient loadings in 1988, amounted to 66 tonnes of N and 29 tonnes of P (see Section 5.2). Thus, the current nutrient excess present in the harbour represents about 6 years of enrichment with respect to N and less than 2 years enrichment with respect to P. Since the harbour has been subjected to nutrient enrichment for many years (see Section 5.2), considerable amounts of nutrients that entered the harbour from external sources have been lost. This inevitably occurred in several ways, including direct losses to the ocean as a result of water exchange, and by nutrient transformations, such as denitrification and volatilization, at the sediment-water interface.

Estimating the assimilative capacity of Princess Royal Harbour for N and P

For the purposes of this report the annual nutrient assimilative capacity is defined as the annual loading of total nitrogen and total phosphorus which the harbour can accept without causing long-term damage. However, before the assimilative capacity of a degraded system such as Princess Royal Harbour can be determined, it is necessary to first determine an acceptable 'stable state' for that ecosystem.

Typically, only small amounts of macroalgae are present in healthy seagrass meadows. Ideally then, it would be desirable to substantially reduce the large amount of macroalgae in the harbour to these 'natural' levels. However, this is not technically possible because total removal of macroalgae may result in unacceptable damage to the remaining healthy seagrass meadows.

An estimated reduction of about 75% of the current standing crop of macroalgae in Princess Royal Harbour would be required in order to leave about 225g macroalgae/m^2 in the remaining seagrass meadows. This level of algal infestation is considered 'acceptable' in Princess Royal Harbour and forms the arbitrary ecological criterion of a 'stable ecosystem' in this waterbody.

To achieve the 'acceptable' density of algae, all the large banks of macroalgae (approximately 4200 tonnes), and half of the macroalgae now associated with the remaining seagrass meadows (approximately 4600 tonnes) would need to be removed. If the proposed algal harvesters operate to their specifications, it is estimated that a 75% reduction in the algae currently present in the harbour can be achieved in one year (see Section 7.2) before significant regrowth occurs.

For the purposes of this exercise, it is assumed that about 10% of the macroalgae remaining after harvesting would be lost by decomposition each year, if there was no source of nutrients to support further growth (that is, internal recycling and external nutrient inputs are assumed to be negligible). This reduction in algal biomass is equivalent to about 10 tonnes of N and 0.6 tonnes of P per year. It follows therefore, that about 10 tonnes of N and 0.6 tonnes of P could be added to the system each year to replace this 'lost' 10% and maintain algal densities in the harbour at no greater than the 'acceptable' level of 225g macroalgae/m^2. This nutrient loading, then, is the assimilative capacity of the macroalgae in the harbour.

Sediments also have a capacity to assimilate nutrients to certain levels above those found in pristine systems. Chronic nutrient loadings into Princess Royal Harbour from external sources has led to enrichment of the sediments, particularly in the deep basin. It is assumed here that the level of enrichment of sediments with nutrients is not detrimental to the marine life of the harbour.

Thus the amount of N and P that is assimilated by the sediments each year can be estimated from the degree of enrichment of superficial sediments and the rate of accretion of these sediments. Information on rates of sediment accretion in seagrass meadows suggests that sediment accumulates at a rate of about 1000cm in 5000 years. On this basis, the nutrient content of the top 20mm of sediments in the deeper portions of the harbour may represent the equivalent of about 10 years accumulation.

Assuming that this nutrient enrichment of sediments progressed at a uniform rate, the estimated excess of 170 tonnes of N and 30 tonnes of P now in the sediments of PRH suggests that the annual accumulation of nutrients in the sediments of this harbour occurred at the rate of about 17 tonnes of N and 3 tonnes of P. This annual nutrient accumulation is used as an estimate of the annual assimilative capacity of the sediments in the harbour.

The assimilative capacity of Princess Royal Harbour for N and P

The sum of the estimated annual assimilative capacities of the sediments and the macroalgae is 27 tonnes of N and 3.6 tonnes of P.

The total nutrient assimilative capacity of an aquatic ecosystem, like Princess Royal Harbour, includes biological and physical processes other than those involving the sediments and the macroalgae alone. For example, the contribution of nutrient uptake by phytoplankton, epiphytes and seagrasses, and the export of water-borne nutrients out of the harbour to King George Sound all contribute to the total nutrient assimilative capacity of the system. Although these were not included, cumulatively, these processes may also contribute to the total assimilative capacity of Princess Royal Harbour. To account for these additional processes, and the errors associated with estimating the assimilative capacity based on macroalgae and sediments alone, the estimate of the partial assimilative capacity (ie sediments and macroalgae alone) have been simply doubled to provide an estimate of the total nutrient assimilative capacity of Princess Royal Harbour.

Thus, the total nutrient assimilative capacity of Princess Royal Harbour, based on the approach and assumptions described above, is estimated to be about 54 tonnes of N per year and about 7 tonnes of P per year.

How does the assimilative capacity of Princess Royal Harbour relate to that of Oyster Harbour?

Because of the complexity of the physical processes in Oyster Harbour (see Section 6.2), the annual assimilative capacity of this harbour for nutrients is difficult to estimate with the information that is currently available. Limited data suggests that the mean annual nutrient loading into Oyster Harbour is approximately 30 tonnes of total phosphorus and about 350 tonnes of total nitrogen and that the source of most of these nutrients are fertilizers washed from agricultural land in the catchment.

However, because Oyster Harbour is severely degraded (ie the assimilative capacity has been exceeded for many years), and because a large proportion of the nutrients that enter the harbour during periods of high river discharge appear to be flushed out into King George Sound, the annual nutrient assimilative capacity of Oyster Harbour is likely to be less than the current mean annual nutrient loading but greater than the annual nutrient assimilative capacity of Princess Royal Harbour.

Nutrient loading into Oyster Harbour is directly related to the amount of rainfall in the catchment, and the retention of nutrients within the harbour is partly related to the intensity of river flow and the formation of a buoyant nutrient-rich plume that flows through Oyster Harbour into King George Sound (see Section 6.2). Therefore, it is likely that the annual assimilative capacity for nutrients in below average rainfall years is similar to that of Princess Royal Harbour while in above average rainfall years it may be considerably greater and is assumed here to be double. The total assimilative capacity of Oyster Harbour for nutrients is, therefore, expressed here as a range of between 7 to 14 tonnes of total phosphorus and 54 to 108 tonnes of total nitrogen.

These estimates should be regarded as initial management targets and indicate that inputs of nutrients into Oyster Harbour from agricultural land must be drastically reduced if the current decline in the seagrass meadows in the harbour is to be arrested. Further investigations into the nutrient dynamics of Oyster Harbour are necessary to refine these initial estimates of the annual nutrient assimilative capacity.

7.1.1 Conclusions

The definition, and resulting calculations, of the annual nutrient assimilative capacities of the Albany harbours have been linked here to the role of nitrogen and phosphorus in regulating excessive growth of free-living macroalgae, which are, in turn, having detrimental effects on seagrasses. The current excess of nutrients that have accumulated in Princess Royal Harbour over many years occurs mainly in the sediments of the deep basin and in macroalgae.

Once the macroalgae and external nutrient inputs are substantially reduced and the system is 'stable', it is estimated that the harbour will be able to assimilate approximately 54 tonnes of total nitrogen and 7 tonnes of total phosphorus per year, without further deterioration.

Preliminary estimates suggest that the nutrient assimilative capacity for Oyster Harbour is approximately 54-108 tonnes of total nitrogen and 7-14 tonnes of total phosphorus per year.

Annual nutrient loads, particularly phosphorus, into the Albany harbours currently exceed the assimilative capacity of both harbours. A significant reduction in nutrient loading into these systems from all sources is required to prevent further deterioration of the environmental condition of the harbours.

This exercise has highlighted deficiencies in knowledge of these systems, which would otherwise help to better define acceptable loadings of pollutants such as nitrogen and phosphorus. The deficiencies include information on the capacity of the sediments to assimilate or release nutrients, the form in which nutrients are exchanged from one compartment to another, what proportion are in a form which is readily usable by the marine life, the role of water circulation (mixing, re-suspension, transport and sedimentation) in determining the fate of nutrients and the resilience of the biota to excessive input of pollutants.

7.2 Feasibility of harvesting nuisance algae

Macroalgae have accumulated in the Albany harbours as a result of high nutrient loading, and these algae have formed thick banks, especially in the shallows of the western and south-eastern ends of Princess Royal Harbour and the middle and south-eastern areas of Oyster Harbour (see Section 4.1). This 'carpet' of macroalgae has caused a severe reduction in light reaching the seagrass meadows. As a result, seagrass meadows in both harbours have declined markedly and the remaining stands of seagrasses are under continual threat.

Physically removing this algae is a possible short-term interim option for relieving the stress on the remaining meadows. Preliminary calculations based on algal growth rates (Masini *et al.,* in preparation) predict that the major algal banks in Princess Royal Harbour could accumulate at a rate of about 0.3m per year. A study was conducted by the Waterways Commission to examine the mechanical feasibility of harvesting the algae, and this study is summarized below. Further details can be found in a report by Crawford (1989).

7.2.1 Objectives and Scope

(i) To determine the feasibility of algal harvesting in the Albany harbours and;

(ii) to outline and evaluate possible harvesting methods.

7.2.2 The feasibility of harvesting macroalgae from seagrass beds

A high proportion of the algae in both harbours is concentrated in limited areas. This feature of algal distribution makes the harvesting of these plants considerably more efficient. The algal biomass in Princess Royal Harbour in February 1988 was about 11650 tonnes (dry weight) compared to about 1200 tonnes in Oyster Harbour. The mechanical feasibility of harvesting macroalgae concentrated on Princess Royal Harbour but the methods discussed below are equally applicable for Oyster Harbour.

7.2.3 Possible harvesting methods

Three alternative methods were proposed, and these are briefly outlined below.

(a) The use of a hydrostatic lift pump to float the algae to the surface and then harvest it by using a conventional or suction weed-harvester.

(b) The use of a suction weed-harvester with its intake nozzle at a fixed height above the seabed to harvest all algae possible or harvest only where algal accumulations are greater than about 2000 gm^{-2} (dry weight).

(c) Use a suction weed-harvester on the surface, with the nozzle mounted on a specially made underwater trailer.

7.2.4 Evaluation of alternative methods

Alternative (a): This method was not considered feasible due to potential problems of maintaining the algae on the surface of the water, a prerequisite for this type of harvesting.

Alternative (b): This alternative is considered practical only if the algal density is very high (ie about 5000 gm^{-2}).

Alternative (c): A purpose-built harvester, designed especially for the Albany harbours is considered the best option. This harvester would be able to harvest approximately 75% of the macroalgae growing in the harbours and has the capacity to leave low residual densities of algae of about 200 gm macroalgae m^{-2} in the remaining seagrass meadows. The unit capital cost and operating cost per tonne of algae are about half of those estimated for the alternative methods.

7.2.5 Conclusions

Algal harvesting is a feasible interim option for controlling seagrass decline in the Albany harbours. A harvesting unit can be built specifically for use at Albany and is the most efficient and cost-effective of the proposed methods. The harvesting of macroalgae will considerably improve the light climate of the seagrass meadows and, in addition, it will remove approximately 12% of the total nitrogen and 6% of the total phosphorus pools of Princess Royal Harbour.

7.3 Catchment nutrient loads and soil nutrient status

Plant nutrients, such as phosphorus and nitrogen, are exported from rural catchments in agricultural produce, in water and bound to soil particles washed off pastures. In general the coastal soils of southern Western Australia have low nutrient retention capabilities, particularly for phosphorus. In the past, the loss of phosphorus off agricultural lands in the catchments of the Peel and Harvey Estuaries has resulted in excessive nutrient enrichment of these waterbodies, leading to a severe decline in their water quality.

Phosphorus exported in agricultural produce is not an environmental problem. Loss of phosphorus attached to soil particles can be managed through erosion control, but phosphorus loss in water, either in surface runoff or through groundwater leaching is more difficult to control. Nutrient losses from soils with low retention capacities can be significant and require careful management if 'downstream' problems associated with nutrient enrichment of receiving waterbodies are to be avoided.

A preliminary assessment of the soil types and fertilizer application practices in the catchments of the Albany harbours suggested that significant quantities of nutrients were likely to be entering these harbours via the rivers and creeks draining these two catchments.

A study was conducted by the Department of Agriculture in order to quantify the nutrient status of soils within the catchments of the Albany harbours and identify possible ways of reducing phosphorus concentrations in surface runoff. A summary of this study is presented below. Further details can be obtained from the Technical Report (Pepper and Prout, in preparation).

7.3.1 Objectives and scope

The primary objective of this study was to identify ways of reducing phosphorus losses in surface runoff from the catchments of Princess Royal Harbour and Oyster Harbour.

This involved determining the relative proportion of the major soil types in, and phosphorus status of, each catchment. The total catchment of Oyster Harbour consists of a number of individual catchments, the largest being the catchments of the King and Kalgan Rivers. As the Oyster Harbour catchment is considerably greater in area than the catchment of Princess Royal Harbour (Figure 7.1), it was divided into a number of sub-catchments (see Section 5.3). Each of these sub-catchments had separate gauging stations to measure water flow and nutrient concentrations in the runoff waters. The Kalgan catchment was divided into upper and lower sub-catchments due to differences in geomorphology and rainfall patterns.

7.3.2 The proportion of major soil types and phosphorus status in each catchment

Soil characteristics were determined for each sub-catchment. Surface soils (0-100mm) were classified as sands when they contained less than 400 parts per million (ppm) of reactive iron. A measure of the relative acidity of the soils within each sub-catchment was also determined as the percentage of samples with a pH value of less than 4.3 in 0.01M $CaCl_2$.

High phosphorus status soils were classified from plant growth response curves and indicated which soils would attain 90% or more of total potential production without application of additional phosphorus. The percentage of high phosphorus sands was determined in the same way.

Since sands have the greatest potential to leach phosphorus, the proportion of sands with high phosphorus status was calculated and an estimate made of the likely area that these sands occupy in each catchment. The results of this survey are presented in Table 7.1.

	Area (000s ha)	% Sandy Soils	% Soils of pH<4.3	% high P soils	% high P sands
Upper Kalgan	201	37	20	59	18
Lower Kalgan	42	49	36	51	22
Chelgiup	5	36	35	56	16
King	17	54	51	67	37
Millbrook	16	50	45	54	23
Willyung	3	38	59	71	16
Princess Royal Harbour	8	45	44	38	13

Table 7.1 Soil characteristics in the catchments of the Albany harbours.

Sandy soils predominate on the surfaces of these catchments, ranging from 36% on the Chelgiup catchment to 54% on the Millbrook catchment. Acidic soils represent a significant proportion of the soil type in all catchments except for the upper Kalgan catchment. The low percentage of acidic soils in the upper Kalgan is likely to be a reflection of the lower rainfall in this area. Between 51 and 71% of soils sampled had a high phosphorus status, that is, these soils would not have required any additional phosphorus to achieve 90% or more of maximum production. The percentage of sandy, high-phosphorus status soils ranged from 13% in the Princess Royal Harbour catchment to 37% in the King River catchment. As mentioned previously, it is the high-phosphorus sandy soils that are most prone to leaching and these would be high on a priority list for management to reduce phosphorus loads in water courses draining these catchments.

7.3.3 Nutrient point sources

Point sources of nutrients have the potential to generate high concentrations of phosphorus in runoff water. These have been identified in many of the catchments draining into the harbours and include dairies, intensive horticulture, potato farms, rubbish tips and disposal areas for solids from sewerage and septic sludge. These sources have been targeted for special management so as to reduce the amount of phosphorus that is leached or discharged onto the catchments.

7.3.4 Reducing nutrient losses

The phosphorus load entering the harbours from surface runoff via the system of rivers and creeks that drain these catchments depends both on the nutrient concentration in surface-water and the volume of this water entering the harbours. Therefore, in rural catchments, management strategies should be directed at reducing both the phosphorus concentration and the volume of surface runoff.

Reducing nutrient concentrations in runoff

Phosphorus concentrations in runoff can be reduced by improving the soil condition and by manipulating the time of fertilizer application. These two strategies are discussed briefly below.

Improved Soil Condition: Improving soil conditions will result in better plant growth and increased uptake of the applied fertilizer, thereby reducing nutrient losses in runoff. Approximately 50% of all the soils sampled had a pH of 4.3 or less. Thus the application of lime to reduce this acidity would promote improved plant growth, and result in less phosphorus loss.

Improved fertilizer practices would result if farmers had up-to-date information on soil nutrient status. This could be achieved if farmers undertook regular soil testing. Fertilizer application rates could then be

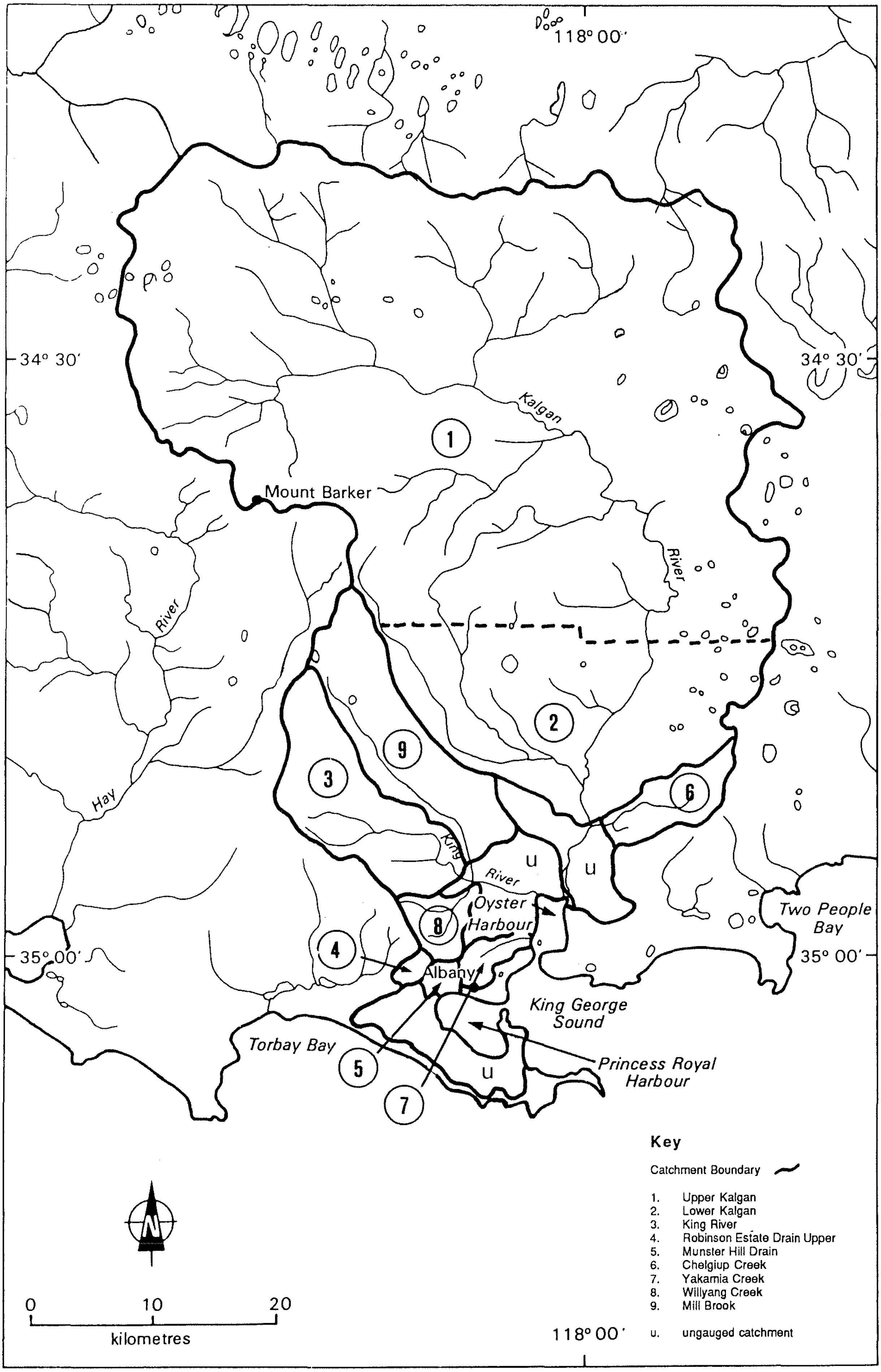


Figure 7.1 Drainage catchment boundaries for Oyster Harbour and Princess Royal Harbour.

matched to soil nutrient levels and plant nutrient requirements. As a result, only the amount and type of nutrients that were deficient would be applied. This would prevent over-fertilizing, reduce costs to the farmers and reduce losses in surface runoff.

Timing of Application: Once soil nutrient requirements are known, decisions can be made in relation to the timing of fertilizer application. In non-responsive situations, where only maintenance applications are needed, reduced application rates can be used in spring. This was demonstrated for a pair of small catchments on the south coast where 41% of phosphorus applied in May was lost compared to only 17% when applied in July (Table 7.2). On some areas of the Albany catchments however, soils are too wet for spring applications, and slow-release fertilizers, applied in autumn, are a possible alternative.

Catchment	West	East
Total Area (ha)	508	622
Cleared Area (ha)	389	474
% cleared	76	76
Soil types (% of cleared area)		
Gravel	36	11
Sand	64	89
Phosphorus loss		
Total phosphorus load (t)	1.8	1.0
Flow weighted mean (mg/L)	0.85	0.44
Phosphorus loss (Kg/cleared ha)	4.6	2.1
Runoff/Rainfall (%)	60	52
Phosphorus applied in 1988 (Kg/ha)	11.3	12.1
Time of application	May	July
Total three years (Kg)	29	33.3
% of 1988 application lost	41	17

Table 7.2 Effect of timing of fertilizer application on phosphorus loss from two experimental catchments.

Reducing runoff volumes

Phosphorus loads into Oyster Harbour can be up to ten times higher in wet (ie high runoff) years than in drier years (see Figure 5.8). Therefore, minimising runoff would be an important strategy for controlling nutrients entering the harbours. On agricultural catchments this can be achieved by adopting practices that use more water where it falls or those that encourage more rainfall to stay on the catchment. Perennial pastures, later-maturing annual pastures and crops, and more cropping would help achieve this goal. The use of deep-rooted fodder and forest trees would also reduce soil nutrient losses. In addition, contour working, absorption banks and dams would all facilitate retention of water on the catchment and therefore reduce surface runoff.

7.3.5 Conclusions

High phosphorus status soils were found to be the predominant soil type in the catchments of the Albany harbours. About one third of these were sands which is the soil type most prone to leaching phosphorus. Catchments with this soil type are recommended as priority areas for management. Strategies to reduce rural sources of nutrients entering the harbours via surface runoff include: soil testing to identify high phosphorus status soils and appropriate fertilizer application rates; optimizing fertilizer application times; improving soil condition; reducing runoff volumes and the promotion of perennial pastures and deep-rooted fodder and tree crops.

7.4 Rehabilitation of seagrass meadows

The loss of extensive areas of seagrass in the Albany harbours has raised widespread community concern in the Albany region about the long-term environmental quality of the harbours. The Albany Harbours Environmental Study was initiated to address these concerns and identify possible long-term solutions to these problems. In attempting to redress the problem of extensive seagrass loss, one option is the possible artificial restoration of degraded seagrass beds.

In Western Australia, most loss of seagrass occurs from a reduction in the amount of light reaching the meadows. Seagrasses can have high productivities and leaf turn-over rates but they have surprisingly slow rates of spreading. Large meadow-forming seagrasses, such as *Posidonia,* have very slow growing rhizomes that do not branch readily. Many flowers and seeds are formed but successful establishment of seedlings appears, in many cases, to be very low. This suggests that the *Posidonia* seagrasses in the Albany harbours and other areas of Western Australia probably take decades, or even perhaps centuries to develop mature meadows.

Western Australian seagrass flora is amongst the most diverse in the world with 17 species currently described. This diversity provides many different choices of locally-adapted seagrasses when the restoration of seagrass meadows in a particular area is considered. It should be noted, however, that the fauna associated with different types of seagrass meadows are likely to vary considerably.

The feasibility of restoring seagrass meadows was investigated by the EPA (Kirkman, 1989). Potential problems and methods associated with the restoration of seagrass meadows, with special emphasis on Western Australia, are outlined. This section presents a summary of the main conclusions of this study and further information can be obtained from the above report.

7.4.1 Objectives and scope

The study addressed the following issues:

(i) An examination of the history of seagrass transplants in Australia and overseas;

(ii) A determination of timescales for natural causes of seagrass decline and restoration;

(iii) A description of the man-made causes of the decline of seagrass meadows;

(iv) An evaluation of planting techniques and;

(v) An identification of environmental conditions necessary for achieving optimum results from seagrass restoration.

The topics are discussed separately below.

7.4.2 History of seagrass transplants

Most studies concerning transplantation of seagrasses have taken place in the United States where the seagrass genera, the reasons for initial loss and most of the habitats, are different to those encountered in Western Australia. Little advancement has been made in the last 15 years since the first trials, and in most cases seagrass transplants have been small scale and met with limited success. Only two reports of field plantings of seagrass in Australia are available.

7.4.3 Time-scales for natural restoration and the natural causes of decline

The natural recolonization of seagrass beds has seldom been documented. Some of the smaller, fast-growing seagrasses such as *Halophila* and *Heterozostera* are often removed by winter storms. These species subsequently recolonise the seabed and grow rapidly. Catastrophic storms can remove stable seagrass beds of the larger species, but events of this magnitude are very rare (once in 60-100 years). There are no records of substantial natural recolonization of meadows of the large *Posidonia* and *Amphibolis* seagrasses in Australia.

7.4.4 Man-made causes of seagrass meadow decline

Seagrass meadow decline is commonly the result of a sustained reduction in available light to the plants. This can be caused by excessive epiphytic growth on the leaves of the seagrasses or by macroalgal and phytoplankton blooms caused by an oversupply of nutrients from industrial, agricultural or domestic sources. Unnaturally high levels of suspended sediment in the water, as a result of dredging activities, can also substantially reduce available light over seagrass meadows.

7.4.5 Evaluation of planting techniques

Four types of 'planting units' are available to restore or create seagrass beds. These are:

(a) *plugs*: excavated sections of rhizome, leaves, shoots and roots with sediment intact;

(b) *sprigs*: vegetative shoots with intact roots, rhizomes and leaves but lacking sediment;

(c) *seeds/seedlings*: either planted in pots or directly into the sediment and;

(d) *sprouting stems*: erect stems with adventitious roots (*Amphibolis* and *Heterozostera* only).

Sediment-stabilizing and wave-dampening devices, and artificial seagrass consisting of plastic strips attached to a wire frame, are all necessary aids in seagrass restoration and can be removed once restoration has taken place.

Many manual planting methods have been attempted successfully but all are extremely expensive (currently about $60,000 per hectare). Planting units must be secured firmly by hand and, at the moment, there is no technology readily available that can be adapted to do this mechanically. Important considerations include the distance separating planting units and the method of attachment. For the restoration of *Posidonia* seagrass meadows in typical Western Australian conditions, clumps of *Posidonia* seedlings, planted 100-150mm apart at 10m intervals, are considered to be optimal. Alternatively, seedlings could be protected by planting 'windbreaks' of the deep-rooted clumping *P. kirkmanii* in rows throughout the area, followed 2 years later with seedlings of *P. australis*.

Amphibolis seedlings may be useful for initial recolonisation of denuded areas due to their 'grappling anchors' which attach easily to dead *Posidonia* rhizomes or other fibrous material. These could also be anchored by wire pegs or planted under chicken wire.

In relatively protected situations, small, fast-growing genera such as *Halophila* and *Heterozostera* may be used for sediment stabilization to aid in the establishment of the more robust species. In all cases, the success of restoration will be influenced by how quickly the planting units coalesce.

Experimentation with growth hormones and genetic engineering or hybridization between species are also worthy of consideration, but the latter options would need careful investigation before being attempted.

7.4.6 Conditions influencing successful restoration

Before successful restoration can be attempted the cause of meadow decline must be identified and eliminated. In exposed areas, excessive sediment movement from increased wave energy at the seabed, caused by less dampening of wave energy as a result of seagrass loss, can interfere with attempts to recolonise the area. This factor is likely to be insignificant in the relatively sheltered environment of the Albany harbours.

Knowledge of critical irradiance requirements for the species in question should be known so that minimum or better light conditions are present before attempts are made to restore meadows (see Sections 4.4 and 4.5). In the Albany harbours this will only occur when nutrient pools and inputs are reduced to limit algal growth to natural or acceptable levels.

Consideration should be given to developing analytical techniques to provide early indications of stress, before the more obvious signs such as leaf loss become apparent. In this way there is a greater chance of identifying and solving the problem before it is well advanced, thus stopping or reversing the process of seagrass decline and, hopefully, eliminating the need for restoration.

7.4.7 Conclusions

Further work is required to establish a successful, reliable and cost-effective method for long-term restoration of seagrass meadows. Species chosen for recolonization must be fast growing with the ability to anchor securely to the substrate. Either of the two *Amphibolis* species found in Western Australia are suggested for restoration trials because of their relatively fast rhizome growth rate.

Seagrass restoration is an extremely expensive exercise, and this expense must be evaluated against the environmental, aesthetic and commercial costs of seagrass decline. Finally, it should be emphasized that seagrass meadows cannot be restored if the cause of their initial decline has not been eliminated.

Part III

Environmental Problems and Solutions

This part of the report consists of three chapters and outlines the principal environmental problems in the Albany harbours, the range of options available for achieving short and long-term solutions and the final recommendations of the study. Chapter 8 draws upon the results of the detailed investigations carried out during the study to define and discuss specific problems and factors affecting them. Chapter 9 describes options available for short and long-term solutions to these problems. Chapter 10 presents the recommended strategies for the sound environmental management of the Albany harbours.

Chapter 8

Description of principal environmental problems

This chapter draws upon the findings of the technical and other studies and briefly outlines the major environmental problems in the Albany harbours. Concepts and options for control of the problems are given in Chapter 9.

8.1 Nutrients and seagrass loss

Past and current nutrient loads into Princess Royal Harbour and Oyster Harbour have stimulated excessive growth of large algae (macroalgae) and smaller algae that grow on the leaves of seagrasses (epiphytes). These algae shade and smother the seagrasses, significantly reducing the amount of light reaching these plants. Light reduction is now considered the primary cause of the widespread loss and thinning of the seagrass meadows in both harbours.

Forty-five percent and 66% of the areas originally covered by seagrass meadows in Oyster Harbour and Princess Royal Harbour, respectively, were lost between 1962 and 1984. By 1988, only 40% of the seagrass present in both harbours in 1984, remained. Thus, almost 90% of the seagrasses in Princess Royal Harbour and 80% in Oyster Harbour have been lost since 1962 when these seagrass meadows were considered to be in a pristine condition.

The rate of seagrass decline has been particularly rapid since 1984, suggesting that if immediate action is not taken to arrest the rate of decline, all the dense areas of seagrass will be lost in Princess Royal Harbour within five years and within 5-10 years in Oyster Harbour, leaving only patchy areas of sparse seagrass in both harbours. Current information on the recovery of seagrass meadows suggests that the luxuriant *Posidonia* meadows that once covered most of the Albany harbours will never return to their former state. However, once the large accumulations of macroalgae that presently occur in the harbours are removed and pollutant inputs are drastically reduced, conditions in the harbours are likely to improve sufficiently to allow the remaining seagrasses to flourish and other seagrass species and animals to colonise suitable bare areas of seabed.

Although phosphorus and nitrogen are both essential elements for plant growth, phosphorus probably controls the growth of algae in the Albany harbours. Thus control of phosphorus loadings into the Albany harbours is the key to long-term management of the excessive algal growth and seagrass decline in these waterbodies. Further additions of phosphorus are likely to result in increased algal growth with continued aggravation of environmental problems. Conversely, if phosphorus inputs are significantly reduced, both algal growth and the rate of decline of the seagrass meadows will decrease.

Nutrients are added to the waters of the Albany harbours in several different ways. Industrial effluents, urban runoff, domestic wastewater and agricultural inputs are the major external nutrient sources. In the past, CSBP & Farmers Ltd (CSBP) has been the major individual contributor of phosphorus to Princess Royal Harbour. Between 1954 and 1984, approximately 650 tonnes of phosphorus entered the harbour from CSBP's industrial estate via direct discharge and surface runoff, and this nutrient loading (about 80% of the total) was probably the single biggest factor in the nutrient enrichment of Princess Royal Harbour and the subsequent decline of the seagrass meadows.

In 1988, industrial, rural and community (including domestic wastewater) sources contributed 61%, 24% and 15% of the total phosphorus load into Princess Royal Harbour. Groundwater nutrient loadings from point sources such as piggeries, septic tanks etc, were estimated during this study but further surveys are required to assess, more accurately, the relative contribution of groundwater pollution. Preliminary data from surveys currently being undertaken, suggest that this source of nutrients to the harbours may be more significant than previously thought. In 1988, industrial wastewater discharges into Princess Royal Harbour, particularly from Metro Meats Pty Ltd and Southern Processors Pty Ltd, and surface runoff from CSBP contributed significant proportions of the total nutrient load into this waterbody.

Most of the nutrient load into Oyster Harbour enters via surface runoff and river discharge, particularly in average or above-average rainfall years. In low rainfall years, point sources of pollution such as dairies, piggeries, septic tanks and the WAWA package treatment plants contribute a more significant proportion of the total annual nutrient load into Oyster Harbour.

Large amounts of nutrients have accumulated in the sediments of both harbours and in the macroalgae in Princess Royal Harbour over the years and these stores provide a large internal store of nutrients, a proportion of which are recycled.

8.2 Heavy metals and pesticides

CSBP discharged significant quantities of heavy metals (lead and mercury) into Princess Royal Harbour in its effluent for about thirty years and this eventually led to the contamination of sediments and biota, particularly in the western end of the harbour. Following the discovery of contaminated fish in 1983, the western end of Princess Royal Harbour was closed to fishing in 1984. The direct discharge of effluent from CSBP stopped in 1984 and although the annual monitoring of mercury in fish from Princess Royal Harbour has indicated that, in general, mercury levels in certain fish species have declined since then, levels remain above the health limit and the western end of the harbour remains closed to fishing.

Other heavy metals such as zinc and chromium were discharged in the effluent from the Albany Woollen Mills Pty Ltd, but recent changes in industrial procedures by this company have substantially reduced the loadings of these metals into the harbour from this source. High concentrations of heavy metals were also found in urban runoff, particularly after the first rains.

Elevated concentrations of dieldrin and other organochlorine pesticides were present in initial urban drain flows and in the effluents of the Albany Woollen Mills and Southern Processors Pty Ltd. The Albany Woollen Mills now ensures that these pesticides are not used for mothproofing wool that is imported from countries where these pesticides are still in common use. Organochlorines are now banned for agricultural use in Western Australia and thus residual levels in soils will gradually decline, resulting in decreasing amounts entering Princess Royal Harbour from vegetable processing. A limited survey of pesticide levels in mussels from Princess Royal Harbour in 1988 indicated that pesticide levels were well below the health limit in all samples.

8.3 Microbiological quality of shores and inshore waters

Elevated concentrations of faecal bacteria in seawater were first reported at Middleton Beach in a study conducted in 1979 (Atkins *et al.*, 1980). Following the recommendations of this study, a program was established to monitor the bacteriological condition of the waters of Princess Royal Harbour and Middleton Beach. Water samples were taken from within the mixing zones of the various effluent outfalls and also from Ellen Cove on 35 occasions from 1982 to 1988.

Faecal coliform counts of less than 50 per 100ml are considered satisfactory for direct contact recreation, while consistent counts above 200 per 100ml suggest that a distinct health risk exists and warrants a sanitary survey. Counts above 2000 per 100ml indicate objectionable water that is heavily polluted.

The nearshore effluent mixing zones of the WAWA King Point domestic wastewater outfall and the Metro Meats outfall in Princess Royal Harbour were found to be the most heavily polluted. Bacterial counts of greater than 100,000 organisms per 100 ml were recorded on 30% of the occasions the mixing zone of Metro Meats was sampled and on 100% of the occasions the mixing zone of the King Point outfall was sampled. The waters within these mixing zones are grossly polluted. The faecal bacterial concentrations at Ellen Cove, a popular swimming beach, were above acceptable levels (200 per 100 ml) on at least 27% of the occasions samples were taken. This beach is north of the King Point wastewater treatment plant outfall and the source of the contamination is assumed to be from this plant.

An extension to the outfall at King Point was completed in early 1989 and discharge now occurs near the seabed in a water depth of 10m, some 30m offshore. The extension is likely to have resulted in a significant decrease in the surface concentrations of faecal bacteria due to increased initial dilution as the buoyant plume rises to the surface. As a result, the frequency of occurrence of unacceptable levels of faecal bacteria reaching Middleton Beach and Ellen Cove is now likely to be lower. Future monitoring will reveal the degree of improvement gained from the changes to the King Point outfall.

8.4 Aesthetic quality of shores and waters

The high aesthetic quality of the marine and estuarine environments in the Albany region is an important attraction to the residents of Albany and tourists alike. The beaches of the Albany waterways have not yet been severely affected by large accumulations of decomposing algae, commonly associated with nutrient enriched waterbodies such as Peel Inlet near Mandurah. Another common symptom of eutrophication, again not yet apparent in the Albany harbours, is the excessive growth of microscopic algae (phytoplankton). These phytoplankton 'blooms' discolour and deoxygenate the water, as well as sometimes producing toxins which adversely affect aquatic life and constitute a public health risk. If no action is taken to reduce nutrient inputs to the harbours, the possibility of the Albany harbours changing from macroalgal-dominated systems to phytoplankton-dominated systems in the future should not be dismissed.

Various parts of the shoreline of Princess Royal Harbour are fouled periodically by lumps of fat originating from Metro Meats and effluent slicks are commonly observed moving downwind from this outfall. During summer, when winds blow predominantly from the south-east, effluent slicks are noticeable near the Albany Town jetty. Strong odours from Metro Meats are also noticeable in the Albany township at times during summer. These conditions significantly reduce the aesthetic quality of this area and are incompatible with the proposed Albany foreshore redevelopment.

The existing state of the detention basins on the Albany foreshore also detract significantly from the visual appeal of this part of Princess Royal Harbour. Landfill and residential development at the water's edge is also destroying fringing vegetation and reducing the natural and aesthetic values of the harbour shores.

Chapter 9

Development and evaluation of solutions

This chapter of the study report describes actions which can control the principal environmental problems identified in Chapter 8. Briefly, these include the following conditions or characteristics: (i) nutrients entering the waters of Princess Royal Harbour and Oyster Harbour, (ii) microbiological quality of shores and nearshore waters, (iii) contamination of fish and shellfish, and (iv) aesthetic quality of shores and nearshore waters.

Some remedial actions can be accomplished readily and some are already being implemented by industries. Other actions require engineering and economic investigations and analyses to fully establish their feasibility. In any event, many of the short-term actions can improve specific conditions or prevent further degradation of the Albany harbours and the community resources they provide.

The environmental problems of the Albany harbours can be divided into three broad categories:

(i) **Ecological** - an oversupply of nutrients into both harbours, causing extensive loss of seagrass due to shading and smothering by algae;

(ii) **Health** - contamination of fish and shellfish in Princess Royal Harbour and microbiological quality of the shore and nearshore waters of Princess Royal Harbour and King George Sound and;

(iii) **Aesthetic** - aesthetic quality of the shore and nearshore waters of Princess Royal Harbour and King George Sound.

The sources and range of pollutants entering the Albany harbours are quite different.

Pollutants that threaten the ecology of Princess Royal Harbour, namely nitrogen and phosphorus, enter from industrial, community and rural sources (Figure 9.1). Industrial effluents are discharged directly into the harbour through outfalls, and indirectly via surface runoff and through groundwater leaching. Pollutants from the community include wastewater discharge at King Point, some of which subsequently enters Princess Royal Harbour, urban runoff and groundwater leaching from septic tanks and the Hanrahan Road tip site etc. Rural inputs enter the harbour via streams and creeks, and through the groundwater.

Fertilizer washed off farms in the catchment of Oyster Harbour enter this waterbody via rivers and creeks with the Kalgan and King Rivers being the major sources of nutrients, especially in years with average or above-average rainfall.

Minor sources include piggeries, dairies, WAWA package plants and septic tanks. No significant quantities of industrial or domestic effluents are discharged directly into Oyster Harbour.

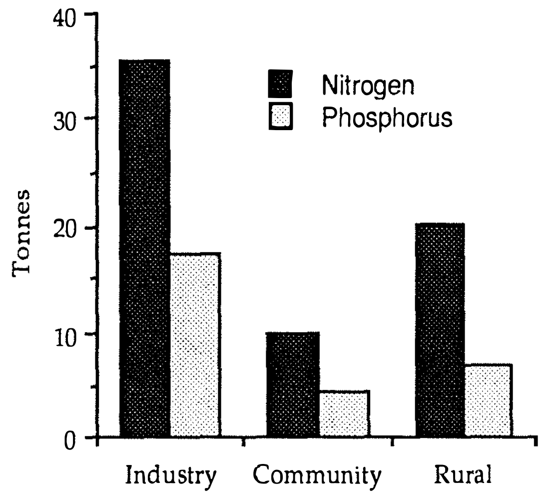


Figure 9.1 Estimated annual nutrient loads into Princess Royal Harbour in 1988 from industrial, community and rural sources.

9.1 Management considerations

The objectives of a management strategy for the Albany harbours are firstly, to arrest the deterioration and, secondly, to improve the environmental condition of Princess Royal and Oyster Harbours. To achieve these objectives the external pollutant inputs to the harbours must be substantially reduced.

There are two broad strategies for dealing with unsatisfactory contaminants entering waterbodies. The first involves removal of the contaminants at their source by effluent treatment, and the second involves diverting the contaminants to a different part of the environment where they no longer have a significant adverse effect.

Pollutants in poorly-flushed aquatic environments accumulate mainly in the sediments and biota, particularly the plants. Reduction of these pollutant pools is mainly confined to the slow, natural process of resuspension and export out of the system by water currents, or by physically removing the sediments (ie dredging) and biota that hold these pools (ie harvesting).

Some short-term actions that will improve specific conditions or prevent further degradation of the Albany harbours and the community resources they provide can be accomplished readily, and some of these are already being implemented by the Albany foreshore industries. Some of the long-term options that will eventually eliminate the environmental problems of the Albany harbours require engineering and economic investigations and analyses before the best alternative can be selected.

This chapter outlines the considerations of possible short-term and long-term management options.

9.2 Short-term options

Extensive loss of seagrass has occurred in both harbours as a result of shading and smothering by algae which have proliferated due to an oversupply of nutrients which stimulated the growth of these plants. To prevent further immediate loss of seagrass, the amount of macroalgae in the harbours must be substantially reduced. In the short-term this can be achieved by physically removing the macroalgae. In the long-term, the supply of nutrients, which is causing the excessive growth of these plants, must be reduced if a recurrence of the problem is to be avoided. The environmental considerations of these management options are outlined below.

9.2.1 In harbour

Algal Harvesting

The harvesting of the macroalgae in the Albany harbours will remove the direct cause of seagrass death, significantly reduce the pool of nutrients bound up in the plants themselves and facilitate oxygenation of the sediments thereby minimising release of nutrients from the sediments. The main accumulations of macroalgae in Princess Royal Harbour occur in depths of less than 3m, particularly in the south-east and north-west sections of Princess Royal Harbour and the south-east corner of Oyster Harbour. As these accumulations occur over essentially bare sediment, any detrimental side effects of harvesting operations on the remaining seagrasses and animals are likely to be minimal. The deoxygenated conditions likely to occur under thick layers of macroalgae are unfavourable for most animals that live in the sediments of the harbours. Removal of macroalgae will provide the additional benefit of aiding oxygenation of these sediments, thereby providing a new habitat for animals.

The harvesting of macroalgae should only be considered as an interim measure. The long-term solution involves reducing the supply of nutrients to these plants by substantially reducing the current external nutrient loadings and the internal nutrient pools. Nutrients also occur in the tissues of plants and, in Princess Royal Harbour, the nutrients that occur in the algae represent a significant proportion of the total nutrient pool in the harbour. For these reasons, removal of the algae will be beneficial.

Reducing nutrient and heavy metal stores in the sediment

Analysis of the nutrient content of the sediments in the Albany harbours reveals that a significant proportion of the sediment nutrient store occurs in the superficial sediments (top 20mm) of the deep basins in water depths over 5m (Figure 1.1). The relative importance, however, of sediment nutrient recycling in the Albany harbours, in comparison to external inputs of nutrients, is unknown and requires investigation. This aspect and a more detailed survey of sediment nutrient concentrations in the deep basins should be undertaken before dredging of the sediments in the harbours is considered. Dredging would substantially reduce the largest nutrient pool in Princess Royal Harbour without significant side-effects on the remaining seagrass meadows because the deep areas of the harbours are devoid of any significant stands of seagrass.

Reducing heavy metal concentrations in the sediments of Princess Royal Harbour may lead to reductions in heavy metal contamination of fish that feed in the western end of the harbour. However, before this option is considered, the current extent of heavy metal contamination in the sediments and biota of Princess Royal Harbour, as well as an assessment of possible detrimental side-effects of removal, should be undertaken. An assessment of the likely time the western end of the harbour will remain closed to fishing if no action is taken should also be made.

9.2.2 Industry regulation

Improved management practices by industries would result in reduced effluent loads entering Princess Royal Harbour. Reductions in nutrients contained in solids and oils & grease inputs can be achieved both through the installation of new equipment and by the improved operation of existing equipment. Progressive reductions in industrial pollutant loads can be implemented by licensing industries under the Environmental Protection Act (1986).

Resiting of industrial outfalls within Princess Royal Harbour was considered but is not feasible due to the flushing characteristics of the harbour. The flushing of water at different locations within Princess Royal Harbour ranges between 1 day to 1 month (typically 20 days), with the areas near the harbour entrance having the shortest residence times and areas in the shallow western end of Princess Royal Harbour having the longest. In addition, some of the seasonal industries such as Metro Meats only operate over the summer months and effluents are discharged during daylight. During summer in Albany, the tide is usually flooding during daylight hours which promotes retention of wastes within the harbour. Given these relatively long residence times and the rapid uptake of pollutants by plants and animals, the possible resiting of outfalls at other locations within the harbour is unlikely to result in any significant improvement in the problems of Princess Royal Harbour and has not been considered further.

9.2.3 Urban

Urban pollution loadings may be reduced by diversion of urban runoff through existing and additional detention basins and artificial lakes on the Albany foreshore. Careful management of such detention basins (through lime-dosing, sediment removal etc) and artificial lakes (as wetland filters) would reduce the existing loading of heavy metals, pesticides and nutrients entering Princess Royal Harbour in urban runoff and also provide additional habitat for water birds and associated biota.

Community education programs in relation to improved use of household chemicals such as detergents, garden fertilizers and pesticides would result in reductions of these types of pollutants at their source.

Although septic tanks contribute relatively minor loads of nutrients to the Albany harbours when compared to other sources, this form of pollution should be minimised. This could be achieved by promoting connections to the sewage system where possible and by encouraging the use of acceptable alternative technologies such as composting toilets where connection to the main sewage system is not feasible.

Significant loads of pollutants are likely to be originating from Hanrahan Road rubbish tip. The main route of pollutants from this tip to Princess Royal Harbour is likely to be through the groundwater although pollutants may also enter the harbour in surface runoff. A detailed survey of groundwater entering Princess Royal Harbour is required before management strategies can be considered.

9.2.4 Rural

Immediate reductions in nutrient loads in rural runoff could be achieved by improved catchment management practices. Much of this nutrient loading is derived from horticultural and clover-based pastures on acidic, peaty, grey soils. These soils are often waterlogged in winter and many have been drained in order to establish agricultural crops. The inability of these acidic, peaty, grey soils to retain applied fertilizers (P and N), the efficient drainage system, high winter rainfall which results in high rates of leaching and shallow crop-rooting depths (particularly at the beginning of the season when fertilizers are applied and annual pasture plants are not fully established), all contribute to the high nutrient loadings observed in waterways draining catchments containing these soils and land-uses.

Reductions in the volume of surface runoff, and hence nutrient loading, may also be achieved through strategic tree plantings within specific catchments. Trees are beneficial because they pump large volumes of water out of the soil profile during transpiration, take up nutrients from a greater depth than shallow-rooted plants and provide a viable cash crop on maturity.

Nutrient losses to the harbours from point sources of pollution such as dairies, piggeries, intensive horticulture and disposal sites for sewerage and septic sludge could be carefully managed through licensing controls. Relocation of catchment nutrient point sources should be considered at existing sites in the catchments of the harbours where nutrient losses cannot be maintained below acceptable levels.

9.3 Long-term options

Pollutants such as the nutrients nitrogen and phosphorus, are discharged directly to Princess Royal Harbour through outfalls and indirectly via surface runoff and groundwater leaching (Figure 9.2).

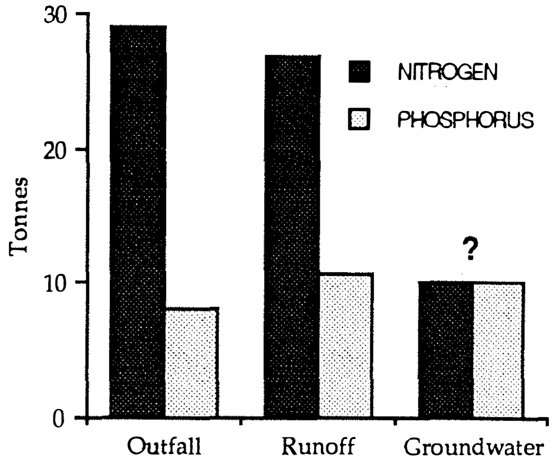


Figure 9.2 Annual nutrient loads entering Princess Royal Harbour in 1988 from industrial and domestic discharges, surface runoff and groundwater leaching. (? = estimates only)

Currently Metro Meats, Southern Processors, Kailis & France and Albany Woollen Mills all discharge effluents directly into Princess Royal Harbour via industrial outfalls. The WAWA outfall at King Point also contributes to the nutrient loading of the harbour. Surface runoff from agricultural and industrial catchments, one of which includes CSBP's industrial estate, also contribute significant quantities of nutrients to Princess Royal Harbour. Groundwater inputs from industrial (eg CSBP), rural and domestic (eg Hanrahan Road Tip) sources are also likely to contribute significant quantities of pollutants to the harbour but these are yet to be determined accurately.

Management options for these input types are outlined below.

9.3.1 Industry and domestic discharges

Continued disposal of existing effluents to Princess Royal Harbour

Continued discharge of the current waste streams from Metro Meats, Southern Processors, Kailis &

France and Albany Woollen Mills into Princess Royal Harbour is undesirable, as these streams reduce the amenity value of the harbour and cumulatively, contribute significantly to the present environmental problems.

Relocation of industry

Relocation of the Albany foreshore industries and their effluents would obviously result in a considerable improvement of the environmental quality of Princess Royal Harbour. The feasibility of relocating these industries from the shores of Princess Royal Harbour to more suitable sites was examined in a study commissioned by the Great Southern Development Authority (GSDA) and carried out by Binnie and Partners Pty Ltd in association with Wilson Sayer Core Pty Ltd. Important considerations were the cost of relocation, retention of the existing workforce (ie within 20km of Albany town centre) and the potential for contaminating water courses, groundwater resources, the Albany harbours and King George Sound.

Most of Albany's immediate hinterland to the north-west lies within the catchment area of the King River and its tributaries. To the west, drainage is via Marbellup Brook and Seven Mile and Five Mile Creeks to Lake Powell and eventually to Torbay Inlet. The Kalgan River catchment is located to the north of Albany and drains into Oyster Harbour. Elsewhere drainage is either to the Albany harbours, to interdunal lakes, or to the coast.

Other requirements for an extensive industrial estate on the outskirts of Albany include:

- relatively impermeable soils;
- flat or slightly sloping topography;
- area preferably greater than 175 ha (to cater for medium growth development);
- access to major roads and electricity supply;
- adequate groundwater or reticulated water supply;
- visually screened from major thoroughfare routes;
- well drained or able to be drained and;
- not located within Albany airport flight paths.

The total estimated cost involved in relocation of the five major industries would be in the order of $200M (Table 9.1).

Industry	Cost ($M)
Southern Processors Pty Ltd	~20
Metro Meats Pty Ltd	15-20
Albany Woollen Mills Pty Ltd	26-27
Kailis and France Pty Ltd	10-11
CSBP and Farmers Ltd	130+

Table 9.1 Estimated cost of relocating the Albany foreshore industries.

Relocation is considered a viable option for three of the factories, Southern Processors Pty Ltd, Metro Meats Pty Ltd and Kailis and France Pty Ltd. Relocation for Albany Woollen Mills Pty Ltd and CSBP and Farmers Ltd is not considered feasible or warranted given the opportunities for improved effluent treatment at their current locations. Voluntary relocation of existing industries is unlikely to occur and forced relocation is likely to require consideration of substantial compensation costs.

Improved on-site treatment

Over the past few years the amount of toxic substances entering Princess Royal Harbour has been substantially reduced. Co-operative action between the EPA and industry in Albany has resulted in massive reductions in lead and mercury (formerly in the CSBP effluent) and chromium and pesticides such as DDT (formerly in Albany Woollen Mills effluent) discharges into the harbour.

Currently, effluents entering Princess Royal Harbour contain only very small amounts of toxic materials such as heavy metals or pesticides but still contain relatively large amounts of biologically active materials such as nutrients, organic material and pathogenic bacteria. Existing discharges into Princess Royal Harbour could continue if the undesirable pollutants were removed by further on-site treatment. The feasibility of additional low-technology on-site treatment was examined in two studies. The first study was commissioned by the GSDA and carried out by Binnie and Partners Pty Ltd in association with Wilson Sayer Core Pty Ltd, and the second was commissioned by the EPA and carried out by Sinclair, Knight and Partners. In general, both studies identified a number of constraints which may preclude this option. Firstly, these studies indicated that the high level of treatment required to permit eventual discharge into Princess Royal Harbour using high-technology solutions would be prohibitively expensive. Secondly, less expensive, low-technology, on-site pond-based treatment was not considered appropriate for the industries discharging directly into the harbour because of the lack of suitable land and likelihood of increased odour generation associated with these ponds.

Low-technology treatment

Although on-site treatment will reduce existing problems it may introduce new ones which, in the long-term, may be more harmful to the marine environment of Princess Royal Harbour. For example, chlorination appears to be the only viable way to substantially improve the bacteriological quality of the effluent from Metro Meats. This process, however, may introduce unacceptable levels of toxic substances such as organochlorines into the harbour.

Further disadvantages identified in these reports are that pond-based on-site treatment with its attendant odour problems and eventual discharge to the harbour would reduce the amenity value of Princess Royal Harbour and, as such, would be incompatible with the proposed Albany foreshore redevelopment.

High-technology treatment

A preliminary study of the feasibility of high-technology treatment of the wastes of the Albany foreshore industries was commissioned by the EPA and undertaken by Campbell Environmental Ltd. This study indicated that biological wastewater treatment technology, using anaerobic digestion of the organic components of effluent streams, has recently been developed. Methane gas is produced during the digestion process and could offset running costs of this type of treatment by partially replacing fossil fuels currently used in industrial processes.

According to the study, a fully contained, on-site facility of this type produces no odours and would require between 0.2 and 0.5ha of land to treat the combined effluent from all industries that are currently discharging directly into Princess Royal Harbour. Coupled with an aerobic treatment system, the final effluent characteristics could be reduced to meet Princess Royal Harbour effluent discharge criteria (Appendix 1).

Preliminary estimates indicate that a fully contained treatment facility could be constructed for an initial cost of about $2M with ongoing annual operational costs of about $100,000. Because high-technology wastewater treatment of this type is largely un-tried in Western Australia, a further evaluation of the different technologies available, in relation to their efficiency and suitability for the Albany foreshore industries, is required.

Diversion of effluent away from Princess Royal Harbour

Most of the environmental problems in the Albany harbours arise from poor flushing of the harbours and restricted interchange of water with the ocean. As a result, there is time for the plants, animals and sediments to absorb pollutants before they can be flushed to the ocean.

Currently, effluents entering Princess Royal Harbour contain only very small amounts of toxic materials such as heavy metals or pesticides but still contain relatively large amounts of biologically active materials such as nutrients, organic material and pathogenic bacteria. In an enclosed waterbody such as Princess Royal Harbour these effluents will continue to cause problems. However, if these effluents were diverted away from the harbour, the environmental problems in the harbour would be greatly diminished. While the diversion of pollutants from one part of the environment to another can reduce the immediate problems at hand, it may also simply transfer the problems elsewhere or create a different set of problems altogether. If these effluents were diverted to a treatment plant via an industrial sewer and then discharged to the ocean or to the land, then several issues, apart from the purely economic considerations, arise. For example, does the new receiving environment have the capacity to assimilate the wastes and will the existing uses of that environment be significantly impaired? Thus, any solution to the environmental problems of Princess Royal Harbour involving the diversion of industrial and domestic effluents away from the harbour requires careful consideration which, ultimately, will involve trade-offs.

The considerations of various options to either partially or totally divert industrial and domestic wastes away from Princess Royal Harbour were examined in two studies. The first was commissioned by the GSDA and carried out by Binnie and Partners Pty Ltd. in association with Wilson Sayer Core Pty Ltd. and the second was commissioned by the EPA and carried out by Sinclair, Knight and Partners. Several of these options are outlined briefly below. For further details of these and the other options these reports can be consulted at the EPA office in Perth and GSDA office in Albany.

(a) Tidally synchronised disposal to Princess Royal Harbour

This option would require storage of the current waste streams for disposal to the entrance channel of Princess Royal Harbour on an outgoing tide. The unavailability of suitable storage facilities, lack of space, difficult topography and the high possibilities of odour generation while the waste is stored make this option unacceptable. Furthermore, although this method of disposal would transfer some of the pollutants to King George Sound where dilution and dispersion is significantly better than Princess Royal Harbour, it is unlikely to resolve all of the environmental problems caused by the discharge of untreated waste to the harbour.

(b) Direct disposal into King George Sound

Waste disposal by this method would involve effluent currently entering Princess Royal Harbour being discharged into King George Sound through a short submarine pipeline. One disadvantage of this option is that it could not guarantee that nutrient loads into Princess Royal Harbour would be significantly reduced as the outfall would be in close proximity to the harbour entrance. In addition the discharge of untreated waste at this point is likely to result in significantly increased coliform counts at Middleton Beach. Disinfection of the waste stream to reduce this health hazard is not considered feasible for a number of reasons. For example, low-cost disinfection by chlorination may introduce unacceptable levels of toxic substances such as organochlorines into the waters of King George Sound.

(c) Diversion of effluent via a combined WAWA/industry sewer

This option would involve all industries currently discharging wastes into Princess Royal Harbour entering a combined WAWA/industry sewer upstream of a WAWA treatment plant. WAWA has established specific criteria for admission to sewer and as a result, some industries would require extensive pretreatment of their effluent to allow pumping and permit entry to the treatment plant. The treated waste could then be discharged either to the ocean or the land. These two alternatives are considered in more detail below. Other alternatives such as a separate industrial sewer discharging to the ocean without further waste treatment other than that required for pumping have been examined but are not considered further here because the discharge of untreated waste to the environment is unacceptable. The discussion that follows is also applicable to the diversion of domestic wastewater alone, without the inclusion of industrial waste streams.

(i) Ocean discharge: The environmental impacts of ocean discharge of wastes at different sites would depend largely on the physical and biological characteristics of the receiving environment and the level of waste treatment. For example, if problems associated with nutrient enrichment are to be avoided, waste discharged into waters that are poorly flushed require substantially more nutrient removal than discharge occurring in well-flushed areas. The discharge of domestic wastewater to the ocean in the Albany area has recently been reviewed by the WAWA in a strategy outlining long-term wastewater treatment and disposal options in the Albany region. Several possible sites were examined and the conclusion reached was that disposal into the Southern Ocean in the vicinity of Sand Patch is likely to be the most suitable alternative on the basis of potential ecological impacts, minimising interference with existing uses, and on engineering and treatment costs. This conclusion relates to the discharge of treated domestic wastewater only but is also likely to be valid for industrial effluents from the industries in Albany which contain relatively high levels of biologically active materials such as nutrients, organics and bacteria but low amounts of toxic substances such as heavy metals and pesticides.

The high wave energy at Sand Patch is likely to promote dilution and dispersion of treated wastes. As a result, the effects of nutrient loading in the nearshore waters at Sand Patch are unlikely to be significant, obviating the need for high levels of nutrient removal from the waste stream and thereby reducing treatment costs. Similarly, the low level of toxic materials in the treated waste stream is unlikely to cause unacceptable levels of contamination in fish or other marine life at this site. A disadvantage of this option, however, is that the wastes would have to be discharged at the shoreline because the exposed nature of this site and the coastal topography is likely to impose severe engineering constraints.

A shoreline discharge of secondary treated waste is likely to result in significant localized concentrations of pathogenic bacteria occurring in the nearshore waters, posing a potential threat to human health. Bacterial concentrations could be reduced by additional treatment but, if chlorination was to be used, may result in further detrimental side effects such as the introduction of organochlorines into the local marine environment. Further disadvantages include the high engineering costs of this option and some disturbance to the ecology of Torndirrup National Park.

(ii) Disposal to land: It is considered feasible to dispose of the waste streams to irrigation or evaporation with appropriate on and off-site treatment prior to disposal providing suitable sites can be found. Considerations of these options are summarized below.

<u>Irrigation:</u> The main concern of using treated industrial and domestic wastes to irrigate crops is the possible leakage of pollutants into the environment. For example, if phosphorus loadings exceed the uptake rates of the irrigated crops, then phosphorus may eventually leach out and contaminate groundwater and water courses. This problem can be reduced by 'amending' high phosphorus leaching soils with material having a high phosphorus retentive capacity, such as laterite loam. Continuous use of an irrigated plot may also result in soil toxicity problems, possibly necessitating two or more plots used in rotation from year to year. The type of crop grown is also dependent on the quality of the effluent. For example, if heavy metals were present in the waste stream then it may be unsuitable for irrigation of edible crops but suitable for growing trees.

The benefits of land disposal, as opposed to ocean disposal, of essentially non-toxic, nutrient enriched wastes is that two scarce resources in Western Australia, freshwater and plant nutrients, would be used to produce commercially valuable crops rather than being 'lost' to the ocean. In addition, the potential environmental risks involved in land disposal are likely to be easier to determine and manage.

Evaporation: Disposal of effluent by evaporation was also considered in the two studies. For this option to be technically viable it would require suitable land being available within 10-15km of Albany and the construction of impervious evaporation ponds. Careful monitoring would be required, however, to ensure that any effluent leaked from the ponds would be detected and remedied promptly.

9.3.2 Rural and Industrial Runoff

Significant quantities of nutrients enter Princess Royal Harbour in surface runoff from rural and industrial land via Robinson Estate Drain. This drain collects runoff from a relatively small catchment which includes CSBP's industrial estate. Runoff enters Oyster Harbour from rural land largely via the King and Kalgan Rivers which drain large catchments to the west and north of the harbour and several smaller creeks and drains. Oyster Harbour does not receive runoff from from industrial sources.

Improved fertilizer strategies including: soil testing to determine minimum fertilizer requirements; the use of slow-release fertilizers; later application of fertilizers (when pasture rooting depth is greater); and liming very acidic soils will all contribute to reductions in nutrient losses from the agricultural catchments of Princess Royal Harbour and Oyster Harbour.

Reductions in phosphate losses in surface runoff from CSBP's industrial estate have been achieved in 1988/89 by diverting runoff through lime-dosing ponds. Strategic tree planting within this catchment would also minimize nutrient losses by reducing surface runoff and by increased uptake of nutrients by the trees.

9.3.3 Groundwater inputs

Groundwater inputs are likely to contribute significant quantities of nutrients to the Albany harbours, particularly to Princess Royal Harbour. The main sources of these nutrients are fertilizer losses from agricultural lands in the catchments of the harbours. Other sources to Princess Royal Harbour include CSBP's industrial estate on the western shores of Princess Royal Harbour, and the Hanrahan Road tip. Estimates of these inputs have been made to determine the relative importance of this type of pollution. More detailed surveys of groundwater inputs to Princess Royal Harbour and Oyster Harbour are required before management strategies can be formulated and implemented.

9.4 Evaluation of management options

A number of possible management options for the Albany harbours were described above in section 9.1. These options were divided into sets of short and long-term options and are evaluated below. Although short-term harbour management options are regarded as interim measures, their effectiveness and suitability must also be evaluated in light of suggested long-term management goals. The long-term goals are centred on improving the ecological health of the harbours by reducing effluent inputs to the harbours, and the size of nutrient pools already present in the harbours.

9.4.1 Short-term options

Algal harvesting

Algal harvesting is feasible using purpose-made equipment, and will greatly reduce the biomass of algae in the harbours and is likely to improve the retention of nutrients in the sediment. In addition, removal of algal accumulations will reduce the size of the nutrient pools of the harbours.

Dredging

Dredging of Princess Royal Harbour and Oyster Harbour is feasible with existing equipment and would significantly reduce the stores of nutrients, as well as heavy metals bound to organic material, in the sediments of the harbours. However, an evaluation of the overall impacts of dredging on the biological communities of the harbours should be undertaken before this option is considered.

Industry Regulation

Resiting of industrial outfalls to other locations within Princess Royal Harbour is not considered feasible as significant improvements in harbour water quality are unlikely to be attained. Reductions in effluent quantity and improvements in effluent quality can be obtained through licensing controls under the Environmental Protection Act (1986).

Urban

It is feasible to intercept and partially deplete nutrients and other contaminants in urban runoff by utilising the existing artificial lakes on the Albany foreshore as retention basins and biological filters. Community education programs are also relatively easy to implement and can help reduce inputs at the source. The interception of nutrient-laden groundwater is likely to be difficult except where possible point sources, such as the Hanrahan Road Tip, are identified.

Rural

Improved catchment management programs that will reduce nutrient loadings into the harbours can be initiated and are feasible to implement. The success of this program depends on co-operation and involvement of farmers within each catchment. However, it is unlikely that significant reductions in rural nutrient inputs to the Albany harbours can be achieved in the short-term without drastic changes in land-use.

9.4.2 Long-term options

(i) *Industry and Domestic Discharges*

(a) Continued disposal into Princess Royal Harbour

Continued disposal of industrial effluent into Princess Royal Harbour, without dramatic improvements in effluent quality, is not considered a feasible option that is compatible with the long-term environmental sustainability of the harbour.

(b) Relocation of Industry

The relocation cost for all industries is estimated to be in the order of $200M and as such, is not considered to be feasible on economic grounds.

(c) Improved on-site treatment

Low-technology on-site treatment is not considered a feasible option at this stage given both the lack of suitable areas of land for pond-based treatment and the incompatibility with the proposed redevelopment of the foreshore due to the increased odours that are likely to be generated by this form of treatment.

Recent information on high-technology on-site treatment suggests that technology is available to treat the industrial wastes from the four industries currently discharging into the harbour to a level that would allow continued harbour discharge.

(d) Diversion of effluent away from Princess Royal Harbour

Effluent diversion from Princess Royal Harbour is a feasible option for controlling and redressing the ecological problems in the harbour.

- Tidally synchronised disposal to Princess Royal Harbour

  This option is not considered feasible with available storage facilities and is unlikely to resolve all of the environmental problems associated with direct disposal into Princess Royal Harbour.

- Direct disposal to King George Sound

  This option provides no guarantees that significant loads of effluent will not enter Princess Royal Harbour via the harbour mouth. Increased contamination of King George Sound and Middleton Beach is also likely to occur. Given this information this option is not considered feasible.

- Diversion of effluent via a combined WAWA/industrial sewer

  Complete diversion of industrial effluent from Princess Royal Harbour via a combined WAWA/industrial sewer is feasible and is likely to cost in excess of $10M. This option, however, should only be considered if high-technology treatment of industrial wastes is not viable. The diversion of domestic wastewater without industrial effluents is feasible.

(ii) *Rural and Industrial runoff*

Catchment management practices have proved to be partially successful in the catchment of the Peel-Harvey Estuary and similar strategies, suitably modified to conditions in the Albany region, could be implemented to reduce nutrient losses from the Albany catchments.

9.5 Conclusions

Seagrass meadows provide food, shelter and a breeding ground for fish and many other animals and, in the past, have been at the base of the food web of the Albany harbours. Since 1962, when these seagrass meadows were considered to be in a pristine condition, about 90% of the meadows in Princess Royal Harbour and 80% in Oyster Harbour have been lost. In recent years the rate of seagrass loss in the harbours has accelerated due to a proliferation of macroalgae which shade and smother the seagrass meadows. The growth of macroalgae has been stimulated by excessive nutrient inputs to Princess Royal Harbour from industrial, rural and urban sources, and to Oyster Harbour from rural and urban sources.

Current information on the 'recovery' of seagrass meadows suggests that the luxuriant *Posidonia* meadows that once covered most of the Albany harbours will never return to their former state. However, once the large accumulations of macroalgae that presently occur in the harbours are removed and pollutant inputs are drastically reduced, conditions in the harbours are likely to improve sufficiently to allow the remaining seagrasses to flourish and other seagrass species and animals to colonise suitable bare areas of seabed.

If the recommendations in this report are implemented, seagrass decline in both waterbodies will slow down and eventually stop as the biological systems stabilize. In addition, pollutants such as faecal bacteria, solids, oils & greases and visible effluent slicks in the waters and along the shorelines of Princess Royal Harbour and King George Sound will be significantly reduced within two years. Furthermore, if the amount of heavy metals in the sediments of the western end of Princess Royal Harbour is significantly reduced, the re-opening of this part of the harbour to fishing is likely to occur earlier than if the removal of heavy metals from the sediment is left to natural processes.

If, on the other hand, the current pollutant loadings into these harbours continue, the bacteriological and aesthetic quality of Princess Royal Harbour and parts of King George Sound will decline further. In addition, most of the remaining seagrasses will be lost within five years in Princess Royal Harbour and within 5-10 years in Oyster Harbour and the general ecology of the harbours will continue to deteriorate.

Chapter 10

Recommendations

This final chapter presents the principal recommendations which resulted from the Albany Harbours Environmental Study. The recommendations are divided into two groups: (i) specific recommendations which, if implemented immediately, will not only retard the rate of seagrass decline but also provide immediate improvements in the general environmental quality of the Albany harbours and; (ii) general recommendations that provide guidelines for long-term environmental management strategies in the Albany region. Recommended Princess Royal Harbour effluent discharge criteria are outlined in Appendix 1.

10.1 Specific recommendations

Large accumulations of algae are the direct cause of historical and current widespread death of seagrasses in both harbours. The harvesting of the macroalgae in the Albany harbours will remove the direct cause of seagrass death, significantly reduce the store of nutrients bound up in the plants themselves, and facilitate oxygenation of the sediments, thereby minimising release of nutrients from the sediments. The main accumulations of macroalgae in Princess Royal Harbour occur in depths of less than 3m, particularly in the south-east and north-west sections of Princess Royal Harbour, and the south-east corner of Oyster Harbour. As these accumulations occur over essentially bare sediment, detrimental side-effects of harvesting operations on the remaining seagrasses are likely to be minimal. Similarly, the effects of harvesting on the animal populations in the harbours are also likely to be insignificant as the deoxygenated conditions that occur under thick layers of algae are unlikely to be favourable for most animals. Removal of the algae will provide the additional benefit of allowing these sediments to become re-oxygenated, thereby providing additional habitat for animals that live in the sediment.

Harvesting of algae should only be considered as an interim measure. The long-term solution involves reducing the supply of nutrients to these plants by substantially reducing the current external nutrient loadings into the harbours.

Recommendation 1

Immediate removal of the large accumulations of macroalgae in Princess Royal Harbour and Oyster Harbour. The rate of algal removal should be sufficient to remove these accumulations within two years.

Analysis of the nutrient content of the sediments in the Albany harbours reveals that a significant proportion of the total sediment nutrient store occurs in the superficial sediments (top 20mm) of the deep basins in water depths over 6m. The relative importance, however, of sediment nutrient recycling in the Albany harbours, in comparison to external inputs of nutrients, is unknown and requires investigation. This aspect and a more detailed survey of sediment nutrient concentrations in the deep basins should be undertaken before dredging of the sediments in the harbours is considered. Dredging would substantially reduce the largest nutrient pool in Princess Royal Harbour without significant side-effects on the remaining seagrass meadows because the deep areas of the harbours are now devoid of any significant stands of seagrass.

Recommendation 2

Evaluation of removal of nutrient-rich sediments from the Albany harbours as an effective environmental management strategy be undertaken, as a matter of high priority, by the proposed Albany waterways management authority.

Pollutants enter the Albany harbours in groundwater, surface runoff and in industrial and domestic effluents. Diffuse sources of pollutants such as in rural and urban groundwater and surface runoff contribute a significant proportion of the total nutrient loads into the Albany harbours but are considerably more difficult to manage in the short-term than industrial and domestic effluent discharges and groundwater and surface runoff from point sources.

Until inputs from diffuse sources are significantly reduced, pollutants from rural runoff and groundwater will consume most of the assimilative capacity of Princess Royal Harbour. Thus, to achieve the goal of reducing total nutrient loads into Princess Royal Harbour to below the assimilative capacity of the harbour within two years and thereby arrest the current rapid decline in the remaining seagrass meadows, inputs from industrial, domestic and urban point sources must be substantially reduced within this timeframe.

Recommendation 3

The four industries currently discharging directly into Princess Royal Harbour be directed to commence immediately, the formulation of a strategy, and to reduce, within two years, industrial pollutant loads currently entering Princess Royal Harbour. In the event of continued discharge to Princess Royal Harbour, as a minimum requirement, effluent quality from these industries is not to exceed Princess Royal Harbour effluent discharge criteria and pollutant loads are to be acceptable to the Environmental Protection Authority.

Recommendation 4

CSBP be directed to commence, immediately, the formulation of a strategy and to reduce, within two

years, surface runoff nutrient loads into Princess Royal Harbour from its industrial estate to levels acceptable to the Environmental Protection Authority.

Recommendation 5

CSBP be directed to complete, within one year, a program to determine the current and likely future groundwater nutrient loads into Princess Royal Harbour from its industrial estate. Upon completion, CSBP be directed, if necessary, to implement a management plan that will reduce, within one further year, current and future groundwater nutrient loads into Princess Royal Harbour to levels acceptable to the Environmental Protection Authority.

Recommendation 6

The Water Authority of Western Australia commence immediately, the formulation of a strategy to reduce, within two years, pollutant loads in domestic wastewater effluent from the King Point outfall to levels acceptable to the EPA. Alternatively, the Water Authority of Western Australia commence immediately, the formulation of a strategy to divert, within four years, the domestic wastewater currently discharged from the King Point outfall.

Recommendation 7

The Town and Shire of Albany be encouraged to complete, within one year, a program to determine the groundwater and surface runoff pollutant loads into the Albany harbours from urban point sources. Upon completion of this program, the Town and Shire of Albany, if necessary, be encouraged to implement a management plan that will reduce, within one further year, current and future groundwater and surface runoff pollutant loads from point sources to the Albany harbours to levels acceptable to the EPA. As an incentive to local government to reduce pollution from urban sources, co-operative use of existing State Government resources such as the Chemistry Centre, the Department of Health and the Department of Agriculture be provided.

Pollutants from diffuse urban sources enter the Albany harbours via groundwater and surface runoff. Fertilizers and pesticides applied to household gardens, septic tanks as well as pollutants from car exhausts, tyres and accidental spillages all contribute to the pollution of the harbours. Minimization of the 'downstream' effects of these pollutants on the harbours requires a commitment by the community to control these pollutants at their source. The innovative approach by the Town and Shire of Albany in establishing the first successful urban-waste recycling program in Western Australia provides a good basis for continuing control of urban pollution.

To achieve a reduction in the pollutant loads from urban diffuse sources, surface runoff into the harbours should be intercepted so that pollutants can be removed. Increased usage of more 'environmentally friendly' household products, appropriate planning strategies regarding the siting of septic tanks and the use of alternative technologies for the management of domestic wastes, should also be promoted.

Recommendation 8

The Town and Shire of Albany be encouraged to develop a management plan to minimize pollution of the Albany harbours from urban diffuse sources. To promote community involvement, the Town and Shire of Albany be encouraged to undertake an education programme related to minimising pollution from these sources.

The annual nutrient assimilative capacity of Princess Royal Harbour is estimated to be approximately 7 tonnes of total phosphorus and 54 tonnes of total nitrogen. Desirable loads during a 'recovery' phase of this waterbody, that is while the decline is arrested and the ecosystem stabilizes, are zero. The rate of 'recovery' will depend on the level of nutrient loading in excess of zero, provided the assimilative capacity is not exceeded. If the assimilative capacity is exceeded during this period, the ecosystem will continue to decline.

In 1988 approximately 29 tonnes of phosphorus entered Princess Royal Harbour. Of this total, about 7 tonnes were estimated to have entered from rural sources, about 4 tonnes from community sources and 18 tonnes from industrial sources. If the recommendations in this report are implemented, inputs from industrial and community sources will decrease, within two years, to less than about 5 tonnes, based on current input estimates. Although this represents a significant reduction in phosphorus loading of about 80%, when the remaining load from industrial and community sources is added to the existing rural phosphorus loading into Princess Royal Harbour, the assimilative capacity will be exceeded by about 50% and the harbour will continue to decline. This emphasizes the urgent need to substantially reduce nutrient losses, particularly phosphorus, from the rural catchment of Princess Royal Harbour.

Because of the complexity of the physical processes in Oyster Harbour, the annual nutrient assimilative capacity is difficult to estimate with the information that is currently available. Limited data suggests that the mean annual nutrient loading into Oyster Harbour is approximately 30 tonnes of total phosphorus and about 350 tonnes of total nitrogen and that the source of most of these nutrients are fertilizers washed off agricultural land in the catchment of Oyster Harbour.

The estimated annual nutrient assimilative capacity of Oyster Harbour is about 7-14 tonnes of total phosphorus and 54-108 tonnes of total nitrogen. These estimates should be regarded as initial management targets and indicate that inputs of nutrients, particularly phosphorus, into Oyster Harbour from agricultural land must be drastically reduced if the current decline in the seagrass meadows in the harbour is to be arrested. Further investigations into the nutrient dynamics of Oyster Harbour are necessary to refine these initial estimates of the annual nutrient assimilative capacity.

Recommendation 9

The Western Australian Department of Agriculture continue, in consultation with farmers and other groups, to develop and promote the adoption of catchment management plans which will assist with the reduction of nutrient loads to target levels as determined by the Environmental Protection Authority. As an incentive to adopt more efficient fertilizer use, funding be provided for two years, for a free soil testing service targeted on sandy (low reactive iron) soils in the catchments of the Albany harbours.

Recommendation 10

The Western Australian Department of Agriculture evaluate current soil survey, land-use and other natural resource information to identify high phosphorus source areas (including point sources) within the catchments of Princess Royal Harbour and Oyster Harbour, and prepare a strategy for their management by June 1990.

Recommendation 11

Further investigations to refine initial estimates of the annual nutrient assimilative capacity of Oyster Harbour be undertaken as a matter of high priority by the proposed Albany waterways management authority.

The levels of mercury in 15 species of fish from Princess Royal Harbour have been monitored annually since 1984 when the effluent (containing lead and mercury) from CSBP's fertilizer works ceased discharging into the western end of Princess Royal Harbour. Mercury levels remain above the health limit in most of the species tested and it appears that the re-opening of the western end of Princess Royal Harbour to fishing is unlikely in the near future. A limited survey of heavy metal concentrations in the sediments in the vicinity of the former CSBP outfall was conducted by the Environmental Protection Authority in 1989. The results of this survey indicated that mercury concentrations in the sediments have not decreased significantly since 1984 suggesting that the natural flushing of heavy metals from the harbour is very slow.

Tourism in the Albany region depends largely on the public perception of the environmental quality of the Albany region, of which the Albany harbours are an integral part. The closure of the western end of Princess Royal Harbour to fishing mitigates against a perception of high environmental quality and thus all options in relation to the re-opening of the western end of the harbour should be examined.

Recommendation 12

CSBP be directed to undertake an extensive survey of the heavy metal concentrations in the sediments and biota of Princess Royal Harbour to assess the current state of contamination of the harbour and, if necessary, to formulate, within one year, a management plan to reduce the state of heavy metal contamination of Princess Royal Harbour to levels, and within a timeframe, acceptable to the Environmental Protection Authority.

10.2 General recommendations

All waterbodies have a capacity to absorb some pollutants without long-term damage to their biological systems. This "*assimilative capacity*", however, is limited and depends on the physical and biological characteristics of the receiving environment and the type of wastes that are discharged into it. For example, poorly-flushed waters have a much lower capacity to assimilate identical pollutant loads than well-flushed waterbodies.

Biological systems like the Albany harbours, where the assimilative capacity has been exceeded for many years, are usually severely degraded. During the 'repair' phase of degraded waterbodies, it is desirable that total pollutant loads are as close to zero as possible, that is, well below the level the system could absorb once decline is halted and the system is stable. Any additional pollutant loads up to the level of the assimilative capacity will lengthen the 'recovery' time. If the assimilative capacity is exceeded during this period the ecosystem will continue to decline.

The assimilative capacity is a resource to be partitioned equitably between all the 'user' groups (industry, rural and community). The partitioning of the assimilative capacity may depend on factors such as the relative socio-economic importance of the 'user' to the community as a whole.

Current information indicates that the annual nutrient assimilative capacity for Princess Royal Harbour is approximately 7 tonnes of total phosphorus and 54 tonnes of total nitrogen. Initial estimates for Oyster Harbour indicate that the annual nutrient assimilative capacity is approximately 7-14 tonnes of total phosphorus and 54-108 tonnes of total nitrogen.

These estimates should be considered as management targets for annual nutrient loading into the harbours and be subject to review as further information becomes available.

Recommendation 1

Annual total nutrient loading into Princess Royal Harbour and Oyster Harbour from all sources should not exceed the nutrient assimilative capacities of these waterbodies.

Princess Royal Harbour and Oyster Harbour are waterways of great ecological, aesthetic and recreational importance to Albany and the Great Southern Region. Currently, however, these waterways are severely degraded. If the recommendations in this report are implemented the environmental condition of Princess Royal Harbour and Oyster Harbour will improve significantly over the next five years. However, if significant reductions in nutrient loadings into the harbours are not achieved, the short-term prognosis for the Albany harbours is one of continued environmental deterioration.

To achieve real improvements to the current environmental state of these two waterbodies, it will be necessary, not only to significantly reduce nutrient loadings from existing sources, but also to severely limit, or prevent, future additional nutrient loadings from new sources. Future industrial, urban and rural developments in the catchments of the Albany harbours should be assessed from this perspective.

Recommendation 2

Future development proposals and management of industrial, urban and rural land-use in the catchments of the Albany harbours should have regard for the capacity of these waterways to assimilate pollutants, particularly nutrients.

Until about 15 years ago, the environmental implications of certain activities in the catchments of enclosed waterbodies, like the Albany harbours, were little appreciated and poorly understood. As a result, the clearing of land for agriculture and the widespread application of fertilizers to supplement nutrient-poor soils, as well as the use of waterways for the discharge of industrial and domestic wastes, were undertaken without considering possible 'downstream' environmental problems.

As these problems became apparent in the 1970s, an appreciation developed of the interconnectedness of activities within the catchments of these waterbodies. By this time however, many of these activities were firmly entrenched and no easy solution to the environmental problems could be found. The end result, in many cases, has been severe deterioration of the biological communities and, as a result, a loss of valuable community resources. This scenario essentially describes the decline of the Albany harbours.

To arrest the decline and facilitate recovery of the Albany harbours, the community as a whole must take account of the influence and potential impacts of activities in their catchments upon the health of the harbours. This requires an integrated approach to environmental management involving extensive community consultation, co-operation and co-ordination of all activities that potentially threaten the long-term ecological viability of the harbours.

Recommendation 3

A regional liaison structure be developed to ensure co-ordination of Government, technical and community responses to the integrated management of the catchments and waterways of the Albany harbours.

The effective management of the Albany harbours requires an on-site management presence. Furthermore, the implementation of several of the recommendations contained in this report requires some form of management structure in Albany. Management-related activities such as algal harvesting, pollution control and refining initial estimates of the annual nutrient assimilative capacities of the harbours as well as providing waterways management expertise to Government, local government and community groups concerned with the 'restoration' of the Albany harbours could be part of the role of an on-site management authority. An annual pollution audit from industrial, urban and rural sources could also be undertaken by a management authority to monitor the effectiveness of the management measures recommended in this report.

Recommendation 4

A management presence be established to provide for future on-site management of the Albany harbours. An Albany Waterways Management Authority could be established under the Waterways Commission Act with direct local government and community involvement.

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Appendix I

Recommended Princess Royal Harbour effluent discharge criteria

Appendix 1: Recommended Princess Royal Harbour effluent discharge criteria

Effluent Category	WAWA sewer entrance criteria (mg/L)	Princess Royal Harbour effluent discharge criteria (mg/L)
Discharge volume	to be determined	to be determined
BOD_5	<3000	<20
Suspended Solids	<1500	<80
Oil&Grease	<100	<30
Surfactants	not applicable	<10
Total nitrogen	not applicable	<10
Total phosphorus	not applicable	<3

Appendix 2

Glossary

Appendix 2: Glossary

Annual load - Total amount of a substance carried in 12 months. Calculated by multiplying concentration of a substance (weight per unit volume *eg* mg/l) in water by the volume of the flow.

Benthic - On the bottom of a waterbody.

Biomass - The weight of living matter in a particular area.

Biota - The plant and animal life found in a particular environment.

BOD_5 - Biochemical oxygen demand. A laboratory-based determination of the 5-day oxygen demand of a water sample, where the activity of micro-organisms and the oxidation (breakdown) of complex molecules (eg fats, starches) provides the oxygen demand.

Catchment - A region or drainage basin which collects all the rainfall that falls on it.

Chlorophyll *a* - Chlorophyll *a* is a complex molecule that, along with other similar molecules, is able to capture sun-light and convert it into a form that can be used for photosynthesis. All plants contain chlorophyll *a* and the concentration of this molecule in water is commonly used as a measure of phytoplankton abundance.

Coliform - Bacteria commonly associated with human and animal waste.

Community - In ecology, any naturally occurring group of different organisms sharing a particular habitat.

COD - Chemical oxygen demand. Provides a measure of the oxygen equivalent of that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant. This measure gives an approximation of the biochemical oxygen demand of a sample.

Decomposition - The separation of organic material into simpler compounds.

Ecosystem - A natural complex of plant and animal populations and the particular sets of physical conditions under which they exist.

Effluent - The liquid, solid or gaseous products discharged by a process, treated or untreated.

Epiphytes - Small unicellular, filamentous and fleshy algae that are attached to the leaves of seagrasses.

Eutrophication - The gradual buildup of nutrients in a system to the point where unnatural growth of algae occurs. Eutrophic systems are nutrient enriched.

Groundwater - Water which occupies the pores and crevices of rock and soil, as opposed to surface water.

Heavy metals - These metals are stored and accumulate in sediments and the tissues of animals, and may be passed up the food chain. Heavy metals include; cadmium (Cd), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), and mercury (Hg). Arsenic (As), is often included in this category.

Kl - Kilolitres or thousands of litres. 1 Kl equals one cubic metre (m^3).

ms^{-1} - Meters per second. 1ms^{-1} is roughly equivalent to 2 knots.

Leaching - The process by which material is washed out of a layer of soil.

Macroalgae - Group of filamentous and fleshy, non-flowering aquatic plants that are found in estuaries and the ocean. Commonly referred to as 'seaweed'.

Meristem - An assemblage of very actively dividing cells that form the growing point of a plant.

Ml - Megalitres or millions of litres.

N and P - Nitrogen (N) and phosphorus (P) are the main nutrients required by terrestrial and aquatic plants. These two nutrients are usually in short supply in marine water and therefore limit plant growth. Increased supply of these nutrients usually results in an increased growth of aquatic plants.

Oils and greases - Includes greases, fatty acids, soaps, fats, waxes and oils that are extracted in the solvent and not volatilized during evaporation of the sample.

Oligotrophic - Applied to a waterboby containing relatively low amounts of nutrients. Opposite of eutrophic.

Organochlorines - These toxic pesticides are highly persistent. If ingested at sub-lethal doses, these compounds are stored and accumulated in the fatty tissues of animals. Organochlorines may be passed up the food chain. They include; aldrin, chlordane, DDT, dieldrin, HCB, heptachlor and lindane.

Organophosphates - These toxic pesticides are far less persistent than the organochlorines. If ingested at sub-lethal doses, these compounds are usually readily broken down by animals and excreted. As a consequence, these compounds are generally not passed up the food chain. Organophosphates include; chlorpyrifos and diazinon.

Perennial - lasting for more than one year or growing season.

Periphyton - Small algae that are attached to artificial substrates.

Photosynthesis - A process, that operates in chlorophyll containing plants, which uses solar energy to convert carbon dioxide and water into carbohydrate.

Phytoplankton - Single celled plants (algae) that live in the water column.

Primary treatment - In relation to sewage treatment this generally involves a mechanical screening process that removes the coarser materials.

Runoff - The discharge of water through surface streams into larger watercourses.

Seagrass - Submerged flowering plants that mainly occur in shallow marine areas although some species are found in estuaries. Seagrasses can form dense meadows in some localities, and these are known to be very important in providing food and shelter for a wide variety of organisms. *Posidonia* species are commonly called 'ribbon weed'.

Sewage - The contents of sewers carrying the waterborne wastes of a community.

Standing crop - The biomass or organic matter present on a given area at a given time; it usually varies with season.

Suspended solids - Solids suspended in a liquid that can be removed by sedimentation.

t - Tonnes.

Toxic - Capable, through chemical action, of killing, injuring, or impairing an organism.

Trophic status - Level of enrichment of a waterbody.

Total soluble salts - Total amount of dissolved salts.

μmol m^2s^{-1} - Unit used to quantify photosynthetically active radiation intensity, that is the wavelengths of light that are suitable for use by plants during photosynthesis. 2000μmol m^2s^{-1} is approximately equal to the intensity of summer sunlight measured in air at midday.

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Temp (C)
20.84
21.03
21.22
Salinity (ppt)
35.66
35.72
35.78
Density (kg/m³)
24.93
25.02
25.11
Depth (m)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Temperature (ºC)
24
23
22
21
20
19
18
Light (µmol m⁻² s⁻¹)
1000
0
14
15
16
17
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28
29
January