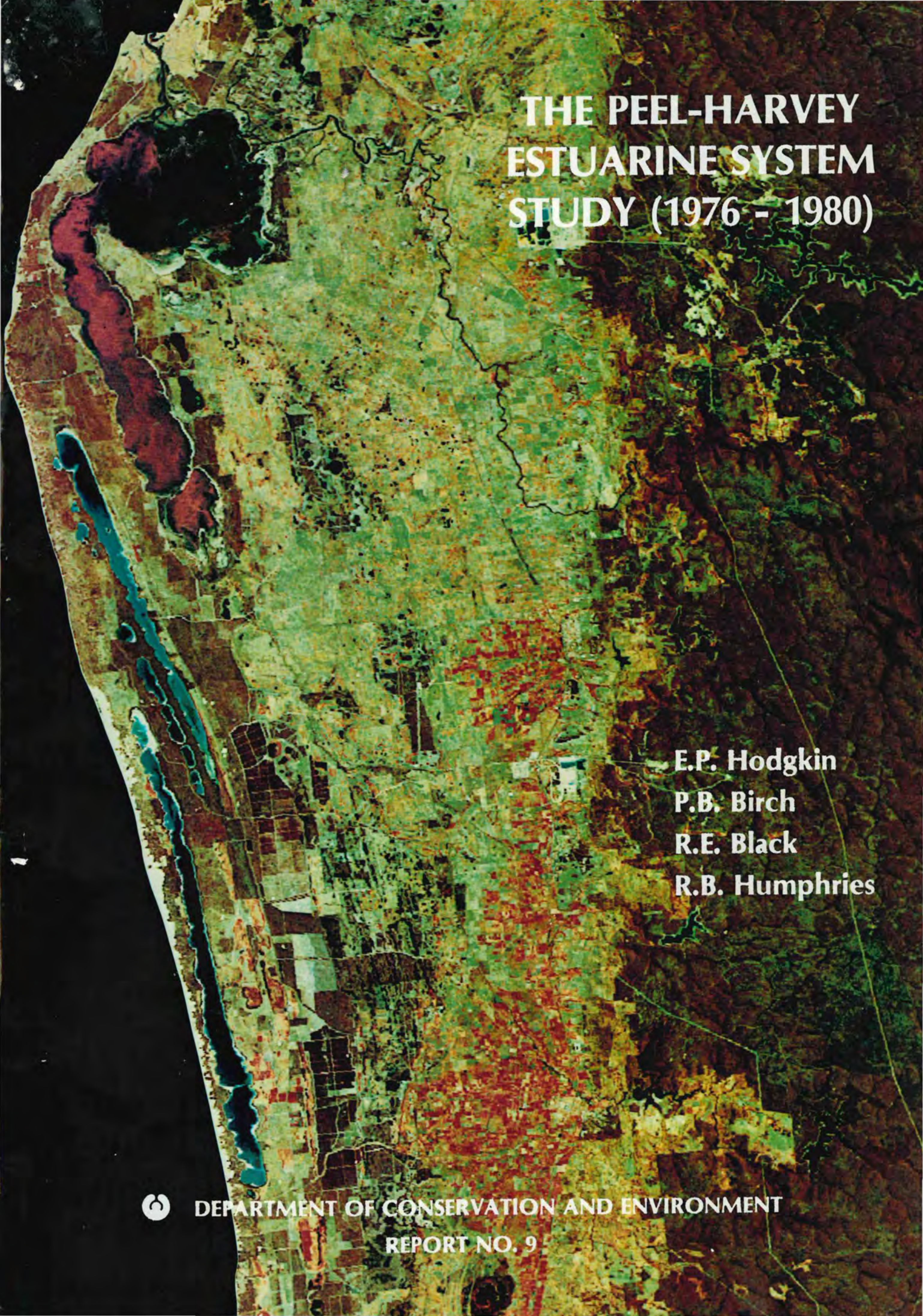

THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976 - 1980)

E.P. Hodgkin
P.B. Birch
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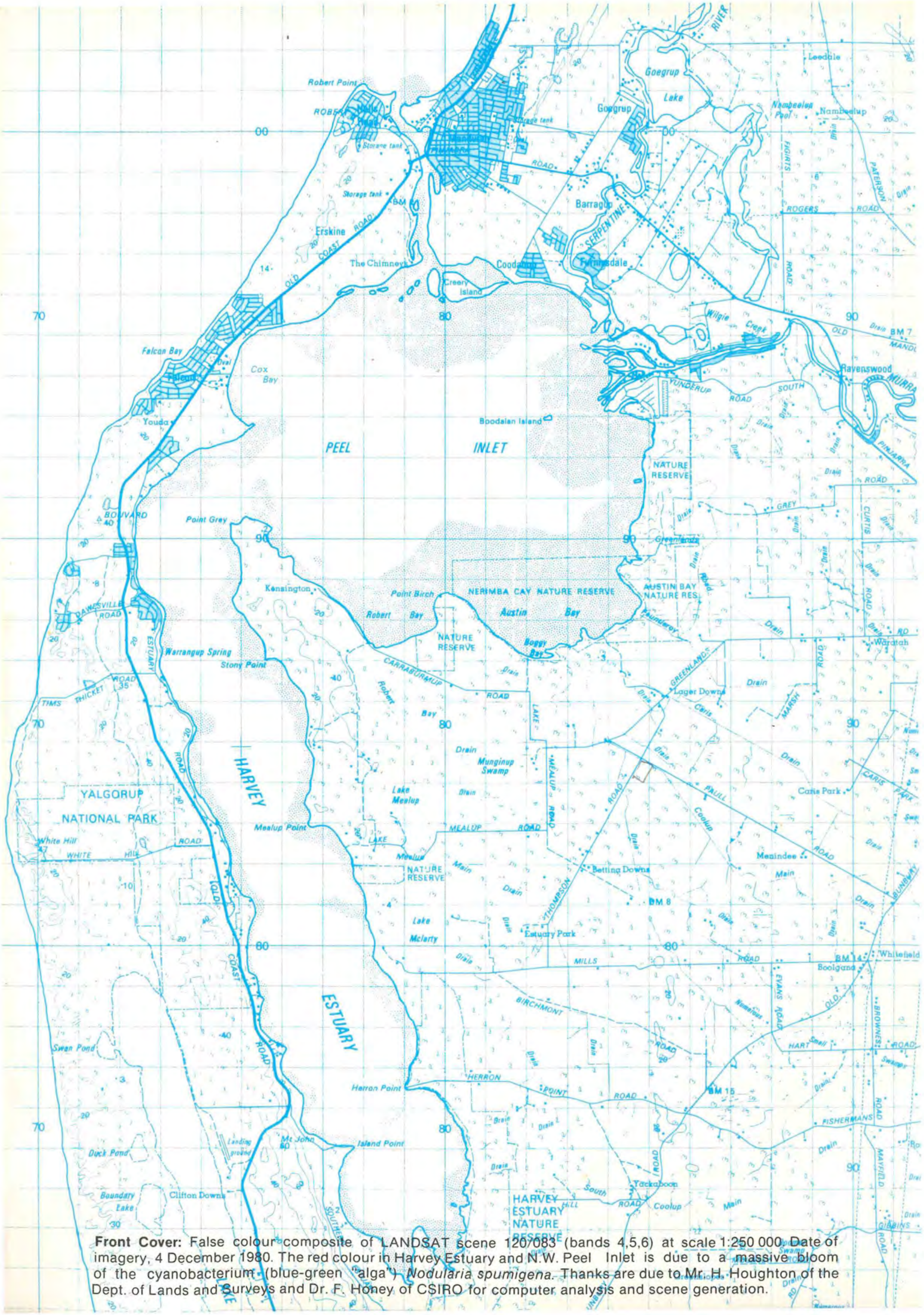
DEPARTMENT OF CONSERVATION AND ENVIRONMENT
REPORT NO. 9



Front Cover: False colour composite of LANDSAT scene 120/083 (bands 4,5,6) at scale 1:250 000. Date of imagery, 4 December 1980. The red colour in Harvey Estuary and N.W. Peel Inlet is due to a massive bloom of the cyanobacterium (blue-green "alga") *Nodularia spumigena*. Thanks are due to Mr. H. Houghton of the Dept. of Lands and Surveys and Dr. F. Honey of CSIRO for computer analysis and scene generation.

THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976-1980)

a report to the

ESTUARINE & MARINE ADVISORY COMMITTEE

December 1980

DEPARTMENT OF CONSERVATION & ENVIRONMENT
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CONTENTS

PREFACE

This report to the Estuarine and Marine Advisory Committee summarises the findings of the research team as they relate to the algal problem and to management problems in so far as they can be foreseen at this time. The report examines a number of possible management options in the light of the research findings, but no attempt is made to evaluate their practicability.

Most of the segments of the study have now been completed and are reported in detail in a series of 14 Technical Reports. At the time of preparation of this report the fish study had ended, but the data had still to be analysed and a final report written. Work on sediment nutrients is still continuing and a further report will be presented later.

In submitting this report we wish to thank the Chairman and members of the Estuarine and Marine Advisory Committee for the active interest they have taken in the study at all stages and the advice and encouragement they have given us, and other members of the research team, throughout the study.

We wish to record our appreciation of the help we have had from members of the research team in preparation of this report and for their willing co-operation throughout the study. Their names appear as authors of the Technical Reports listed on page 6. This has been a most rewarding exercise and the free exchange of ideas and information in workshops and in individual discussion has contributed enormously to the success of the study.

It has been a pleasure to have the freely given help and advice of many people in the various bodies with which we have worked and of professional fishermen and other individuals in the Peel-Harvey area. In particular we are glad to record the cordial relations we have had with the Chairman and members of the Peel Inlet Management Authority and with their staff.

E.P. Hodgkin

P.B. Birch

R.E. Black

R.B. Humphries

TECHNICAL REPORTS

BULLETIN No.

89 The Peel Inlet and Harvey Estuary System Hydrology and Meteorology. R.E. Black and J.E. Rosher. June 1980.

90 Sediments and Organic Detritus in the Peel-Harvey Estuarine System. R.G. Brown, J.M. Treloar and P.M. Clifton. August 1980.

91 The Ecology of *Cladophora* in the Peel-Harvey Estuarine System. D.M. Gordon, P.B. Birch and A.J. McComb. 1981.

92 The Decomposition of *Cladophora.* J.O. Gabrielson, P.B. Birch and K.S. Hamel. October 1980.

93 The Control of Phytoplankton Populations in the Peel-Harvey Estuarine System. R.J. Lukatelich and A.J. McComb. 1981.

94 Cyanobacteria and Nitrogen Fixation in the Peel-Harvey Estuarine System. A.L. Huber. October 1980.

95 Phosphatase Activities in the Peel-Harvey Estuarine System. A.L. Huber. October 1980.

96 The Sediment Contribution to Nutrient Cycling in the Peel-Harvey Estuarine System. J.O. Gabrielson. 1981.

97 Aspects of the Biology of Molluscs in the Peel-Harvey Estuarine System, Western Australia. F.E. Wells, T.J. Threlfall and B.R. Wilson. June 1980.

98 The Fish and Crab Fauna of the Peel-Harvey Estuarine System in Relation to the Presence of *Cladophora*. I.C. Potter, R.C.J. Lenanton, N. Loneragan, P. Chrystal, N. Caputi and C. Grant. 1981.

99 Phosphorus Export from Coastal Plain Catchments into the Peel-Harvey Estuarine System, Western Australia. P.B. Birch. October 1980.

100 Systems Analysis of an Estuary. R.B. Humphries, P.C. Young and T. Beer. 1981.

101 Peel-Harvey Nutrient Budget. R.B. Humphries and R.E. Black. October 1980.

102 Nutrient Relations of the Wetlands Fringing the Peel-Harvey Estuarine System. T.W. Rose and A.J. McComb. August 1980.

SUMMARY AND CONCLUSIONS

The conclusions presented in this report are based on a limited data set from observations made over periods of two to four years for various segments of the study. This period, 1976 to 1979, was one of unusually low rainfall and river flow. It was also one during which the 'algal problem' is thought to have declined, following a peak in 1974-75. For these reasons, some conclusions are tentative and further research will be required to fully substantiate them. Recommendations for continuing research and monitoring have been made to EMAC.

In spite of the limitations noted above, a clear picture emerges of an estuary which has changed progressively during the last 40 years or more, becoming increasingly eutrophic. The features which make it attractive to residents and visitors alike have suffered as a consequence: previously clean sandy beaches are fouled with piles of rotting algae; removal of these by tractors has resulted in destruction of marginal vegetation, rushes and shady trees; periodic massive blooms of blue-green 'algae' (cyanobacteria) stain the water and beaches, and may cause deoxygenation and fish mortality. There is no prospect for improvement unless remedial action is taken to reduce the eutrophic condition of the estuary.

The estuary and its environs are under increasing pressure for residential and recreational purposes which can only exacerbate the present unsatisfactory condition of the estuary, unless they are carefully controlled.

The findings of the study are summarised in the conclusions presented below and proposals for management of the estuary, made in the light of the research findings, are discussed in the final chapter (Chapter 11).

1. The Peel-Harvey estuarine system is nutrient enriched (eutrophic) in that there is an abundance of nutrients available for algal growth at all times, even though nutrient levels in ambient water are relatively low during much of the year. This eutrophic condition is manifested in Peel Inlet principally by an excessive growth of benthic green algae and in Harvey Estuary by an abundance of phytoplankton.
2. The 'algal problem' in Peel Inlet, the accumulation of masses of green algae on the shores, is caused mainly by a species of *Cladophora* that is probably new and undescribed. The growth characteristics of this species, as small cottonwool-like balls, and its mobility favour both its use of the available nutrients and its accumulation in the shallows. Other species of benthic algae are seasonally abundant and contribute to algal accumulations.
3. The algal problem is of recent origin, since the 1960's. Its development was coincident with a great increase in plant nutrient input to the estuary over the last 30 years, especially of phosphorus. The problem is here attributed to the consequent increase in available nutrients within Peel Inlet and to other factors that favour this alga rather than phytoplankton, as in Harvey Estuary.
4. The increase in nitrogen input is probably attributable to planting with pasture legumes on agricultural land throughout the catchment, and also to greater use of nitrogenous fertilizers over the same period.
5. The increased input of phosphorus results from the application of superphosphate to phosphorus deficient soils of the coastal plain catchment during the last 30-40 years. Tonnages of superphosphate applied increased rapidly to 1973-74, since then usage has decreased greatly as the result of higher prices. Nevertheless the input to the estuary in 1978 was at least ten times that of 1953, a year with very similar rainfall and river flow.
6. The volume of flow to the estuary is not thought to have changed greatly during the last 30-40 years (except in response to variation in rainfall), but the sources of the water and its nutrient content have. Dams on hills catchments have reduced the input of nutrient poor water, while clearing, cultivation, and drainage on the coastal plain have increased the input of nutrient rich water. Flow from the plateau catchment of the Murray River (undammed) is relatively rich in nitrogen, but poor in phosphorus, and any reduction in flow from this source, as a result of damming, would reduce its beneficial flushing action on the estuary.
7. River flow and the consequent nutrient input to the estuary is strongly seasonal. About 85% of both nitrogen and phosphorus input to Peel Inlet occurred in a period of 10 weeks (July-August) in 1978. During the river flow period, nutrient levels are high in estuary water. They rapidly return to the relatively low levels present during the greater part of the year in Peel Inlet, but less rapidly in Harvey Estuary. Re-release of nutrients from surface sediments may briefly raise levels considerably at other times of the year.
8. Dense phytoplankton blooms (chiefly diatom species) develop at times of high nitrogen and phosphorus load in estuary water, during river flow. Massive blooms of nitrogen-fixing blue-greens develop in response to relatively high phosphorus levels, a low N : P ratio, and water temperatures above about 18°C, especially in Harvey Estuary.

9. While much of the nutrient input is lost to the sea with river flow, a considerable proportion is retained in the estuary by phytoplankton, flocculation and sedimentation and is thus transferred to the sediments as a nutrient store. Re-release from this store contributes to the nutrient supply to *Cladophora* when levels in the ambient water are low.

10. During the period of high ambient nutrient levels there is little growth of *Cladophora* because of low water temperatures and low benthic light. There is however sufficient uptake of nutrients to a cellular store (luxury uptake) to permit doubling of algal biomass when light is again adequate for photosynthesis and growth in spring-summer. At that time the low nutrient availability in ambient water is supplemented to *Cladophora* from the sediment nutrient store.

11. Of the nutrients, it is phosphorus rather than nitrogen which limits algal growth. The ratio of available N : P is > 15:1 most of the time and moreover a deficiency of nitrogen is adequately supplemented by nitrogen-fixing blue-greens, except at low temperatures in winter. At that time a deficiency of nitrogen may temporarily limit diatom growth and consequent transfer of nutrients to the sediments.

12. As stated above, the algal problem in Peel Inlet is attributed to the high levels of nitrogen and phosphorus available to an algal species adapted to making good use of these nutrients and which is mobile and readily transported to shore. The only satisfactory long term solution to the problem will be to substantially reduce the availability of nutrients, especially phosphorus, to algae.

13. Management of the algal problem is discussed in Chapter 11 and possible management options for its control are suggested. While it is believed that these offer solutions which warrant serious consideration, it must be stressed that the research team has not attempted to evaluate the practicability or social cost benefits of these measures. It will be evident that there is no single corrective action which will immediately and permanently eliminate the algal problem and its cause: the eutrophic condition of the estuary.

14. The fish studies were not complete at the time of writing this report and it is uncertain what long term effects the *Cladophora* problem may have had on fish and crab populations. There is now a greater relative abundance of crabs and certain fish species than formerly, but it is not clear how this may relate to the presence of *Cladophora*. Recent localised fish kills are probably attributable, directly or indirectly, to the blooms of blue-green 'algae' and these are likely to recur as long as the estuary is eutrophic.

    Records have been maintained for many years of catches by professional fishermen, with quantities of the various species taken, but there are no data on the amateur fishery. It is thought that as great a weight of fish is taken by amateurs as by professionals, although the composition of the catch differs considerably.

Decomposing algae being raked to shore.

CHAPTER ONE

HISTORY, AIMS AND PROGRESS OF THE STUDY

HISTORY

Early in 1976 the Environmental Protection Authority of Western Australia asked its Estuarine and Marine Advisory Committee (EMAC) to undertake an investigation of Peel Inlet. The reasons for this were:

1. In recent years large quantities of green algae had accumulated and decayed on the shores causing a nuisance to residents. The continuing 'cosmetic' action required to ameliorate the effects of this was costly and offered no prospect of a permanent solution. It was desirable to identify the cause or causes of this 'algal problem' and, if possible, propose long-term solutions.
2. The Metropolitan Water Supply Board was investigating the possibility of damming the Murray River in order to supply water to the Metropolitan area. The Board had commissioned a study by WAIT AID (Black, 1975; Rippingale, 1974). Reduced freshwater input to Peel Inlet could greatly alter the aquatic environment and it was desirable to be able to identify the nature of anticipated changes.
3. Both residential and recreational usage of the area were increasing rapidly and their effects on the estuary needed to be understood in order to formulate management policies that would minimise adverse environmental change.

OBJECTIVES

The Study has two objectives:

1. Specific : To determine the causes of the excessive growth and accumulation of green algae in Peel Inlet and if possible to propose methods for its control.
2. General : To gain an understanding of the working of this estuarine ecosystem so that environmental problems can be foreseen and decisions made about its management on the basis of sound knowledge.

The two objectives are compatible. Most of the work has been directed primarily towards achieving the first objective, but the study also supplies much of the information required for a general understanding of the ecosystem and its management. It also adds greatly to our knowledge of the estuarine systems of south western Australia in general.

PROGRESS

The earlier WAIT AID studies made a good case for regarding the estuarine system as eutrophic and from the outset the present study has focussed on biology of the principal nuisance alga and on nutrient flux and related biological processes in the system, as recommended in a submission to EMAC of March 1976 by Dr. B.W. Logan and Professors J. Imberger and J. Pate of the University of Western Australia (UWA).

A study of sedimentology of Peel Inlet was already in progress (Logan and Brown 1976) and this was later extended by Treloar (1978). Detailed studies of the biology of *Cladophora* began early in 1976 and have been continued and extended throughout the investigation in the Botany Department, UWA. Studies of the hydrodynamics of the system were started soon after, by the Physics Department of the Western Australian Institute of Technology (WAIT), the emphasis being on measurement of fresh water input, evaporation and other meteorological factors. Early in 1977 the Applied Science Group, Centre for Resource and Environmental Studies (CRES) of the Australian National University joined the research team to assist principally with data processing and modelling the system.

An assistant to the Research Co-ordinator was appointed in 1977 and weekly water sampling at fixed sites in the estuary and on tributary rivers and drains started in September 1977 (Fig. 1.1) and an analytical facility was established in the Department of Botany, UWA, to process these samples. With realisation of the important role played by sediments in nutrient cycling a study of these began with the appointment of a Research Officer to the Soil Science Department, UWA, in February 1978. This is still continuing.

In view of the need to be able to have some basis on which to judge possible effects on the fish fauna of changes in algal abundance and eutrophication generally, a one year study of fish populations in the estuary started in July 1979. Supplementary to this there are good data relating to the commercial fishery in the estuary for the last 40 years.

With realisation of the importance of the agricultural use of superphosphate as a source of phosphorus to the system, a small study was undertaken in 1980 in order to identify sources and quantify them as far as possible.

Subsidiary studies relating to other aspects of the ecosystem have also received funding through EMAC. These relate to: phytoplankton, blue-green 'algae' (cyanobacteria), phosphatase activity, molluscs, the fringing vegetation, subsoil nutrient movement. An independent study is also being made of benthic Foraminifera. These studies contribute significantly to our understanding of the ecosystem.

Lastly it is relevant here to emphasise one important limitation to the study, the significance of which will become apparent later. This is that the study has been conducted during a period when rainfall and river flow have been exceptionally low. The four years of the study have been the driest during the entire 40 year period for which there are records of river flow. Even in 1978, the one 'wet' year, flow in the Murray River was below average and each of the other three years was below all but the 1940 flow.

RESULTS

Results of these studies are presented in detail in the series of Technical Reports submitted in support of this general account (see page 6).

The report relates mainly to the specific objective — the cause of the excessive growth and accumulation of green algae in Peel Inlet — and concludes with a discussion of possible methods of control. Nevertheless there is in this report, and more in the Technical Reports, much that is relevant to a general understanding of the working of the ecosystem and that will be of value in making management decisions. The available data resulting from the study is summarised in Appendix 1.

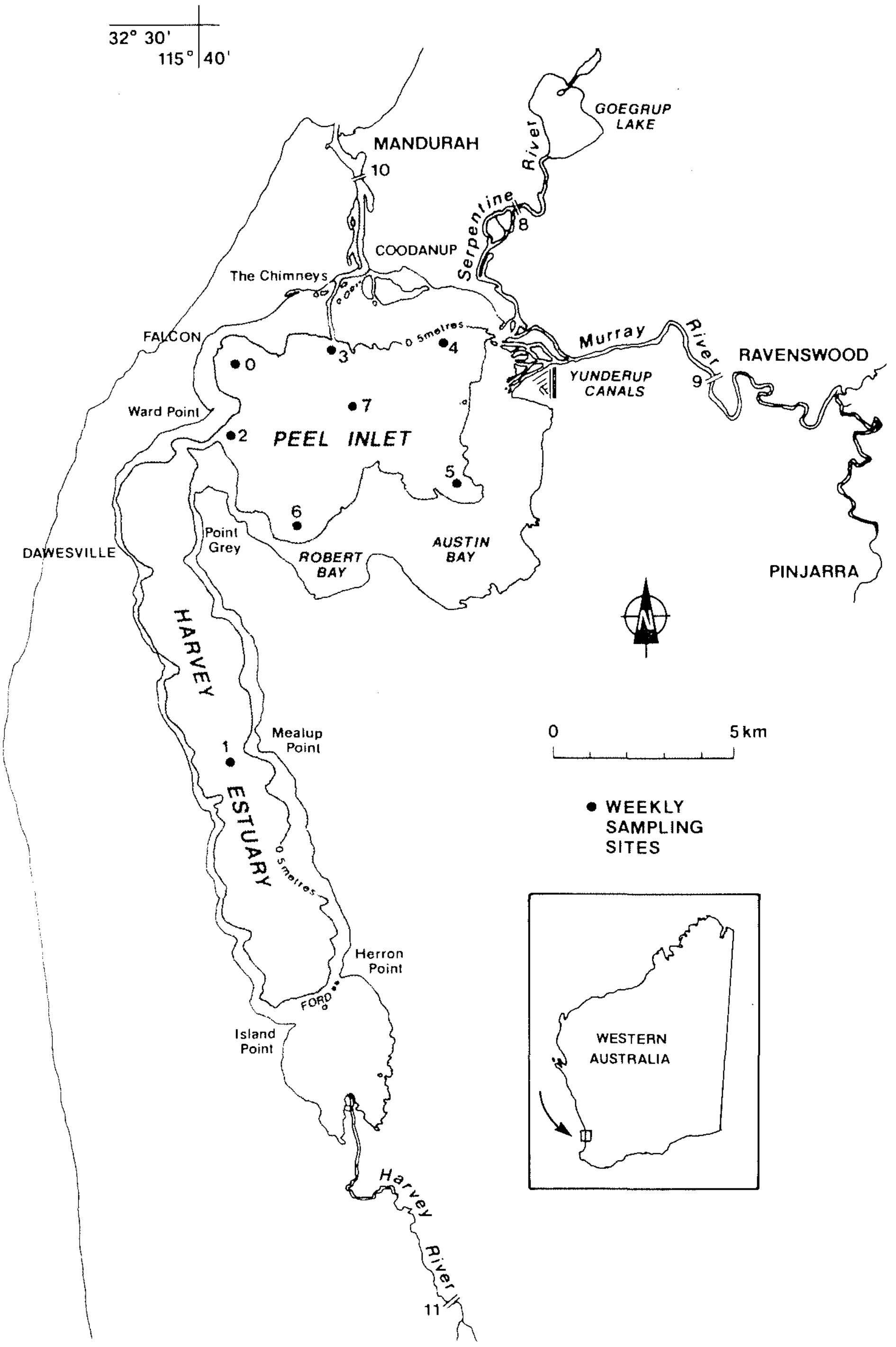

Figure 1.1 The Peel-Harvey estuarine system and CRES weekly sampling sites.

CHAPTER TWO

THE ALGAL PROBLEM, ITS NATURE, HISTORY AND POSSIBLE CAUSES

THE PROBLEM

The 'algal problem' that is the cause of complaint by locals is primarily an aesthetic and economic problem. It takes three forms:

1. Masses of green algae accumulate in the shallows of the northern (Coodanup) and western (Falcon) shores of Peel Inlet. The algae foul what were previously clean beaches and decompose to a black ooze with evolution of unpleasant odours. The extensive sheets or mounds formed by both living and rotting algae are removed from the shallows near residential areas by a tractor equipped with rakes. This 'cosmetic' activity began in September 1974 and costs about $20,000 a year.

   Algae also accumulate on other shores, notably those west of the Chimneys, the Murray River delta, and in Austin Bay. There, in the absence of habitations, they cause no offense. Harvey Estuary is largely free of algal accumulations, though there is some fouling of beaches north from Dawesville, also at Heron and Island Points.

2. Sheets of living and decomposing algae in deep water foul the nets of professional fishermen and cause them considerable inconvenience.

3. Accumulation of drifting algae is not generally recognised as a biological problem. However, it may indeed be of considerable importance because large accumulations have been found to kill marginal rushes and smother seagrasses. Bank erosion from this and other causes, is evident in many parts of Peel and Harvey. The weed clearing has also resulted in shore erosion.

4. Massive phytoplankton blooms, mainly of blue-green 'algae', occur from time to time with resulting unpleasant odours and deleterious effects on fish and crab populations.

HISTORY OF THE PROBLEM

From all accounts the 'algal problem' is new and dates from the mid 1960s. The first complaints about accumulation and decomposition of algae of which we have record date from 1969. However, air survey photographs of January 1967 show weed accumulations off the Coodanup shore essentially similar in appearance to those seen in air photos of the 1970s, and there appear to be fairly extensive weed beds in the shallows. It is puzzling that Allender who made a survey of algae of the estuary in 1966 recorded no *Cladophora* from Peel Inlet, though he found some in Harvey Estuary.

Air photos of March 1946 show the marginal shelves to be clean sand and the general belief is that in the early 1960s the beaches were free of algae. However, notes in PWD files suggest that algae (probably *Cladophora)* were already a problem for fishermen. "In 1958 the bar was closed and migratory fish were unable to enter the estuary" and the run was again missed in the following year, but in 1960 "This freshening of the estuary by the sea has brought about the disappearance of the algae, which was creating a serious hindrance to the netting of fish".

Algal accumulations on the beaches appear to have increased between 1969 and 1974-75 and decreased again during the period of the Study.

Accumulation of aquatic angiosperms (the seagrasses *Ruppia* and *Halophila*) is reported to have occurred for a long time without apparently being regarded as a nuisance (the weeds were carted away for use as fertilizer). This may be because the accumulations were too small, because these plants are less offensive when they decompose than algae, or simply because few people were affected.

Fishermen have observed progressive changes in the estuary, including different types of phytoplankton blooms. They interpret these as a sequence of ecological change which began when agricultural drains were dug on the coastal plain during the period from 1909 until shortly after World War II. A massive bloom of the blue-green, *Nodularia* similar to those observed in 1978 and 1980 occurred in the Serpentine River in 1970 forming a "thick greenish-brown coating along much of the river" (West Australian, 12 November 1970).

THE ALGAE

Algal accumulations consist principally of a single species of green alga, locally known as 'goat weed' and provisionally identified as *Cladophora* aff. *albida* although it is probably a new species. This forms cottonwool-like balls 1-3 cm in diameter which grow mainly in deeper water, but float to the surface and drift to the beaches. Other species of *Cladophora* are commonly associated with eutrophic conditions in inland waters in many parts of the world and sometimes also in marine and estuarine waters. In most instances these are attached plants. Some literature is available on *Cladophora* and its role in eutrophication, however this is of limited value to this study because it does not relate to the local species.

Other green algae become entangled with *Cladophora* in varying quantities. The most important of these are filamentous species of *Chaetomorpha* and of *Enteromorpha*, both of which may be locally abundant in shallow water, particularly in spring when *Enteromorpha* may cover extensive areas of the shallows. A red alga (*Chondria* sp.) may also be common at times, both in Peel Inlet and Harvey Estuary. Few other species of larger algae occur in the estuary and they form a very small part of the algal biomass.

The areas of growth and accumulation of algae have expanded and contracted during the study, although *Cladophora* is always present in the principal growth areas (Fig. 2.1). The main *Cladophora* growth areas are in water greater than about 0.5m deep in the eastern half of Peel Inlet and in the western embayment. There is a small growth area in the northern segment of Harvey Estuary.

The principal areas of accumulation are on shores of the northern half of Peel Inlet where algae drift onto shelving beaches or build up into sinuous piles a hundred metres or more from the shore and are carried slowly to shore by wave action.

Figure 2.1 Principal areas of *Cladophora* growth and accumulation in Peel Inlet.

Decomposition takes place both in deep water under a thin blanket of living algae and in the sheets or piles of algae near and on shore. In both situations this results in formation of a black ooze in which living material may be incorporated.

It is difficult to determine quantities of *Cladophora* because of its mobility, however estimates have been made (as discussed in Chapter 8) and it is clear that there has been a reduction in biomass both in the growth areas and in beach accumulations, during the study. The quantities being raked from Coodanup and Novara shores are now considerably less than they were in 1974.

POSSIBLE CAUSES

The algal problem has been attributed to a variety of causes, some more plausible than others. While, as this study shows, the principal cause has probably been the increased input of plant nutrients to the estuary, it must be kept in mind that there may well have been other contributing factors. The following possible causes have been considered in the course of the study, only some of which have warranted further investigation:

1. *Clearing, cultivation and stocking of the coastal plain, with the associated drainage.* This resulted in a considerable increase in freshwater input from this source, with a greater particulate and dissolved organic content, and some increase in plant nutrients. This may well have initiated the series of changes observed by fishermen, with increased phytoplankton blooms and a decrease in the abundance of seagrasses. However, coastal plain soils are very deficient in phosphorus and clearing is unlikely to have been the major cause of the present eutrophic condition. On the other hand, fertilization of the cleared land has been of great importance (see 8 below).

2. *Construction of reservoirs and the consequent reduced river flow to the estuary from hills catchments.* This has probably been more than compensated for by increased flow from the coastal plain as a result of clearing and drainage (this preceded construction of most of the hills reservoirs) and clearing in the upper Murray catchment. There is no observable difference between the salinity of estuarine waters now and 30 years ago, as might be expected if there had been a substantial reduction in freshwater input. However, the hills dams have reduced the flow of phosphorus-poor water to the estuary, water which helps to flush phosphorus-rich water from the coastal plain to the sea.

3. *Floods and the consequent flushing effect.* These have been suggested as a possible cause, perhaps because the 1964 floods immediately preceded recognition of an algal problem.

4. *Construction of training walls at Mandurah in 1967.* Before this the bar shallowed each summer, reducing tidal exchange, and sometimes closed completely making estuary water stagnant for several months (6 months in 1914-15). Presumably the training walls have improved tidal exchange and possibly therefore reduced nutrient levels, although greater water clarity may have favoured benthic algae rather than phytoplankton.

5. *The great increase in boat usage.* Algal beds and the underlying black ooze may be disturbed by boat propellors and so release dissolved plant nutrients to the overlying water. This is unlikely to be of any quantitative significance. The effect of sediment stirring on nutrient release has been examined and found to be very short lived.

6. *Changes in populations of weed-eating and predatory birds and fish.* There is reported to have been an increase in black swans, which feed largely on seagrasses, and also of cormorants (predators on fish). However, it is unlikely that they have had any marked effect on populations of primary producers. The present condition of the estuary favours detritus-eating fish (sea mullet and Perth herring), which have increased in abundance in the 1970s, but this is likely to be a result, rather than a cause, of the increase in algae.

7. *Growth of the urban population and associated changes in water usage and sewage disposal.* Although nutrient concentrations in groundwater are high and may have been even higher in the past, thus possibly triggering the algal problem, the quantities of nitrogen and phosphorus involved are not adequate to account for the nutrient levels now present in the estuary and available to the algae (Chapter 10). There is little groundwater flow to the estuary in summer.

8. *The increase in plant nutrient concentrations in estuary waters.* The input of both nitrogen and phosphorus has increased dramatically in the last 25 years and concentrations of phosphorus especially appear to be considerably higher now in estuary water than those recorded by CSIRO Division of Fisheries in 1951-56 (Chapter 10). Investigation of the external sources of plant nutrients and internal nutrient cycling, and of the alga *Cladophora,* have been the main thrust of this study.

Algal accumulation, Coodanup shore; pile of decomposing algae, and dying ***Casuarina*** *isolated by shore erosion.*

CHAPTER THREE

PHYSICAL FEATURES OF THE CATCHMENT

The principal relevant features of the catchment are shown in Figure 3.1. There are three main regions: The Swan Coastal Plain, the forest region on the plateau, and the cleared agricultural region on the plateau.

COASTAL PLAIN

This is mainly cleared pasture, for beef and dairy cattle (Fig. 3.2). Except for the coastal dunes and in the immediate vicinity of the Darling Scarp it is less than 20m above sea level and is still subject to flooding. Drains were first dug about the turn of the century from Coolup to Peel Inlet and to drain the area now irrigated, between Waroona and Harvey, to the Harvey River swamps. Since then the drainage system has been progressively extended and improved.

However, development was slow . . . "The pioneers were defeated by the poverty of natural drainage, the fundamental infertility of most soils in the area (Coolup), their own inexperience and failure to discover . . . a suitable market" (Cooper, 1976). By 1918 few of the original settlers remained.

Coastal plain soils are naturally deficient in phosphorus and there was little significant advancement in agriculture until the use of phosphatic fertilizers and subterranean clover became widespread from about 1940.

The Swan Coastal Plain is divided into 5 geomorphic elements (Fig. 3.3): three dunal systems of increasing age and distance from the sea (the Quindalup, Spearwood and Bassendean Dunes), the Pinjarra Plain and, easternmost, the Ridge Hill Shelf along the foothills of the Darling Scarp (McArthur and Bettenay, 1960). These elements are each divided into soil associations which represent a diversity ranging from very sandy soils of the Bassendean System to alluvial clays found within the Pinjarra Plain (Bettenay *et. al.* 1960).

Mean annual rainfall is 900mm on the coast (Mandurah) and the 1100mm isohyet lies along the escarpment (Fig. 3.1).

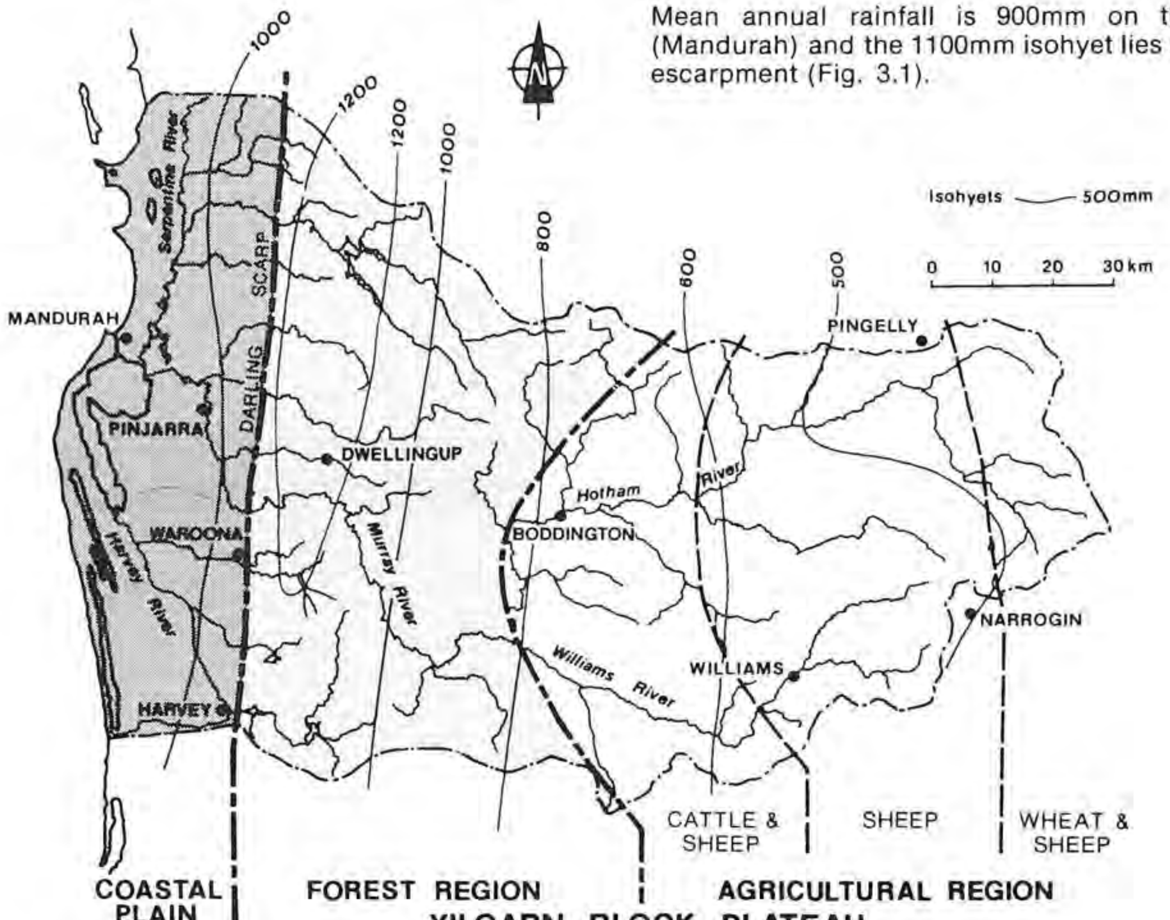

Figure 3.1 Physical features of the catchment of the Peel-Harvey estuarine system.

FOREST REGION

This lies on the plateau, the Yilgarn block, within the zone of young, or rejuvenated, drainage of Bettenay and Mulcahy (1972) the streams being deeply incised in laterite uplands cut through to basement granites and gneisses near the escarpment. Much the greater part is in State Forest dominated by jarrah, with marri, blackbutt and varied understorey species.

Rainfall averages 650mm a year on the eastern edge of the region and rises to 1400mm in a limited area 10km east of the Scarp. Stream flow from the region is fresh (< 3 ppt salinity) and most is < 0.5 ppt S (Collins, 1974). Gradients in streams are steep and flow is perennial in many, although flow is dissipated when it reaches the coastal plain so that there may be no flow to the estuary over several months in a dry year. Most of the smaller rivers are dammed near the scarp (Chapter 4).

AGRICULTURAL REGION

This part of the catchment lies in Bettenay and Mulcahy's (1972) zone of mature drainage where the valleys are U-shaped with relatively flat floors, low gradients and alluvial soils. The area of cleared land has doubled since 1945 and now the greater part of the region is cleared for grazing, with some cereal crops in the east. A small area of State Forest is open woodland dominated by wandoo, York gum and mallets.

Rainfall decreases from 650mm to 450mm a year at the eastern extremity and streams are all seasonal and saline (>3 ppt) with salinities exceeding 10 ppt in headwaters. In consequence, the salinity of Murray River water is always >1 ppt during winter flow and increases progressively upstream (Collins, 1974; Morrissy, 1979).

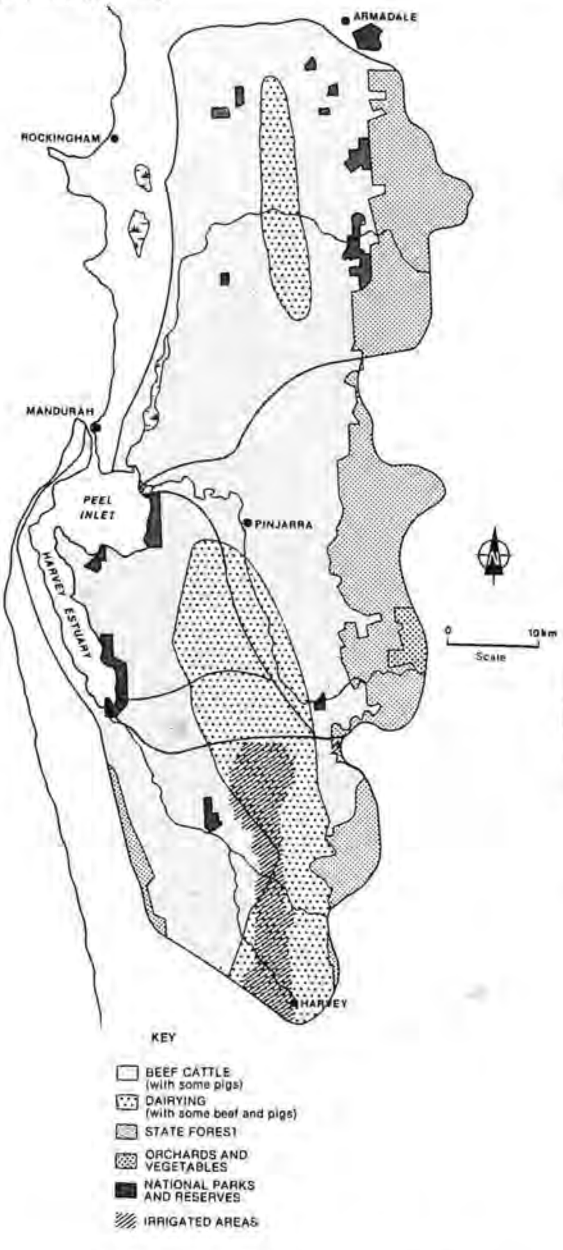

Figure 3.2 Land use on the coastal plain.

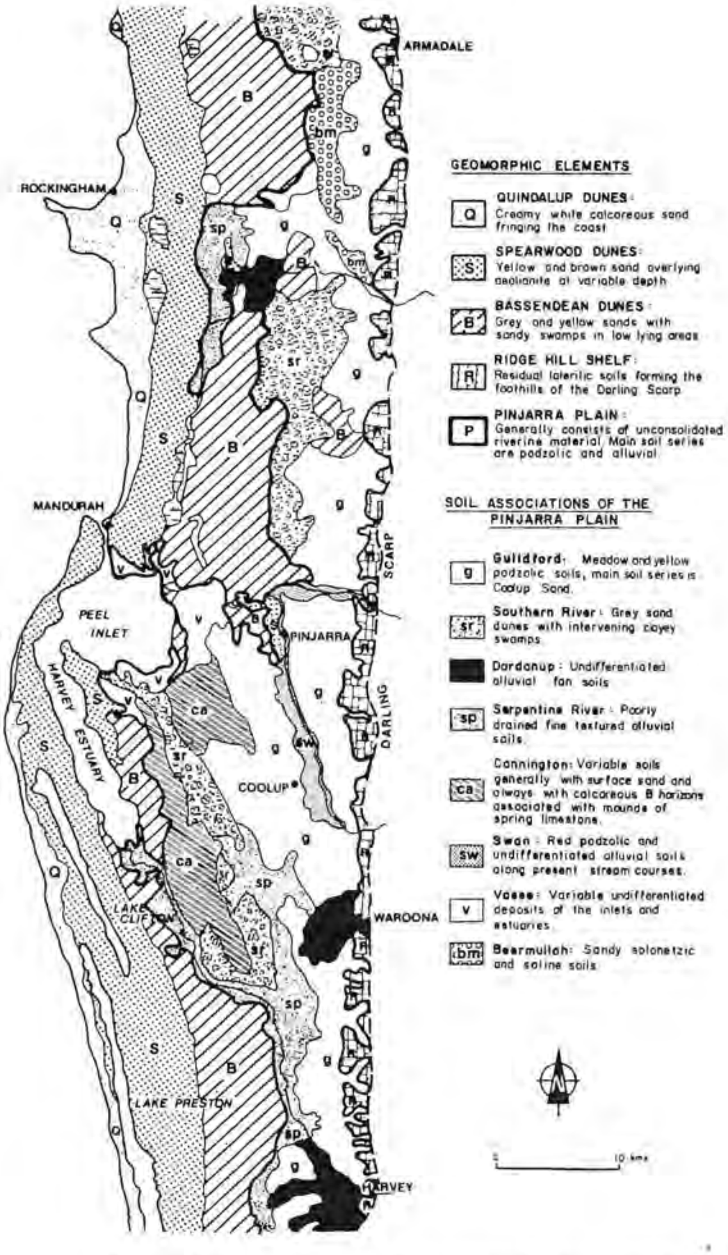

Figure 3.3 Geomorphic elements and soil associations of the coastal plain. After McArthur and Bettenay (1960) and Bettenay *et al* (1960).

CHAPTER FOUR

CATCHMENT RAINFALL AND RUNOFF

Freshwater enters the system from the Murray River, Serpentine River, Harvey River, agricultural drains, groundwater and rainfall. In addition, there is free exchange with the ocean so that there is a gain of sea water to the system, as well as a loss of estuary water to the sea. The oceanic "flushing" is described in Chapter 6.

CATCHMENT AREAS

The catchment of the estuary is shown in Figure 3.1. The total possible catchment area is 11,300km^2 and of this, 6,890km^2 is in the hills catchment of the Murray River and is not dammed; 1,720km^2 of the Serpentine and Harvey River catchments are dammed (Table 4.1), and another 500km^2 of hills catchments of these rivers are undammed. The remainder lies on the coastal plain and drains to the estuary via the three rivers or direct through agricultural drains (Fig. 4.1, Table 10.10).

Excess flow from Harvey Weir is discharged to the Harvey River Drain with provision for sluice gate release of up to 5.66m^3 sec^{-1} down the Harvey River Main Drain to the Harvey River and into Harvey Estuary.

RAINFALL

From long-term daily rainfall records at Mandurah (79 years), Waroona (39 years) and Waraba (15 years) and 3 pluviometers established in 1976 and 1977 for the study, an analysis was made of rainfall affecting the estuary catchment. In addition 37 years of Murray River catchment wide rainfall averages were utilised to demonstrate the relative magnitude of rainfall and river flow in the study years 1977/78 and 1978/79 (Fig. 4.2). The assumption is made that the Waroona gauge is representative of Harvey River catchment rainfall, whilst Mandurah long term records are used to describe the Serpentine River coastal plain catchment.

It must be appreciated that frequency of rainfall does not equal frequency of riverflow. Nevertheless, Figure 4.2 gives a reasonable approximation of the relative magnitude of river inputs to the system over the two years of the study. From it we see that the rainfall (or river flow) in 1977/78 would be expected to be exceeded on approximately 80% of all years while the very dry 1978/79 year would be bettered on more than 90% of all years.

The three pluviometers established for the study were used to calculate estuary-wide rainfall averages. This is important because of the large surface area of the water body itself (133 km^2) the direct rainfall to which is a significant percentage of total water inputs. Tables 4.2 and 4.3 show the monthly totals and relative importance of direct precipitation on the estuary.

RUNOFF

Murray River

Table 4.4 shows the monthly inputs to Peel Inlet from the Murray River for the period of the study. River flow is gauged by PWD Water Resources Section at Baden Powell Water Spout (614 006, Fig. 4.1) some 36km upstream from the Pinjarra Weir, the upper limit of tidal intrusion. Flow routing studies, using dye dilution gauging techniques, showed that a 'gain' of 1.15 was applicable to flows measured at 614 006 to provide estimates of flow at Pinjarra as shown in Table 4.4.

TABLE 4.1 DAMS IN THE CATCHMENT OF THE PEEL-HARVEY ESTUARINE SYSTEM: dates built and catchment areas

	Dam	Pipehead	Main Dam	Catchment km^2
Serpentine River	Serpentine	1957	1961	665
Dandalup River	North Dandalup	1970		152
	South Dandalup	1971	1973	320
Harvey River	Waroona		1966	47
	Samson Brook		1941, 60	65
	Logue Brook		1963	39
	Harvey Weir	1916	1931	181
	Stirling	1920	1948, 58	251

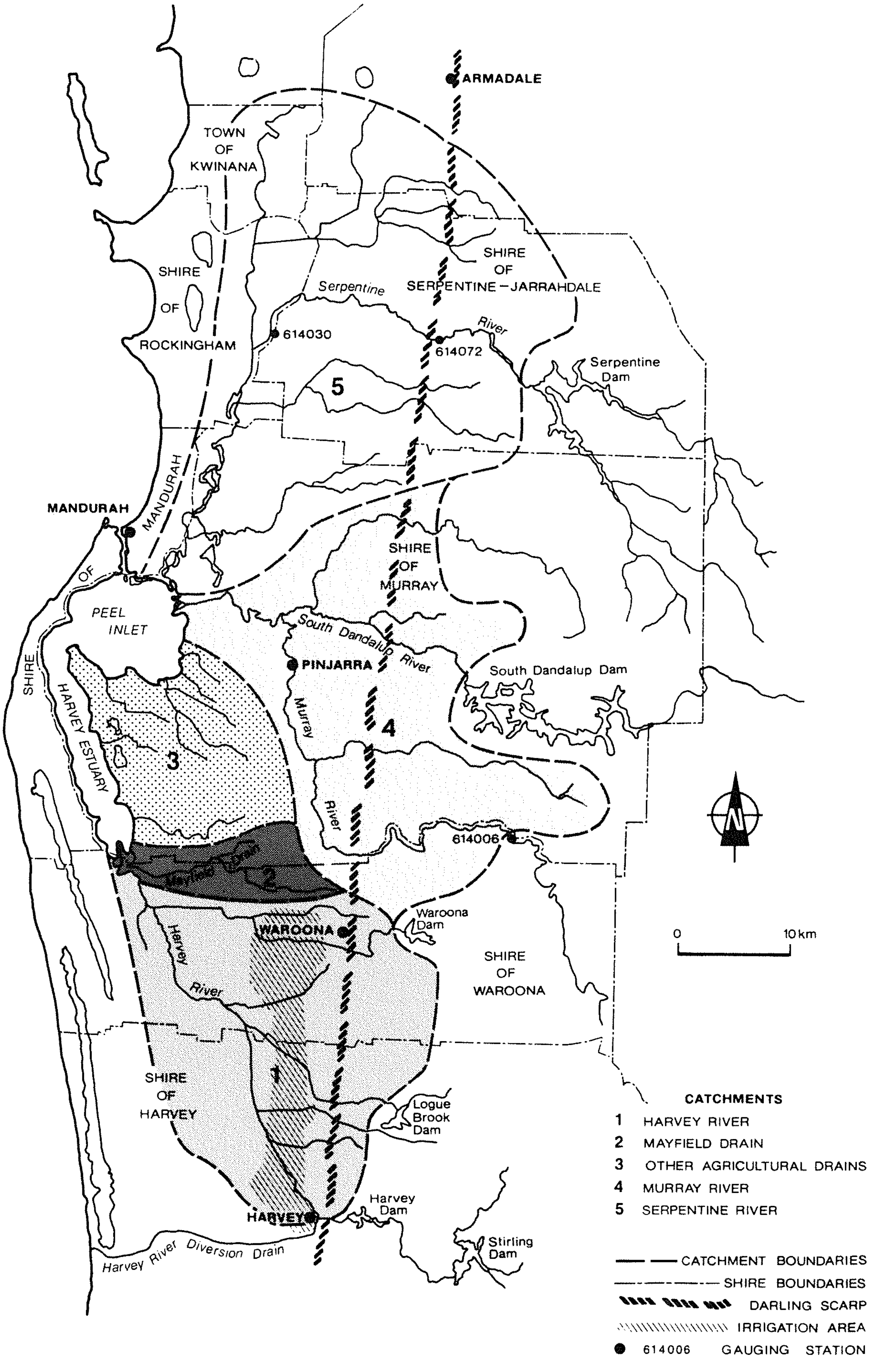

Figure 4.1 Drainage catchments of the coastal plain.

TABLE 4.2 PEEL INLET - HARVEY ESTUARY THIESSEN WEIGHTED MONTHLY RAINFALL DATA (mm)

YEAR	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1977	—	—	2*	1*	81*	86*	70	113	35	49	6	2
1978	0	6	10	11	150	185	142	42	143	18	23	12
1979	4	2	12	38	86	156	134	63	62	—	—	—

* Robert Bay gauge only installed March — July, 1977.

TABLE 4.3 RAINFALL ON THE ESTUARY VERSUS RIVER DISCHARGE

Water Year	River Discharge into Estuary (m^3 x 10^6)				Rainfall on Estuary	
	Murray (at 614 006)	Serpentine (estimated)	Harvey & Drains	Total	Volume (m^3 x 10^6)	% of Total flow
1977/78	238	65	206	509	99	19.5
1978/79	62	55	150	267	81	30.3

TABLE 4.4 MURRAY RIVER SYSTEM: MONTHLY INPUTS TO PEEL INLET

River	Year	MONTHLY FLOW VOLUMES (m^3 x 10^6)												Annual Total
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	
Murray (Pinjarra)	1977/ 1978	9.0	6.4	1.0	0.2	0.1	0.1	0.1	1.6	14.0	180.0	42.7	18.1	273.3
North Dandalup (614 016)		1.7	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.8	6.2	1.5	2.1	12.7
South Dandalup (614 022)		0.2	0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.5	1.3	0.1	0.5	3.2
TOTAL		**10.9**	**6.8**	**1.1**	**0.2**	**0.2**	**0.2**	**0.2**	**1.8**	**15.3**	**187.5**	**44.3**	**20.7**	**289.2** *
Murray (Pinjarra)	1978/ 1979	18.9	2.3	1.1	0.5	0.2	0.1	0.1	0.8	3.8	18.0	13.3	12.7+	71.8
North Dandalup (614 016)		2.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.9	2.3	2.5+	13.7
South Dandalup (614 022)		1.4	0.1	0.1	0.0	0.0	0.1	0.1	0.2	0.4	0.8	0.6		
TOTAL		**23.1**	**2.6**	**1.2**	**0.5**	**0.2**	**0.2**	**0.2**	**1.0**	**4.4**	**20.7**	**16.2**	**15.2+**	**85.5** *

* The inclusion of flows from Little Dandalup River (614 233) adds approximately 1% to total flow.

\+ Estimated only from gauged flows to 11/9/79.

Figure 4.3 shows the long term flow record of the Murray River and its extreme variability is readily apparent (annual total ranges from 56 to 1,143 x $10^6 m^3$). Furthermore its very low yield of only 7.6% on a long term average basis, fell to only 6.4% in 1977/78 and to 2.0% in the very dry 1978/79. Only on one occasion (1940) was less flow recorded than in 1979. Yield is defined as the ratio of flow to catchment rainfall, i.e.

$$\text{Yield} = \frac{\text{flow}}{\text{rainfall}} \times 100\%$$

Serpentine River

Figure 4.1 shows the Serpentine coastal plain drainage systems. The only continuous flow record is at 614 072 (Serpentine Falls) and estimates of flows into Peel Inlet from this system made by the PWD indicate that a gain of approximately 6.0 is appropriate. Given the brief period of analysis and the large area of the catchment, the Serpentine system must be acknowledged to be poorly defined. Table 4.5 shows the estimates of flow for the study years.

Based on the use of the Mandurah rainfall records, it would seem that the yield of the Serpentine coastal plain drainage system is of the order of 20%-25% and that annual volume of flow is much less variable than the Murray.

Harvey River

The Harvey River drains the largely irrigated pastures of the Waroona-Harvey drainage area (Fig. 3.1). There are no continuous flow records for the Harvey River, but during the study flow was recorded continuously at a point 8km from Harvey Estuary (site 11, Fig. 1.1). Flows to the estuary from six minor drains were measured weekly for a sufficient period to correlate them with Harvey River discharges. Thereafter, they were considered as a single input to the Harvey Estuary (Table 4.6).

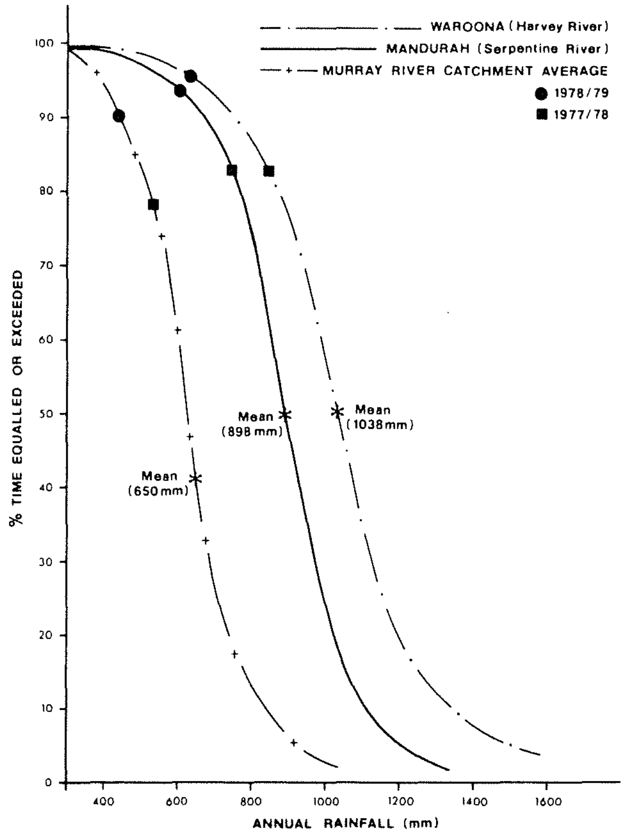

Figure 4.2 Frequency analysis of catchment rainfall of the Peel-Harvey estuarine system.

TABLE 4.5 SERPENTINE DRAINAGE SYSTEM — STATISTICS OF FLOW

Water Year	SERPENTINE DRAINAGE SYSTEM — ESTIMATED FLOWS INTO PEEL INLET ($m^3 \times 10^6$)												
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1977/1978	5.2	1.2	0.7	1.0	1.2	1.4	1.1	2.0	7.7	26.6	7.3	9.5	64.9
1978/1979	12.5	1.9	0.9	1.0	0.8	0.9*	0.9*	1.4	4.4	9.5	11.6	9.0*	54.8*

* Based on incomplete record at 614 072

Water Year	SEASONALITY — STATISTICS OF FLOW			
	Summer (Nov, Dec, Jan, Feb, Mar.)		Winter (June, July, Aug, Sept.)	
	Total ($m^3 \times 10^6$)	% of Annual	Total ($m^3 \times 10^6$)	% of Annual
1977/1978	5.5	8.5	51.1	78.7
1978/1979	5.5	10.0	34.5	63.0

TABLE 4.6 MONTHLY FLOWS HARVEY RIVER MAIN DRAIN AND MINOR DRAINS*

Water	TOTAL RIVER AND DRAIN FLOW TO HARVEY ESTUARY ($m^3 \times 10^6$)												
Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1977/1978	4.5	1.7	1.8	1.6	1.4	1.8	1.6	10.4	43.9	87.4	18.9	30.9	205.9
1978/1979	25.9	3.1	2.1	1.9	1.8	2.9	2.3	2.8	22.2	58.9	20.6	6.0	150.5

* Includes 002 Fauntleroy Drain, 003 Caris Drain, 004 Coolup Drain, 006 Mealup Drain, 007 South Coolup Drain, 008 Mayfields Drain.

Using rainfall from the Waroona gauge, yield for the study years 1977/78 and 1978/79 was 24% and 22% respectively. As with the Serpentine River, the annual volume of flow probably does not vary greatly. However, there is greater summer flow because of periodical release of irrigation water.

CONCLUSIONS

In the very dry 1978/79 water year, the coastal plain catchments of the Serpentine and Harvey suffered nowhere near as badly as the Murray, whose 6,840 km² catchment upstream of 614 006 is 60% agricultural and was affected throughout by drought. Furthermore, the impact of this greatly reduced rainfall is made worse by the very low yield of the Murray catchment. Thus while in most years riverine inputs to the system are dominated by the Murray River, in 1978/79 they were dominated by flow from the coastal plain catchments.

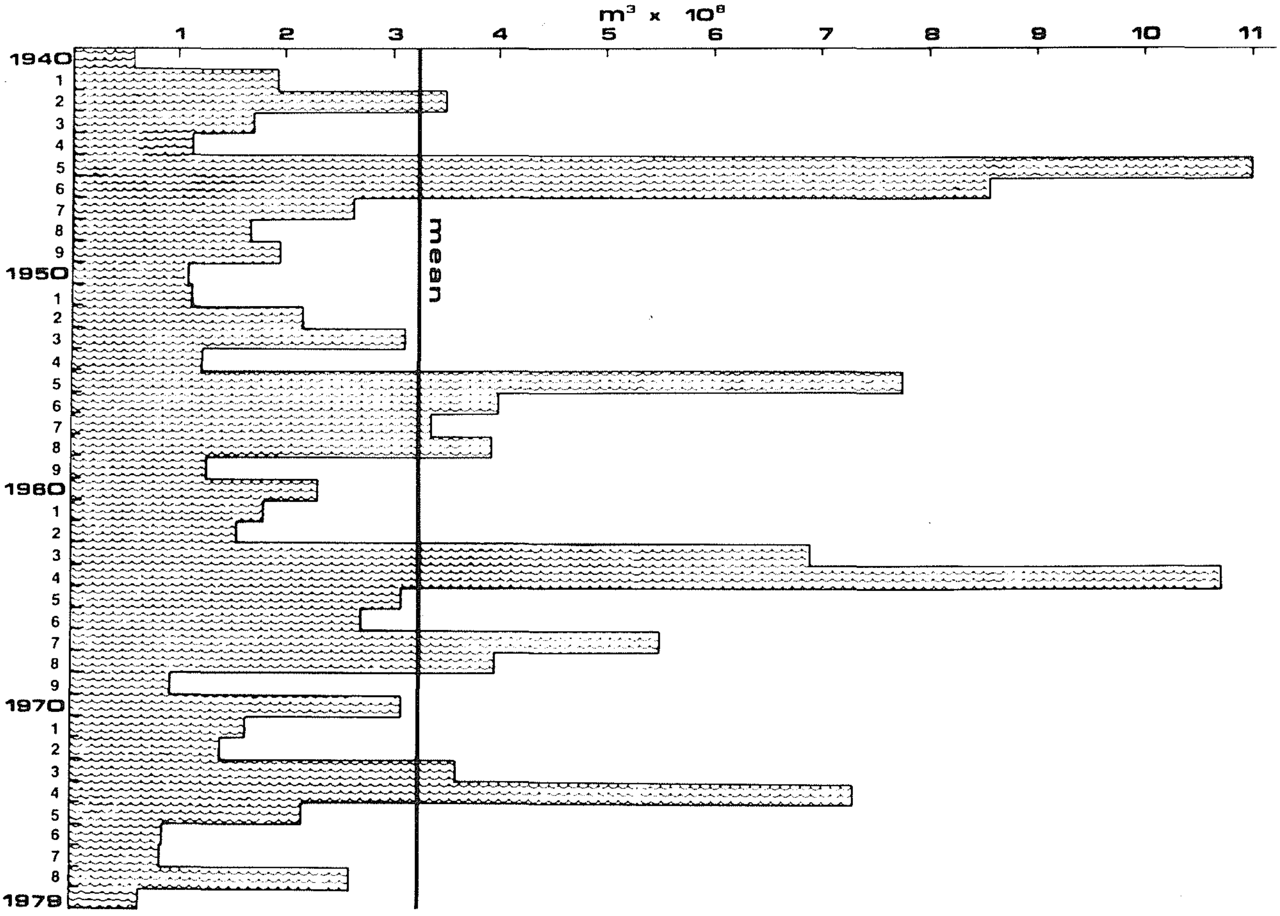

Figure 4.3 Murray River annual flow at gauging station 614 006 (near Baden Powell Water Spout).

CHAPTER FIVE

PHYSICAL FEATURES AND HISTORY OF THE ESTUARY

GEOMORPHOLOGY

The estuary lies on the western edge of the Swan Coastal Plain, separated from the sea by the line of Spearwood (late Pleistocene) dunes with their core of Tamala limestone. It opens to a coastal embayment through a narrow N-S inlet channel.* Peel Inlet is a shallow lagoon within the Spearwood and Bassendean dune systems, while Harvey Estuary lies in a long narrow inter-dune depression (Fig. 3.3).

Dimensions of the system are shown in Table 5.1 and the bathymetry and other features in Figure 5.1. From these it will be seen that the 5km long inlet channel is small in relation to the size of the estuary; this has a severe damping effect on diurnal tides (Chapter 6). Moreover the channel is obstructed at both ends; by a sea bar which tends to close and a tidal delta that dries out at lowest low water (LLW). The 2km long Sticks Channel has been dredged across the tidal delta to a depth of 1.9m.

The Murray River discharges to Peel Inlet through the Yunderup delta with its six distributaries; one of these is dredged for navigation, but the mouths of others are closed by bars which dry at LLW. It is tidal to the Pinjarra Weir. The Serpentine River discharges to the north side of the Yunderup delta and it also has a dredged channel. The Harvey River discharges at the southern end of Harvey Estuary through a crowsfoot delta with a number of distributaries all of which have shallow bars. Agricultural drains discharge at points along the eastern perimeter of Peel and Harvey; the largest, Mayfields, alongside the mouth of the Harvey River. Small deltas have formed at mouths of some, most notably the Coolup Drain.

The estuarine part of the Murray River is scoured to 5m in the narrower reaches and is navigable at all times. Narrow reaches of the Serpentine River are also relatively deep, however the lakes are very shallow.

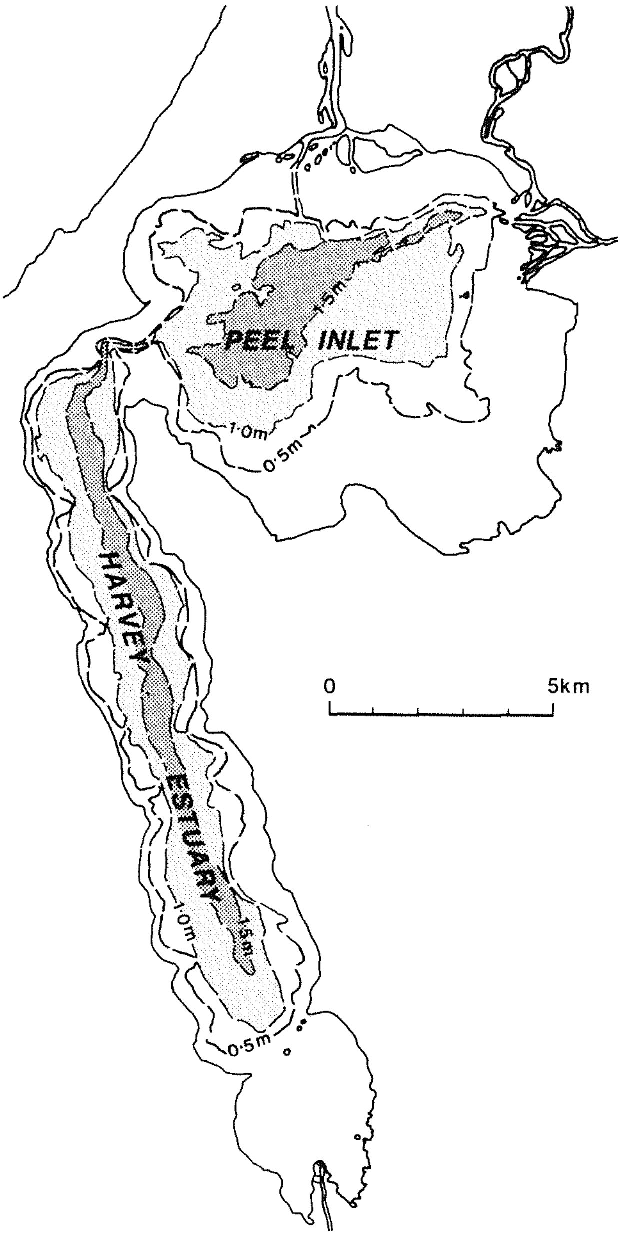

Figure 5.1 Bathymetry of Peel Inlet and Harvey Estuary. Depths below sounding datum which is 0.45m below AHD.

Peel Inlet is roughly circular, about 10km in diameter, and has a central basin about 2m deep. The basin is surrounded by a wide marginal shelf, large areas of which are dry at LLW, especially in the south east. The tidal delta and Murray River delta (fluvial shelf) form part of this shelf (Fig. 5.2). Harvey Estuary, in contrast, is 20km long and 2-3km wide with its long axis oriented NNW-SSE. It has a 2m deep central trough with narrow marginal shelves on both sides. The shallow Point Grey Sill between Peel and Harvey has a narrow, deep channel (50m x 2-3m) connecting the two basins.

Salt marshes on either side of the inlet channel are subject to inundation at normal winter high water level and there are similar salt marshes on the eastern side of Peel Inlet and in the southern segment of Harvey Estuary. Narrow fringing marshes also border other parts of the system. (Fig. 7.9).

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* In Bulletin No. 90 (Sediments and Organic Detritus) the term 'inlet channel' is used to denote the Pleistocene channel and the present day channel is termed the 'tidal channel'.

TABLE 5.1 DIMENSIONS OF THE ESTUARINE SYSTEM

Inlet Channel

Length : 5 km
Cross sectional area at Mandurah Bridge : 700 m^2

Peel Inlet

Shoreline area : 75 km^2
Shoreline volume* : 60 x 10^6 m^3

Volume at sounding datum = 117 x 10^6 m^3

Harvey Estuary

Shoreline area : 56 km^2
Shoreline volume* : 56 x 10^6 m^3

Mean observed volume for study period = 152 x 10^6 m^3

Rivers

Serpentine	appr. 24 km, includes Goegrup Lake (2 km^2)
Murray	24 km
Harvey	appr. 4 km

* The sounding datum adopted for Peel Inlet and Harvey Estuary is 0.45m below State Mean Sea Level. It is the lowest level which will be reached under the most unfavourable conditions.

SEDIMENTS AND SEDIMENTATION

The principal features of Peel Inlet sediments are illustrated in Figure 5.3. It will be noted that a maximum depth of about 3m of Holocene sediments fill the shallow Pleistocene valley now occupied by Peel Inlet. The apparent slow rate of sedimentation (0.3mm p.a.) may be an artefact in that there is evidence that the lower member (skeletal sand and mud) may have been formed during the first 2000 years after inundation (i.e. to 4000 BP). The upper basin member (sandy silty mud) may be at wave base and showing no net accretion at the present time.

These Holocene sediments are derived from four sources:

a) Pleistocene soils eroded from the margins of the basins by wave action;

b) quartz sand, silt and clay, and organic matter brought down by the rivers, principally the Murray;

c) marine sand brought in by tidal currents;

d) organic material that has originated mainly within the basins themselves, also shell material.

Wave erosion of the margins and sediment transport was probably initially rapid and the lagoons had acquired much of their present form by about 5000 years BP. Much of the material eroded from the margins was deposited close by and built out the marginal shelves. Erosion has exposed the Pleistecene soil in several places on the shelves. The Point Grey Sill was formed by sediment transported along marginal shelves. This continuing process is evident in the series of mobile sand bars on the eastern shore of Harvey Estuary.

Coarser material brought down by the rivers is deposited mainly in the deltas, while finer silt and clay size material falls out in still water of the basin or is carried out to sea.

Tidal currents have carried marine sand into and through the inlet channel, and this sand has been deposited along both margins of the channel and especially at its southern end, where it forms the tidal delta. In many places this delta is overlain by sandy organic mud of the salt marshes.

Material of organic origin is present throughout the estuarine sediments both as decayed plant and animal matter and as abundant mollusc shells and other skeletal material. This skeletal material is most abundant in the lower members of the basin sheet (skeletal mud) and the tidal delta unit (skeletal sand) and is less common in the marginal sheet (skeletal silty sand). Similarly, the organic carbon content is higher in the basin sheet units (sandy silty mud, 0.6-1.4% and skeletal mud, 0.7-3.0%) than in the shelf sediments (0.3%). However, higher organic carbon levels (12%) are found in the black mud layers usually associated with major beds of benthic algae in Peel Inlet. This rich mud, apparently of recent origin, is a loose accumulation of detritus and faecal pellets.

Surface sediment of the Harvey Estuary basin is a sticky, grey to black, organic mud with a higher clay content than Peel Inlet sediment, some skeletal material, and a higher organic carbon content (3%, 1.3-5.1%).

HISTORY OF THE ESTUARY

It is inferred from knowledge of sea level changes that the channel through the Tamala limestone would have been flooded about 8000 years BP, resulting in formation of a narrow estuary. The main lagoonal depressions would then have been flooded by 6000 years BP, and during the next 2000 years sea level rose to slightly above present level (variously estimated at +0.5m to +3m) before returning to its present level.

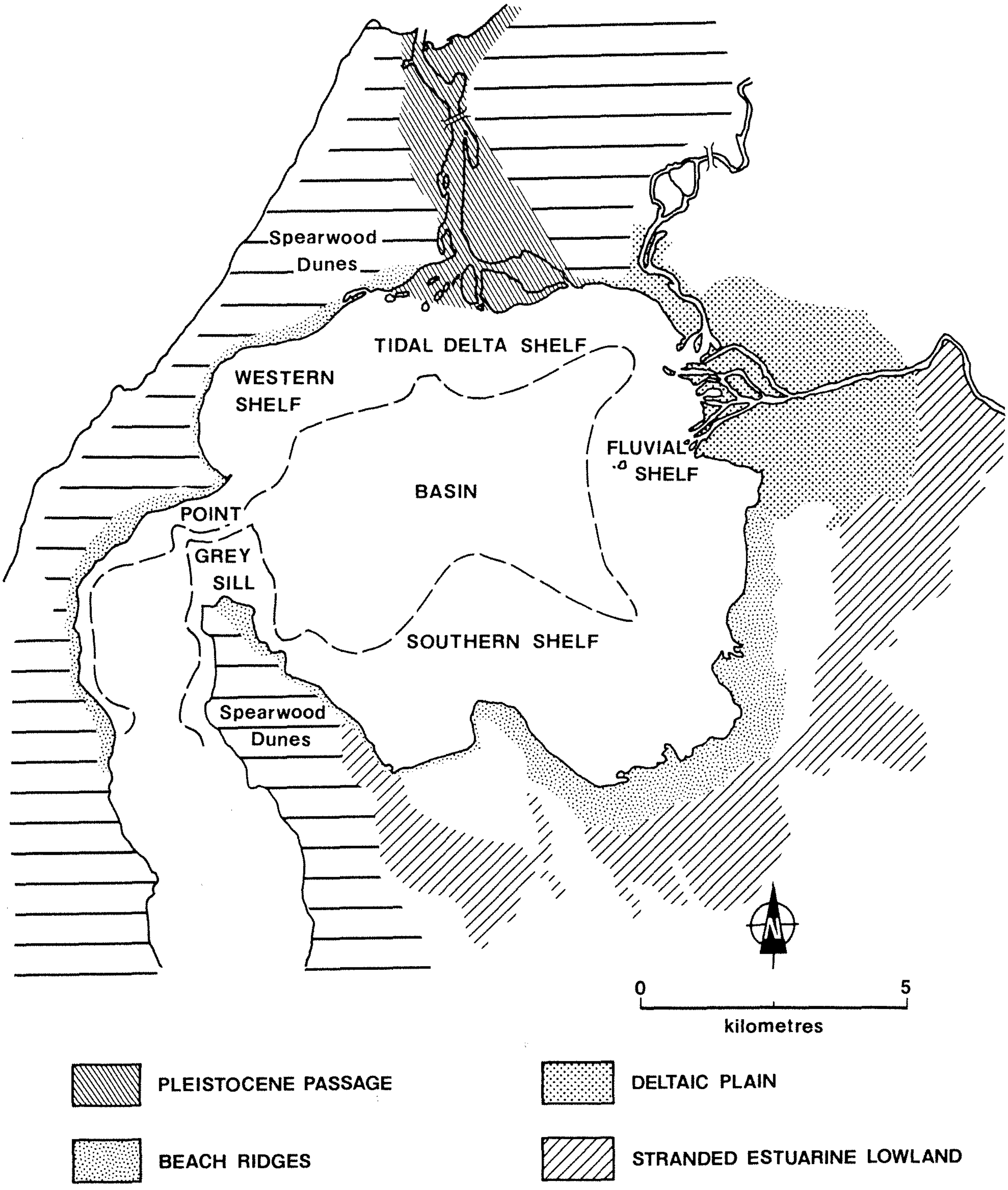

Figure 5.2 Geomorphic units, Peel Inlet.

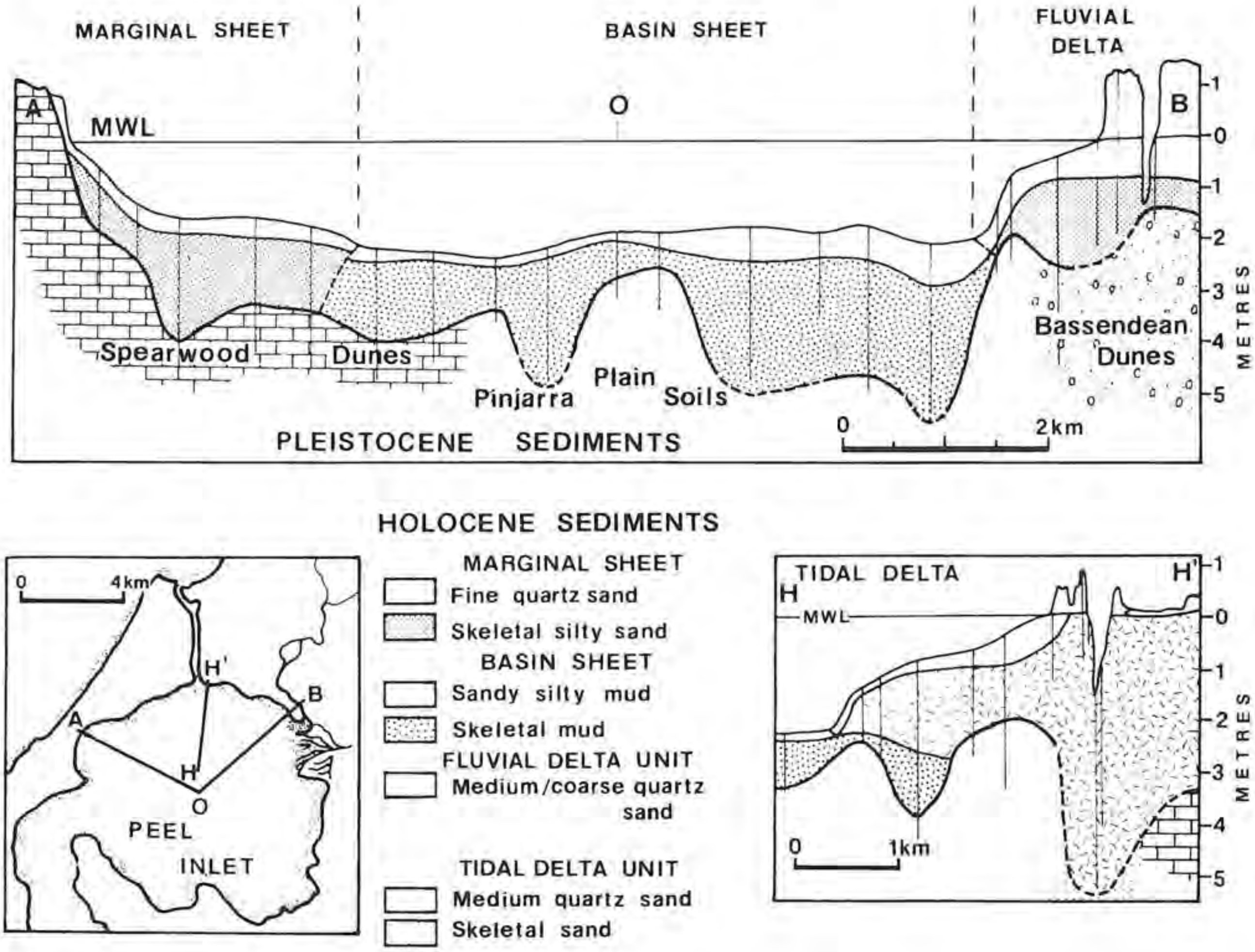

Figure 5.3 Sediments of Peel Inlet.

The abundant fossil material of the lower sedimentary units indicates that at least between 5250 and 4500 years BP the system was much more marine than it is now. About 40 species of mollusc are represented, most of which are regarded as of marine or estuarine-marine affinity; this assemblage is similar to that now found in Oyster Harbour. This is in contrast to the present mollusc fauna of about 12 species, most of them true estuarine species, and which are the only molluscs represented in the upper basin unit.

There is a small progressive loss of species through the lower sediment unit, but the sharp change to the upper unit implies that relatively marine conditions ended rather abruptly, giving way to the extreme hydrological conditions of the present day where salinity varies from 2-50 ppt; conditions unfavourable to all except the present restricted mollusc fauna.

This change probably resulted from a number of inter-connected processes: infilling of the channel by the skeletal sand unit, which reduced the cross sectional area of the channel to one seventh of that present initially; formation of the tidal delta; a fall in sea level from its higher stand between 4000 and 6000 BP; infilling at the seaward end of the channel thus reducing its length; periodic closure of the sea bar. Kendrick (1977) suggests there may also have been a climatic change resulting in a different pattern of river flow.

Coming to recent history, there have been complaints about closure of the bar ever since the earliest days of settlement. It is evident that it often closed to the stage at which boats could not enter or leave the estuary, and tidal exchange was severely restricted. However, it is less clear just how often it closed completely, so that all water exchange ceased, or for how long. There is a record that it closed for five to six months in the summer of 1914-15 and apparently again in 1935 and 1958. Tydeman (1948) states: "At intervals of about eight years this channel becomes completely blocked with sand for a few months; this is then breached by sea action from outside."

It may reasonably be concluded that complete closure of the bar is not the result of human activities and may indeed have been a natural feature of the estuary for a long time. The present condition of continuous, if periodically restricted, exchange between estuary and ocean is itself an artefact of recent date, i.e. since construction of the training walls in 1967.

CHAPTER SIX

HYDRODYNAMICS AND HYDROLOGY OF THE ESTUARY

Figure 6.1 is a conceptual model of the estuary. The major *inputs* to this model, river flow and rainfall, have been discussed in Chapter 4, so we concentrate here on their relative importance in water budget terms.

WATER BUDGET TERMS

Evaporation
In the summer condition of the estuary, when river flow and rainfall are negligible, we may write (for Peel Inlet):

$$\frac{V_1 \, dS_1}{dt} = Q_0 S_0 - Q_0 S_1$$

where V_1 = tidal volume of Peel Inlet in m^3.
S_1 = average salinity of Peel Inlet in ppt.
t = time in sec.
Q_0 = volume of rate of exchange between Peel Inlet and the ocean in $m^3 \, sec^{-1}$.
S_0 = mean ocean salinity in ppt.

i.e., the salt content of Peel Inlet is dependent upon and must therefore soon become that of sea water (about 36 ppt) and this argument also extends to Harvey Estuary. Salinity measurements taken weekly throughout the study clearly reveal that this is not the case and in summer 1978 salinity exceeded 45 ppt. This occurs because evaporation becomes dominant. Ocean salinities are not again reached until late May when the effect of reduced solar radiation is to allow tidal exchange to be dominant again.

Figure 6.2 shows salinity, evaporation, rainfall and total river flow into the estuary throughout the study period. Estuary evaporation was estimated from measurements from a U.S. Class "A" pan evaporimeter located at Robert Bay adjacent to the water body itself. Table 6.1 lists monthly evaporation for the study period.

Rainfall
Direct precipitation into the estuary water body in the years 1977/78 and 1978/79 was 99 and 81$m^3 \times 10^6$ respectively (Table 4.3).

Groundwater
Field studies in January and July 1977 supplied detailed information on absolute elevations (to Australian height datum) of the water table from some 130 bore holes into the Quaternary sediments to the east of the estuary. These revealed a general slope from the Darling Scarp to the estuary of approximately 1 in 1000. Geological Survey of Western Australian logs suggest that these sediments are of the order of 10m thick and are likely to have hydraulic conductivities of about $5m^3/day/m^2$.

Application of the Darcy equation to the perimeter of the estuary yields an extreme upper limit for unconfined groundwater flow to be $4000m^3 \, day^{-1}$. The possibility of further discharge from one or more confined aquifer systems can not be entirely dismissed but we have no evidence for such a mechanism. Thus the likely annual groundwater input to the estuary is of the order of $2 \times 10^6 m^3$ which is approximately 0.5% of the total of river flow and direct precipitation.

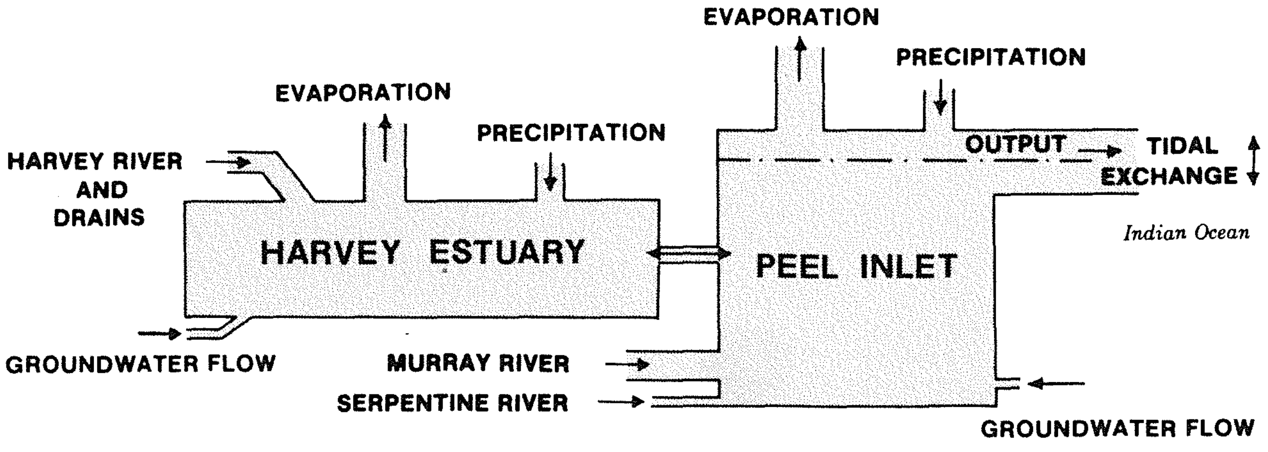

Figure 6.1 Peel Inlet-Harvey Estuary: water balance model.

River Flow

Tables 4.4, 4.5 and 4.6 list the annual contributions (to the estuary) of the Murray, Serpentine and Harvey River systems.

THE WATER BUDGET

The simplest application of the continuity equation takes the form of the water balance equation:

$$\text{Inflow} = \text{Outflow} \pm \text{Storage} \qquad (6.1)$$

For the estuary we may expand 6.1 thus:

$$Q_M + Q_S + Q_H + G_W + P_I \pm \Delta S = Q_O + E \qquad (6.2)$$

Where Q_M, Q_S and Q_H are Murray, Serpentine and Harvey River flow volumes.

G_W is ground water flow volume
P_I is weighted average rainfall volume on estuary
ΔS is change in storage volume
Q_O is outflow to sea volume
E is estuary-wide evaporation volume (units are $m^3 \times 10^6$ throughout).

Table 6.2 shows the inputs and outputs to equation 6.2. In the absence of direct and continuous measurement of outflow to the sea (at Mandurah channel) we must determine Q_O as a residual so that it inherently includes the net effect of errors in all other (measured) terms of the equation. This is only possible by evaluating 6.2 over a time period of sufficient length to validate the approximation $\Delta S \to 0$; e.g. one year.

TABLE 6.1 ESTIMATED MONTHLY EVAPORATION PEEL INLET AND HARVEY ESTUARY (converted from Robert Bay U.S. Class "A" pan evaporimeter).

	Estimated Evaporation (mm)	
Month	**1977/78**	**1978/79**
October	122.1	126.8
November	151.2	158.6
December	195.9	185.6
January	176.8	180.5
February	147.4	137.0
March	155.1	138.4
April	118.2	86.3
May	86.9	80.4
June	57.2	46.5
July	68.4	59.8
August	66.3	67.2
September	75.8	62.9
Total (mm)	1421.2	1330.0
Volume * ($m^3 \times 10^6$)	189.9	176.9

* Based on area of 133 km^2

A necessarily subjective assessment of errors in the estimation of all terms in 6.2 leads to a most probable error in Q_O of ±18% (1977/78) and ±27% (1978/79).

TIDAL FLUX

Flushing model

Weekly measurements of salinity at 0.5m depth increments were taken at 7 sites within the estuary (Fig. 6.3). Figure 6.2 shows the variations in salinity at site 4 (Coodanup) together with the associated total evaporation and total river flow and rainfall. This time series of salinity data is the only data set which enables us to estimate the exchange of ocean and estuarine water. The series inherently reflects variations due to:

i) low salinity river flow inputs;
ii) concentration due to evaporation; and
iii) the input/output of marine water at an assumed concentration of 35 ppt.

TABLE 6.2 WATER BUDGET OF THE ESTUARY Volumes in $m^3 \times 10^6$

YEAR 1977/78

Inflow		**Outflow**	
Q_M	289	E	190
Q_S	65	Q_O	471*
Q_H	206		
G_W	2		
P_I	99		
Inflow = 661		Outflow = 661	

*Q_O is the residual term and is about 84% the magnitude of 1977/78 river inflow.

YEAR 1978/79

Inflow		**Outflow**	
Q_M	86	E	177
Q_S	55	Q_O	197*
Q_H	150		
G_W	2		
P_I	81		
Inflow = 374		Outflow = 374	

*Q_O is the residual term and is about 67% of the magnitude of 1978/79 river inflow.

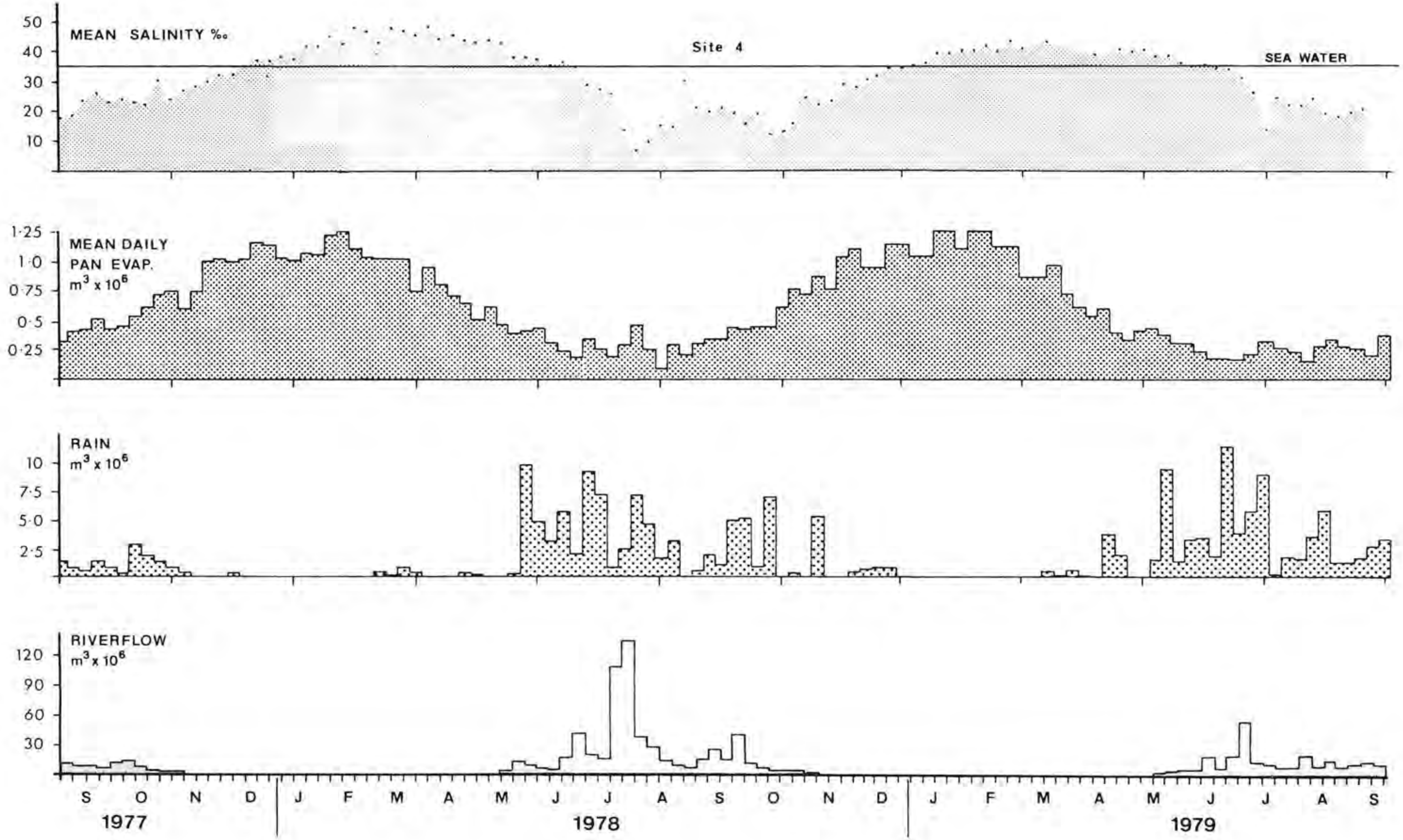

Figure 6.2 Weekly salinity, evaporation, rainfall and total river flow.

Thus a "flushing model" was written using an estimated marine or river salinity series (depending on the season) and these input salinity changes (S_i) can be defined as a step-like function as shown in Figure 6.4. The upper level of the step is 35 ppt indicating ocean forcing; the lower level is 10 ppt. indicating a mixture of ocean and river forcing. The output series is of course the observed salinity, measured weekly at each of the seven sites.

Flushing rates

The estimated flushing rates between the Peel Inlet and Harvey Estuary (Site 1 to Site 2) are shown in Table 6.3. This shows that flushing of the Harvey Estuary to Peel Inlet takes on the average between 1.0 and 1.7 weeks. Between the whole and 0.6 of the estuarine water is exchanged per week.

More importantly, the exchange between the Peel-Harvey system and the ocean is evaluated similarly. Table 6.4 lists the *average* flushing rates for Peel Inlet (sites 2 to 7 inclusive) whilst Table 6.5 includes the full details of flushing rates and residence times for all sites. Figure 6.3 also depicts these calculated rates.

Direct measurements of ocean exchange

Two intensive (5 day) exercises were undertaken during which measurements of current speed and direction, water temperature, and salinity were taken at Mandurah Road Bridge (Fig. 6.5). One was during the summer no flow period (12-17 February 1978) and the other during a period of significant river discharge (13-18 August 1978). Figures 6.6 and 6.7 show the measured salt and volume fluxes calculated during these periods. During the August exercise, the computation of salt fluxes is complicated by the marked difference between surface and bottom salinities as shown in Figure 6.8.

These estimated fluxes enabled the computation of nutrient losses/gains to the ocean and are further discussed in Chapter 10.

CONCLUSIONS

In retrospect, it seems that **direct measurement of ocean exchange** as carried out for the two intensive exercises is the only way that really reliable estimations of ocean loss/gain can be made. However, the manpower and equipment requirements of such a monitoring task rendered this impracticable. Furthermore, it is felt that the results of nutrient budgeting using the flushing model are adequate for this purpose, given the errors inherent in such a time series, with weekly sampling at only 7 sites in a 133km^2 water body (see also Chapter 10).

TABLE 6.3 ESTIMATED RESIDENCE TIMES* : PEEL INLET-HARVEY ESTUARY Site 1 to Site 2

Description	Estimate weeks	Lower bound weeks	Upper bound weeks
Long Term	1.25	1.7	1.0
Minimum (summer)	1.7	2.4	1.3
Maximum (winter flushing)	0.7	0.9	0.5
Min. (evap. effects)	1.7	2.4	1.3
Max. (evap. effects)	1.0	1.3	0.7

* 'Residence time' is defined within the context of the dynamic flushing equation, and is NOT the simple conventional definition of V/Q — see Technical Report 100.

TABLE 6.4 AVERAGE RESIDENCE TIMES FOR PEEL INLET based on the six sampling sites, 102 weeks

Description	Estimate weeks	Lower bound weeks	Upper bound weeks
Long Term	4.3	7.1	3.1
Minimum (summer)	6.7	20.0	4.3
Maximum (winter flushing)	1.9	2.3	1.5
Min. (evap. effects)	5.9	12.5	3.8
Max. (evap. effects)	3.6	5.3	2.7

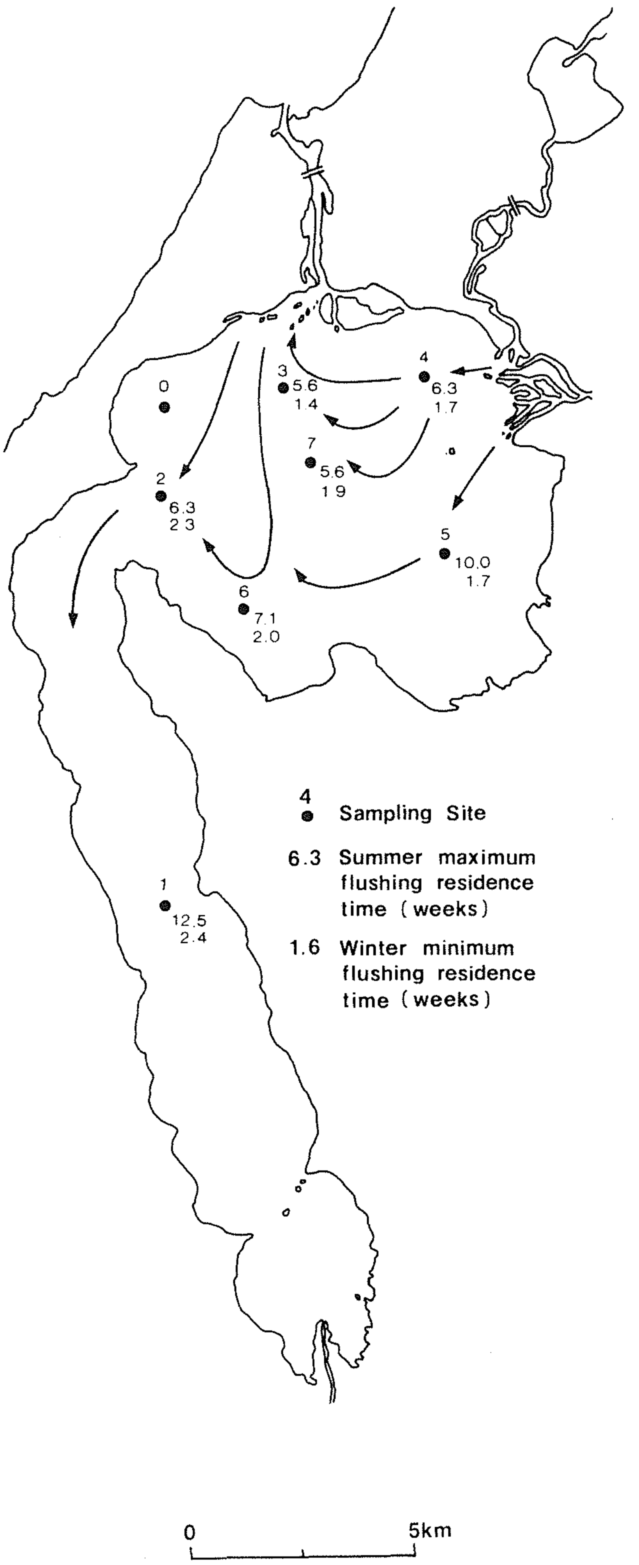

Figure 6.3 Circulation directions and flushing residence times in Peel Inlet and Harvey Estuary.

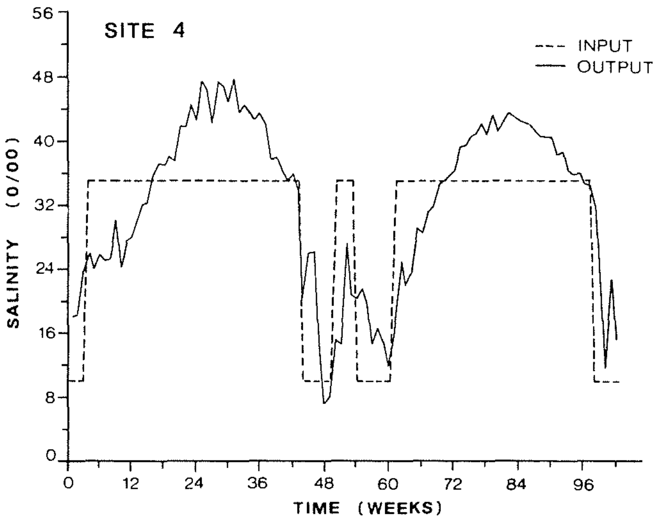

Figure 6.4 Modelled salinity at site 4, 1977-79. Input step-like forcing function and output salinity at site 4.

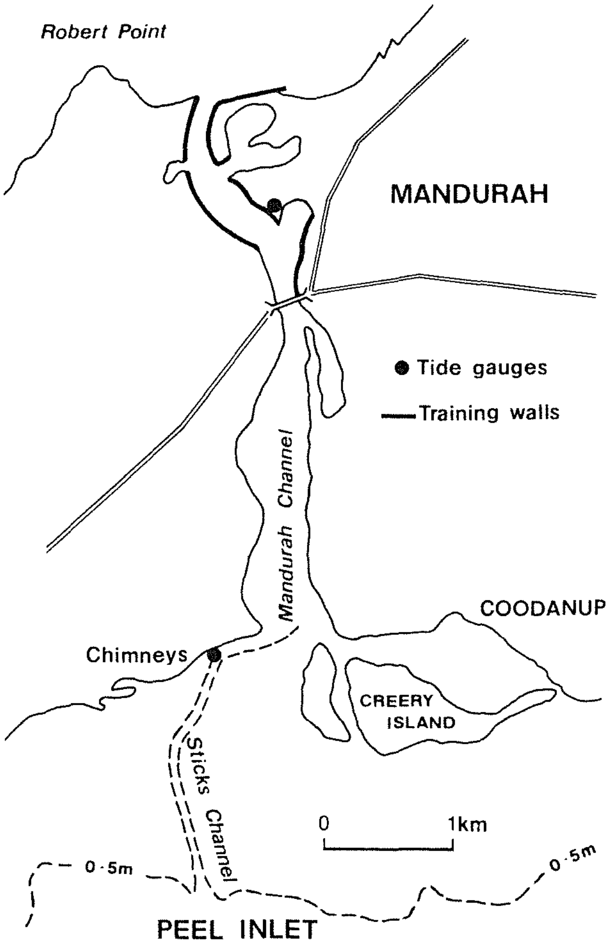

Figure 6.5 The Mandurah channel.

TABLE 6.5 FLUSHING RATES AT SAMPLING SITES. Equivalent flushing (residence) times in weeks shown in italics.

SITE 1

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.2 *5.0*	0.12 *8.3*	0.29 *3.4*
Minimum (Summer)	0.08 *12.5*	0.01 >*30*	0.16 *6.3*
Maximum (River Flushing)	0.42 *2.4*	0.31 *3.2*	0.53 *1.9*
Min. (Evap. Effects)	0.13 *7.7*	0.05 *20.0*	0.21 *4.8*
Max. (Evap. Effects)	0.29 *3.4*	0.20 *5.0*	0.38 *2.6*

SITE 2

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.24 *4.2*	0.16 *6.3*	0.31 *3.2*
Minimum (Summer)	0.16 *6.3*	0.1 *10.0*	0.24 *4.2*
Maximum (River Flushing)	0.43 *2.3*	0.34 *3.3*	0.53 *1.9*
Min. (Evap. Effects)	0.19 *5.3*	0.12 *8.3*	0.26 *3.8*
Max. (Evap. Effects)	0.29 *3.4*	0.21 *4.8*	0.37 *2.7*

SITE 3

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.26 *3.8*	0.18 *5.6*	0.33 *3.0*
Mininum (Summer)	0.18 *5.6*	0.11 *9.1*	0.25 *4.0*
Maximum (River Flushing)	0.71 *1.4*	0.59 *1.7*	0.83 *1.2*
Min. (Evap. Effects)	0.21 *4.8*	0.14 *7.1*	0.29 *3.4*
Max. (Evap. Effects)	0.30 *3.3*	0.23 *4.3*	0.38 *2.6*

SITE 4

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.25 *4.0*	0.17 *5.9*	0.33 *3.0*
Minimum (Summer)	0.16 *6.3*	0.08 *12.5*	0.24 *4.2*
Maximum (River Flushing)	0.59 *1.7*	0.48 *2.1*	0.71 *1.4*
Min. (Evap. Effects)	0.19 *5.3*	0.11 *9.1*	0.27 *3.7*
Max. (Evap. Effects)	0.30 *3.3*	0.21 *4.8*	0.40 *2.5*

SITE 5

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.18 *5.6*	0.09 *11.1*	0.29 *3.4*
Minimum (Summer)	0.10 *10.0*	0.02 >*30*	0.19 *5.3*
Maximum (River Flushing)	0.59 *1.7*	0.45 *2.2*	0.77 *1.3*
Min. (Evap. Effects)	0.12 *8.3*	0.04 *25.0*	0.22 *4.5*
Max. (Evap. Effects)	0.24 *4.2*	0.15 *6.7*	0.36 *2.8*

SITE 6

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.21 *4.8*	0.11 *9.1*	0.31 *3.2*
Minimum (Summer)	0.14 *7.1*	0.05 *20.0*	0.24 *4.2*
Maximum (River Flushing)	0.50 *2.0*	0.37 *2.7*	0.63 *1.6*
Min. (Evap. Effects)	0.16 *6.3*	0.07 *14.3*	0.26 *3.8*
Max. (Evap. Effects)	0.26 *3.8*	0.16 *6.3*	0.37 *2.7*

SITE 7

Description	Estimate (weeks-^{1})	Lower Bound	Upper Bound
Long Term	0.24 *4.2*	0.16 *6.3*	0.31 *3.2*
Minimum (Summer)	0.18 *5.6*	0.11 *9.1*	0.25 *4.0*
Maximum (River Flushing)	0.53 *1.9*	0.43 *2.3*	0.63 *1.6*
Min. (Evap. Effects)	0.20 *5.0*	0.13 *7.7*	0.27 *3.7*
Max. (Evap. Effects)	0.28 *3.6*	0.20 *5.0*	0.36 *2.8*

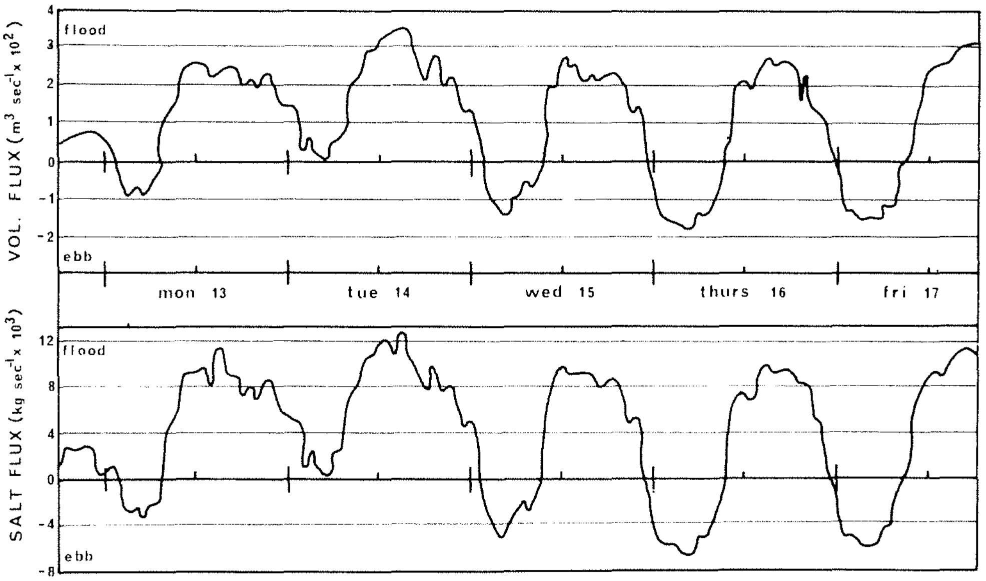

Figure 6.6 Salt and volume fluxes, Mandurah channel, February 1978.

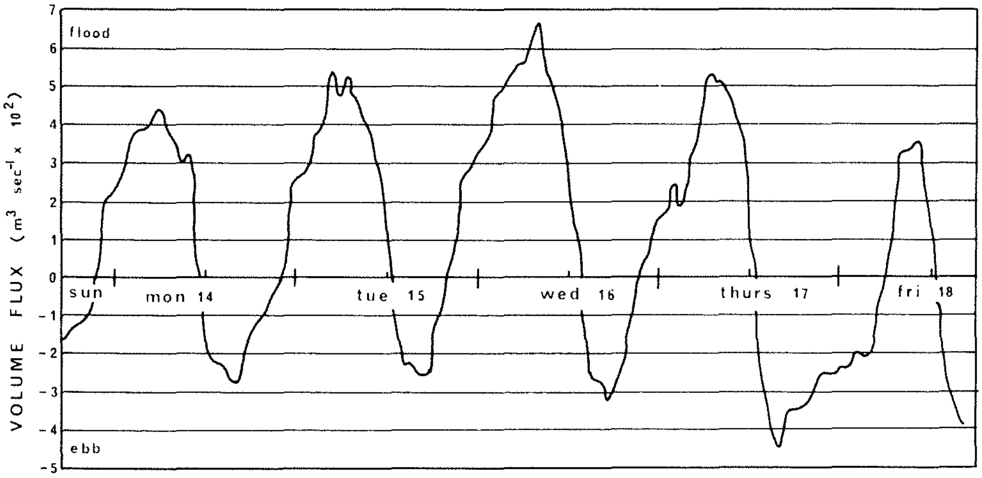

Figure 6.7 Volume fluxes, Mandurah channel, August 1978.

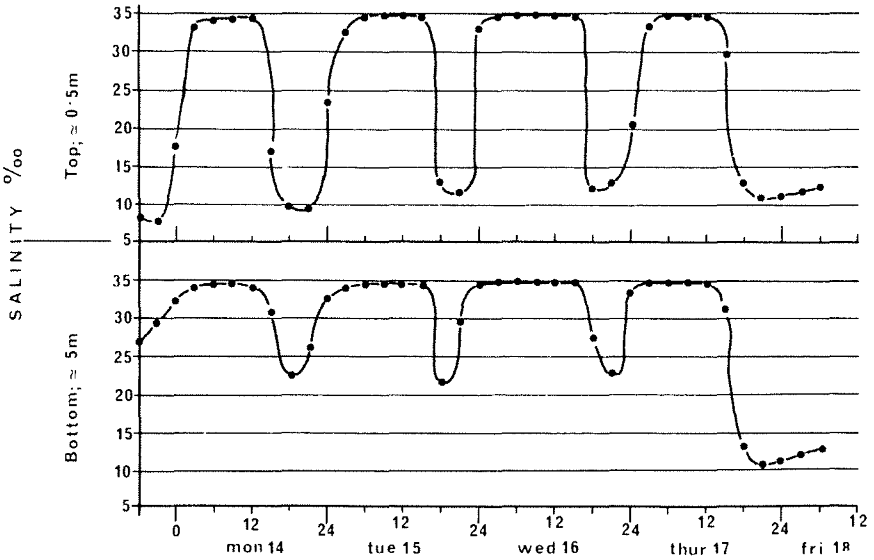

Figure 6.8 Salinity, Mandurah channel, August 1978.

CHAPTER SEVEN

BIOLOGICAL CHARACTERISTICS OF THE ESTUARINE SYSTEM

GENERAL

This chapter summarizes the biology of the major groups of plants and animals living within the Peel-Harvey estuarine system. The plant community includes the phytoplankton, macro-algae (*Cladophora* is covered separately in Chapter 8), seagrasses and marsh vegetation. The animal section will cover crustaceans, molluscs, fish, foraminifera and birds. In each case, the discussion will deal with the composition of the particular plant or animal group, its ecological importance, and distribution (temporal and spatial) within the system. The major components of the biota and their trophic relationships are shown in simplified form in Figure 7.1.

ESTUARINE PLANTS

Phytoplankton

During the greater part of the year the phytoplankton community is dominated by diatoms, with relatively high species diversity in summer and low in winter. The summer diatom community is dominated by *Pleurosigma* species (3); other common genera and species are *Amphora, Navicula, Nitschia* and *Rhizoselenia alata.* During winter blooms, *Rhizoselenia deliculatum* and *Chaetoceros* species are most common.

Nodularia spumigena dominates the blue-green flora and *Nostoc* is the next most prominent genus. Harvey Estuary has higher numbers of blue-greens than Peel Inlet, with *Nodularia* being the dominant organism. Surveys indicate that the blue-green population of Peel Inlet can be divided into two sections; on the eastern side there is a high non-*Nodularia* population, while the western half generally has low numbers but may be invaded by *Nodularia* blooms from Harvey Estuary.

The diatoms bloom mainly in winter following high nutrient inputs from the rivers. During these blooms, chlorophyll *a* levels often exceed 20 ug L^{-1}, producing turbid unaesthetic conditions (Fig. 7.2). Blue-green blooms mostly occur in the warmer months of the year and during the study period (1977-79) there was a massive bloom of *Nodularia spumigena* during November 1978 - January 1979 in Harvey Estuary (Fig. 7.3)*.

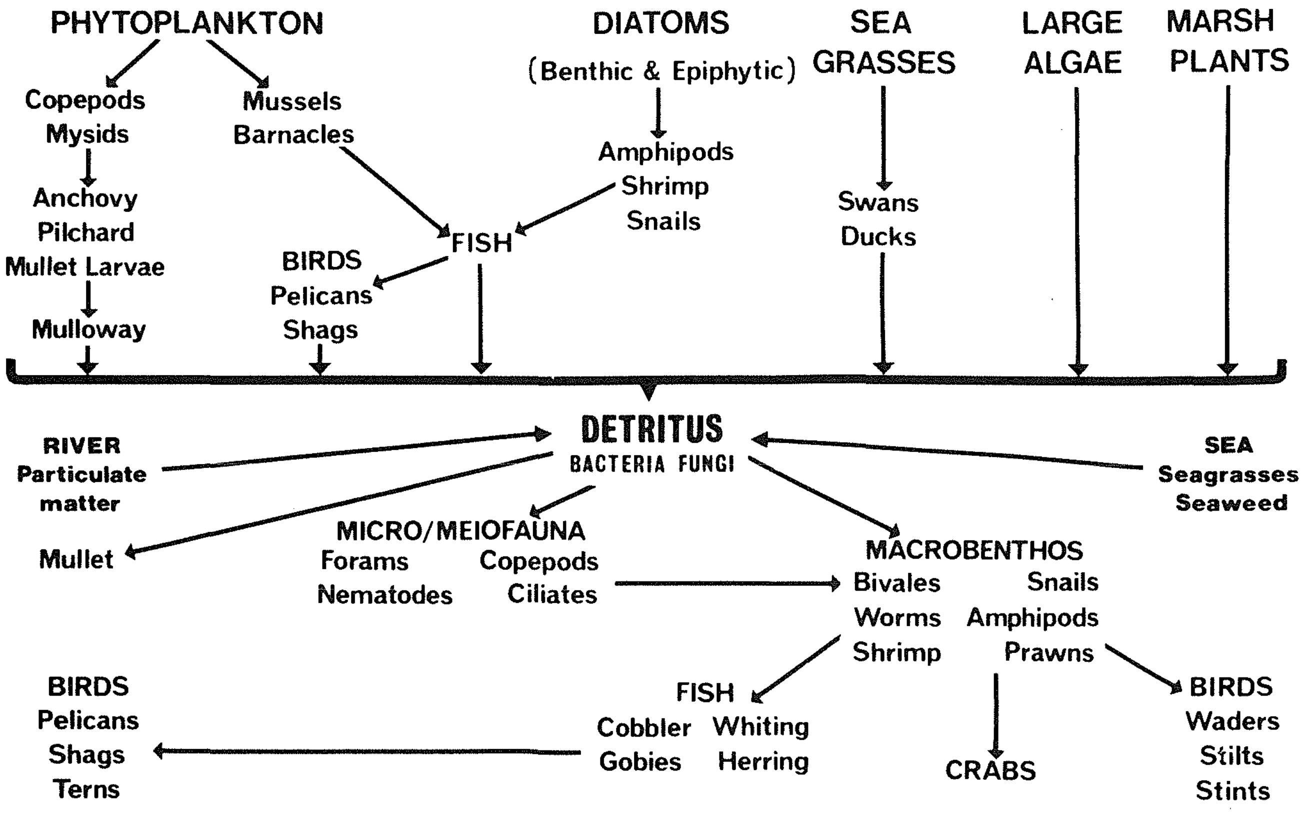

Figure 7.1 Food web of the Peel-Harvey estuarine system. A simplified scheme of probable main pathways.

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* Another, even larger, bloom occurred October 1980 —January 1981.

This bloom fixed significant quantities of nitrogen, as is illustrated by the spike in total nitrogen in the water at site 1 in Harvey Estuary (Fig. 7.4). The amount of nitrogen fixed, based on total nitrogen measurements, is estimated at 270 tonnes, almost as much as was contributed by the Harvey River input in the 1978/79 water year.

Bioassays and nutrient analyses show that growth of phytoplankton in the estuary is limited much of the time by low levels of both nitrogen and phosphorus; only in winter or spring, during high river flows, are nutrient inputs sufficient for phytoplankton blooms. The *Nodularia* blooms occurred when there was high phosphorus availability combined with a low N : P ratio in Harvey Estuary. This bloom of a nitrogen-fixing blue-green was therefore a response to conditions of low nitrogen supply when phosphorus was relatively abundant.

Overall, Harvey Estuary appears to be a better habitat for phytoplankton than Peel Inlet as evidenced by higher chlorophyll *a* concentrations in Harvey Estuary. This is thought due to higher phosphorus inputs coupled with a lower flushing rate. Also, the flocculant sediments, which are richer in nutrients, are constantly resuspended by wind action. Resuspension also brings benthic diatoms into the water column and would account, in part, for the higher chlorophyll *a* levels there.

Phytoplankton play an important role in recycling nutrients for the benthic algae, especially *Cladophora*. The winter diatom blooms prevent some of the river-borne nutrients from being lost to sea. Part of these blooms settle to the bottom where they decompose and release nutrients for subsequent phytoplankton blooms and for benthic algae.

There is also evidence that tidal action distributed part of the *Nodularia* bloom from Harvey Estuary into western Peel Inlet where it decomposed and provided significant amounts of nitrogen and phosphorus to the extensive *Cladophora* bed in this embayment. This idea is supported by sediment studies which showed an increase in extractable nutrients there at this time. A similar rise in extractable sediment N and P was also observed at the other *Cladophora* growth areas in August 1978 after the winter diatom blooms. Further support for nutrient recycling comes from the CRES Modelling Studies. Expected chlorophyll *a* levels, computed on the basis of water nutrient concentrations, were often less than those observed (Fig. 7.5).

Benthic macro-algae
After *Cladophora* the most abundant macro-algal genera are *Chaetomorpha*, *Enteromorpha* and *Chondria*. All of the species recorded so far are listed below in Table 7.1.

Whilst *Cladophora* is the most abundant macro-alga, there are sizeable blooms of *Enteromorpha* during later winter and early spring in shallow waters (Fig. 7.6) with subsequent drift onto beaches, especially off Coodanup and in the Austin Bay area. *Chaetomorpha* is often found in significant amounts mixed in *Cladophora* beds in the eastern area of Peel Inlet and contributes to the offensive algal accumulations on the beaches.

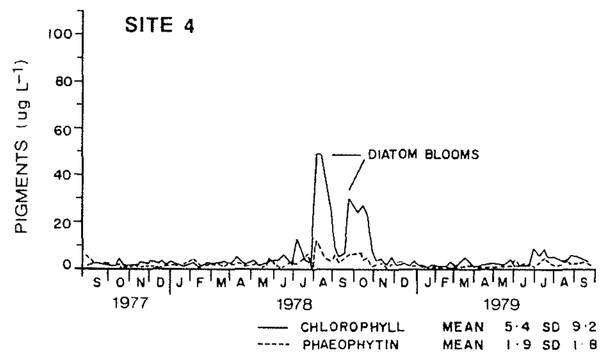


Figure 7.2 Chlorophyll *a* pigments at site 4, Peel Inlet.

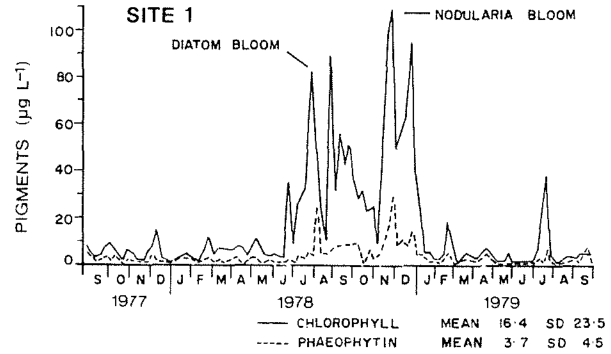


Figure 7.3 Chlorophyll *a* pigments at site 1, Harvey Estuary.

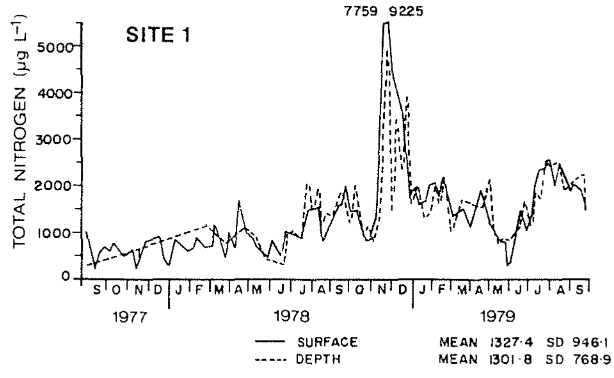


Figure 7.4 Total nitrogen at site 1, Harvey Estuary. The high levels during November-December 1978 were caused by a bloom of *Nodularia*.

Limited laboratory studies suggest that *Chaetomorpha* may have some growth requirements very similar to those of *Cladophora*. *Chondria* appears better adapted to low light than the other macro-algae and is mostly found in deeper or turbid waters; it occurs commonly in Harvey Estuary. In Peel Inlet an increase in its abundance was observed in 1978 during the winter and spring when turbid conditions prevailed.

Even though macro-algae other than *Cladophora* are not major contributors to the algal accumulation problem in the estuary more work on their biology would be useful. It is possible that relatively small man made or natural changes in the estuarine environment could alter conditions enough to greatly change the present suite of species, which in turn could have marked effects on the beach accumulation problem.

Aquatic angiosperms

The two major species of aquatic angiosperms in the estuary are *Ruppia megacarpa* and *Halophila ovalis;* minor species are *Zostera mucronata* and *Lepilaena cylindricarpa*. *Ruppia* and *Halophila* have a clearly defined distribution pattern in Peel Inlet, the former plant growing in the shallowest (< 0.3m) waters of the marginal shelf (Fig. 7.7), whilst the latter occupies slightly deeper areas of the shelf (~0.3 — 0.6m; Fig. 7.8). These distributions are possibly related to water turbulence, with the more fragile *Ruppia* being confined to the more protected shallows (< 0.3m). Light probably delimits the deeper boundary of *H. ovalis*. *Ruppia* begins growth in the shallows about two months earlier than *Halophila* which is a shorter, more robust plant which regenerates in November. This temporal difference enables *Ruppia* to invade the shallows first. In Harvey Estuary, *Halophila* dominates shallow waters of the eastern margin possibly because of the greater turbulence there compared with Peel Inlet.

Of the minor species of aquatic angiosperms, *Zostera mucronata* is mainly confined to the inlet channel indicating that this plant is better suited to more marine conditions. Only a few clumps of *Lepilaena cylindricarpa* have been found in the estuary, in eastern Peel Inlet.

Halophila and *Ruppia* grow mostly in spring and summer, *Halophila* regenerating mainly from rhizomes, and *Ruppia* from seed in very shallow water and rhizomes in deeper water. Detachment of leaves and shoots occurs in autumn, but drift from degenerating plants has never caused offensive beach accumulations as have rotting piles of algae. This is important since the present seagrass community is threatened to some extent by excessive growth of *Cladophora*, which drifts into piles on the marginal

TABLE 7.1 AQUATIC MACRO-ALGAE OF THE PEEL-HARVEY ESTUARINE SYSTEM

CHLOROPHYTA

Acetabularia calyculus. Quoy and Gaim.
Acetabularia peniculus. (R.Br), Solma.
Chaetomorpha aurea. (Dillw.), Kuetz.
Chaetomorpha linum. (Muell.), Kuetz.
Cladophora spp. — several species.
Enteromorpha spp. — several species.

CHAROPHYTA

Lamprothamnium papulosum. (Wallr.), J.R.em.R.D.W.

PHAEOPHYTA

Caulocystis uvifera. (Ag.), Areach.
Cystoseira trinodis. (Forsk.), Ag.
Dictyota sp.
Hormophysa triquetra. (L.), Keuta.

RHODOPHYTA

Chondria spp.
Corynospora australis. Harv.
Gracilaria verrucosa. (Huds.), Papenfuss
Polysiphonia spp.
Laurencia spp.

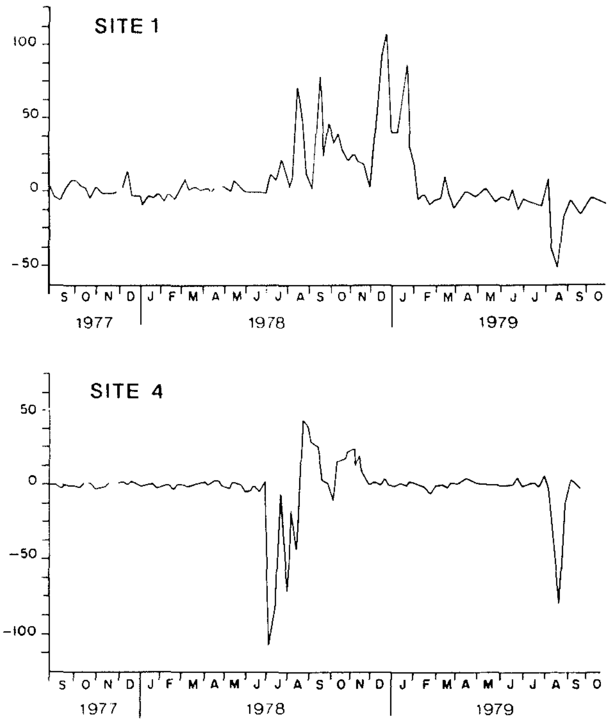


Figure 7.5 Plots of the difference between observed chlorophyll *a* concentrations and those expected on the basis of water column nutrient concentrations. Positive deviations indicate a possible contribution of nutrients from recycling; negative deviations indicate that nutrient supply was greater than that which could be used by the phytoplankton.

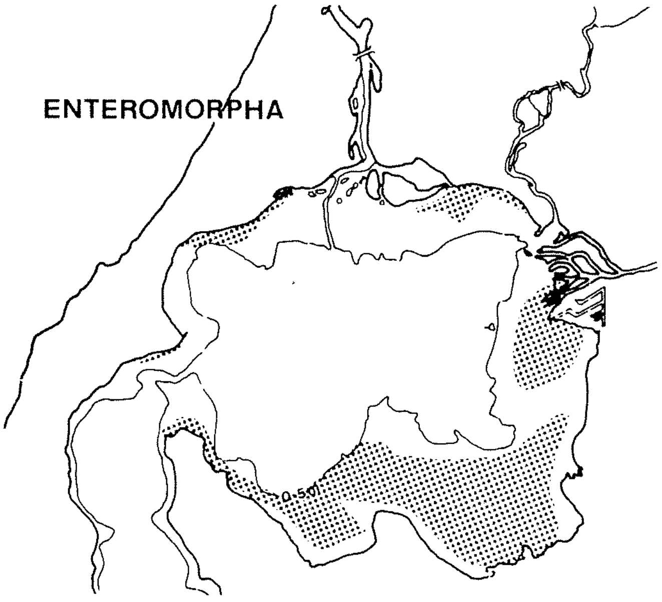


Figure 7.6 Distribution of *Enteromorpha* in Peel Inlet, September 1979.

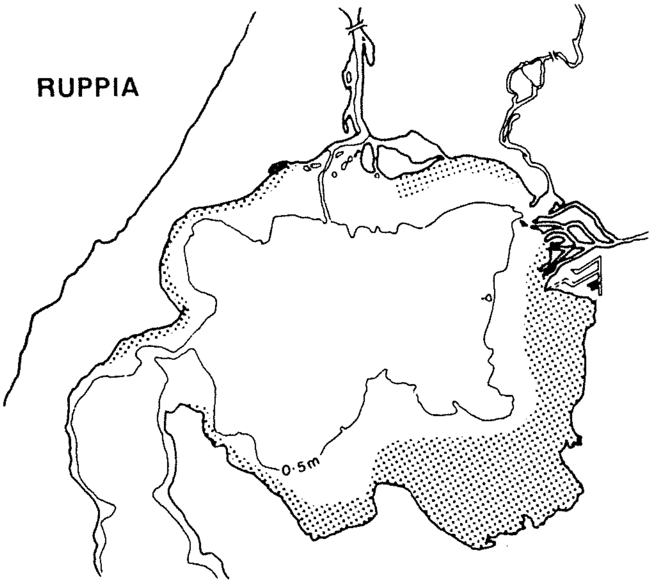


Figure 7.7 Distribution of *Ruppia* in Peel Inlet, September 1979.

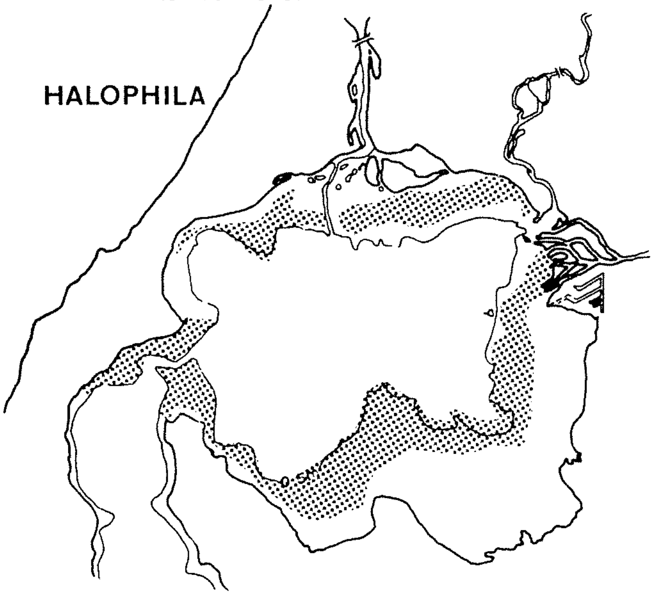


Figure 7.8 Distribution of *Halophila* in Peel Inlet, September 1979.

vegetation and smothers it. The smothered area may be re-invaded if the *Cladophora* is subsequently removed.

Marsh Vegetation

The total area of marshes is about 13km², or some 10% of the total marsh plus open water area (Fig. 7.9). The major components of the fringing vegetation are the *Sarcocornia* marsh, and meadows of *Scirpus maritimus* and *Juncus krausii.* The *Sarcocornia*-dominated marsh is the most extensive marsh type and occurs in most localities where relief is low. Away from the water's edge *Atriplex paludosa* and *Suaeda australis* are found in association with *Sarcocornia.* The most extensive areas of *Sarcocornia* marsh occur along the eastern edge of Peel Inlet between Fauntleroy and Greenlands drains, and round the southern segment of Harvey Estuary. *Scirpus maritimus* grows in many places along the eastern shores of Peel inlet and there is an extensive meadow in the southern end of Harvey Estuary extending from the waterline to the extensive *Sarcocornia* marshes behind. *Juncus krausii* does not exist as extensive meadows, and has a patchy distribution around most of the estuary, often as a narrow discontinuous zone only three or four clumps wide. However, it is important in stabilizing the shore line.

In terms of nutrients, the marshes represent about 5-20% of the nitrogen and phosphorus contents of the estuary, exclusive of the sediments. Most of this nutrient bank is probably recycling within the marsh system although part could be exported to the open water.

The recent excessive growth of *Cladophora* in the estuary has had a detrimental effect on the marshes by drifting onto and smothering them in places. Although most of the nutrients are retained in the smothered areas, the degeneration of the marshes will lead to potentially serious destabilization of shorelines. It is necessary therefore to obtain a better understanding of the significance of the marshes to the general ecology of the area, including their role in shoreline stabilization, nutrient dynamics, and bird life.

ESTUARINE FAUNA

Molluscs

The mollusc fauna is dominated by a few estuarine species. Marine species (12) occur in the inlet channel and some marine affinity species (6) (species with more or less continuous estuarine representation) occur also in Peel Inlet and one *(Spisula trigonella)* is common in Harvey Estuary. A total of 18 species have been found in Peel Inlet and 7 in Harvey Estuary.

The common species which form more than 90% of the mollusc biomass are:

Hydrococcus graniformis Thiele	(Gastropoda)
Arthritica semen Menke	(Bivalvia)
Spisula trigonella Lamarck	(Bivalvia)
Anticorbula amara Laseron	(Bivalvia)

The first two, small (2-3mm) species were studied in some detail, giving information on seasonal biomass variation, reproduction, growth rates, salinity and temperature tolerances. Both species occupy sandy substrates and feed on the benthic microbiota, converting plant detritus to mollusc tissue. They are an important part of the food of some bottom feeding fish and wading birds.

Spisula is a larger bivalve (to 25mm) that is particularly abundant in the black sticky mud of the Harvey Estuary basin. *Anticorbula* is common on rocks and logs in the tidal rivers where it grows best, but small animals are sometimes abundant on sandy marginal shelves of the lagoons.

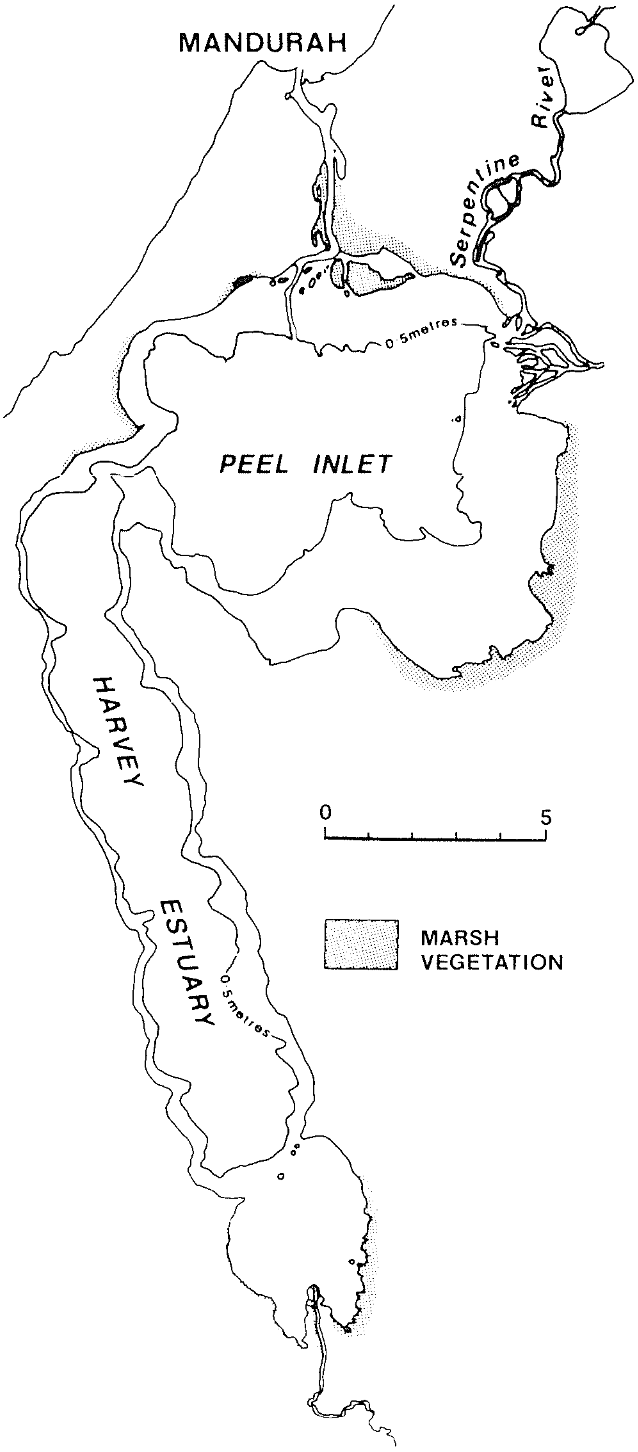


Figure 7.9 Fringing marsh vegetation of the Peel-Harvey estuarine system. Much of the water's edge carries a narrow fringe of marsh, not shown here.

Other benthic macro-invertebrates

A few species of polychaete worms (6) are abundant, here as in other estuaries. They burrow in the sediment and occur also in the masses of decaying weed. Most are detrital feeders, but some are predators.

Three species of amphipod crustaceans have been identified from the estuary, they are common species found in other estuaries of the south-west. At times they are enormously abundant in the surface sediment and among living and decaying algae. They probably have an important role in the breakdown of plant debris and in turn are eaten by many species of fish. Although normally benthic, they, and a species of mysid, are often present in large numbers in night plankton in summer.

Foraminifera

Examination of Foraminifera from sediment cores indicates a change from marine to estuarine, similar to that seen with fossil molluscs, though less abrupt. The distribution of living species corresponds broadly with the estuarine flushing characteristics shown in Figure 6.3. More than 50 species have been identified from the inlet channel. The number decreases between the Chimneys and the Harvey channel and although marine species continue to be common, the fauna is dominated by *Ammonia beccarii*. This species tolerates a wide range of salinity and is almost the only species in most samples from the eastern half of Peel Inlet and Harvey Estuary.

Zooplankton

During winter flow the zooplankton is dominated by a single species of estuarine copepod, *Gladioferens imparipes*, which may be enormously abundant; it is a phytoplankton feeder. It may be followed by 2 or 3 other copepods, but in summer these true planktonic species are replaced by other Crustacea that are normally regarded as benthic: amphipods, mysids, harpacticoid copepods.

Clear estuary water is devoid of zooplankton during the day and it is only after dusk that they enter the water column. True planktonic and bentho-planktonic species retreat to the bottom in the shallow water of the estuary by day. Harvey Estuary tends to support a larger zooplankton population than does Peel Inlet, probably reflecting lower flushing losses to the sea and the higher phytoplankton production and greater suspended detrital material.

Fishes and large crustaceans

These taxonomically unrelated groups are pooled in this section because of their economic as well as biological importance in the estuary. The Peel-Harvey system supports the largest professional and amateur estuarine fishery in Western Australia and any damage to that fishery would be serious.

The species composition of the estuary is very similar to that of the Swan-Avon, though so far only about 50 species have been identified (100 in the Swan). River prawns and the blue-manna crab are also important commercial species. Fisheries statistics are available since 1942, and monitoring of the commercial fishery is carried out by the Department of Fisheries and Wildlife.

The estuarine fishes are presently being studied to:

1. complete a checklist of fish species found in the system;
2. investigate the seasonal distribution and abundance of fishes and of the blue manna crab *(Portunus pelagicus);*
3. determine habitat preferences in relation to *Cladophora.*

There is evidence of historical change in composition of the commercial catch between 1952 and the present day. There has been a decline in the catch of mulloway and black bream and an increase in catches of crabs, scaley mackerel and pilchards. There has also been an increase in catches of the detritus-eating sea mullet.

It is not known whether these changes are related to the increased eutrophication of the estuary, and to the resulting change from a seagrass-dominated benthic flora to a *Cladophora*-dominated benthic flora. Current research should improve our understanding of the habitat requirements of the major fishes, and clarify linkages between the flora and fish biology.

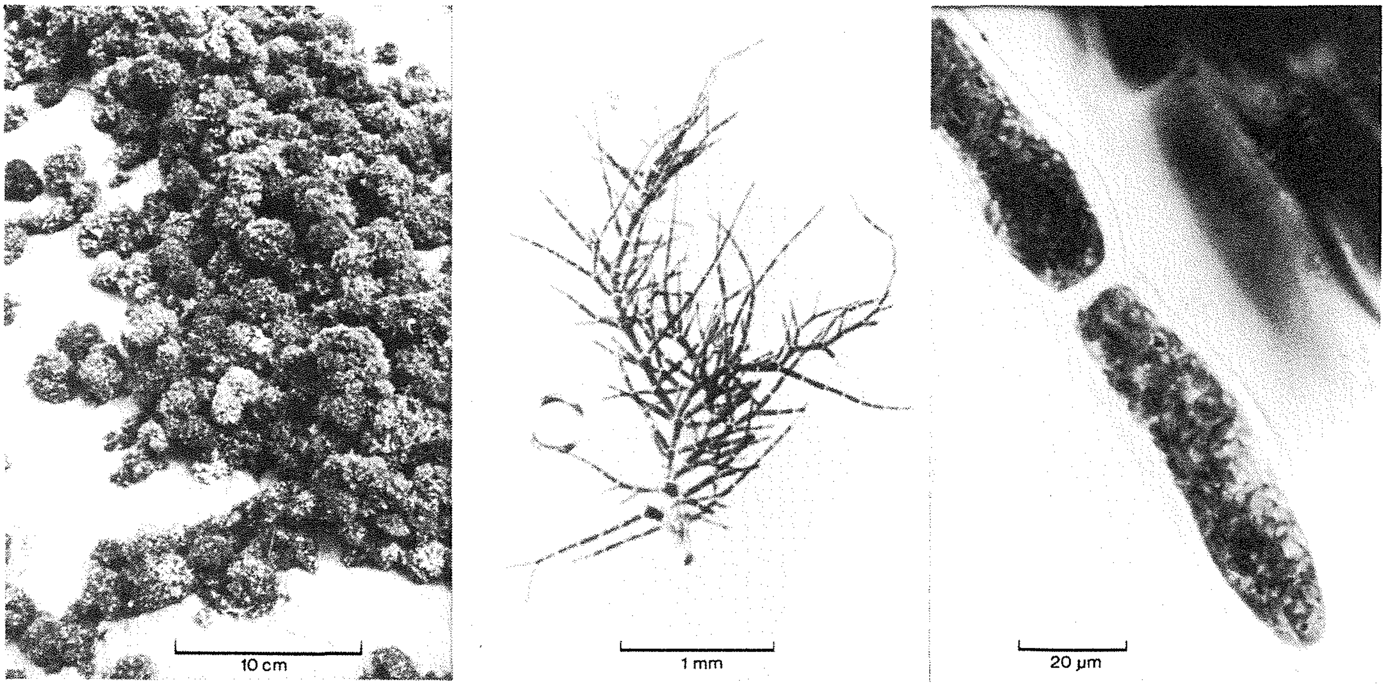
The composition of the contemporary fish fauna changes greatly with season. These changes may be related directly to the annual hydrologic regime or less directly to changes in the composition and abundance of the food supply in the estuarine system. Most species are general, non-selective, feeders preying largely on the invertebrate fauna; very few are algae eaters.

Birds

Birds are an important and conspicuous component of the biota of the estuarine system — indeed the Peel-Harvey system is the most important estuarine bird habitat in southern Western Australia. Seventy species of birds have been recorded, of which five species have populations of more than 10,000 birds, and eighteen species populations between 1,000 and 10,000.

The most important areas of waterbird habitat are the shallows, tide flats and marshes of the Creery Island-Channel Island area, Austin and Robert Bay, the Murray-Serpentine delta, and the southern end of Harvey Estuary. These areas support large numbers of waterfowl, many of which are game birds, waders (both resident and migratory), cormorants and pelicans. The Peel-Harvey system is estimated to have contained about 68% of all pelicans known to occur in southwest estuaries during November 1976.

Birds are an important mechanism by which nutrients are recycled and transported to and from the estuarine system, although no estimates of the magnitude of this is possible at present.



Cladophora: *balls on the shore, low power and high power magnification.*

CHAPTER EIGHT

BIOLOGY OF *CLADOPHORA*

GROWTH HABIT

Cladophora aff. *albida* is a green alga which grows as small ball-like clumps of densly branched, radiating filaments. These balls (which are 1-3cm in diameter) lie unattached on the estuary floor, where they may form large beds, usually 1-10cm deep. The lower sections of these beds decompose to form an anoxic black ooze over the bottom sediments (Fig. 8.1). Although individual algal balls are mobile, the beds are essentially permanent along the eastern area of Peel Inlet. There is also a large bed off Falcon and a smaller one in northern Harvey Estuary off Dawesville (Fig. 8.2).

Cladophora generally reproduces vegetatively from small pieces of filament. Occasionally it spores in the estuary; however a life cycle involving spores does not have to be completed every year.

BIOMASS IN THE ESTUARY

Biomass measurements from one site in eastern Peel Inlet from 1976-1979 are summarized in Fig. 8.3. The amount of *Cladophora* increased markedly between July 1976 and February 1977, and then after a decrease in March, remained relatively static until April 1978. At this point there was a rapid decline until the bed had almost vanished by September 1978. The decline was the result of continuing losses from the bed by physical export and decomposition at a time when growth rates were low (see Fig. 8.4). Physical export may have accounted for about 80 per cent of the biomass lost. This estimate was based on a comparison of observed biomass with that expected from measurements of *in situ* growth and decomposition. The low growth rates over this period were probably caused by low nutrient levels in autumn, whilst in winter, even though nutrients were abundant, light and temperature became limiting. Light intensity on the estuary floor was especially low in July and August, 1978 because of high river flow and increases in water turbidity. There was a slight recovery in the biomass during early 1979. This could be explained by field growth rates (Figs. 8.3 and 9.3) assuming some continued export and decomposition losses.

Biomass measurements were also made at other sites in the estuary; weekly at sites 4, 5 and 8 and six-monthly at sites 1-36 during special "grid" studies (see Fig. 8.3 and Appendix Fig. 1). Results differed in detail but all had generally lower biomass in 1979 than in 1978. The total average *Cladophora* biomass in 1978 was estimated to be approximately 26,000 tonnes (dry weight), falling to only 5000 tonnes (dry weight) in September 1979. Lower biomass in 1979 could have been due to prolonged turbidity in 1978, a series of several dry years or reduced use of superphosphate on the coastal plain (see Chapter 10), or a combination of these factors.

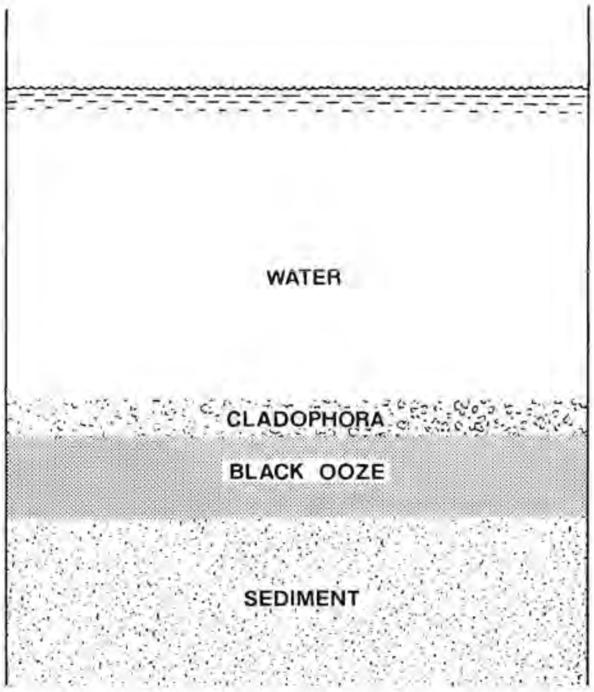


Figure 8.1 Schematic diagram of a *Cladophora* bed.

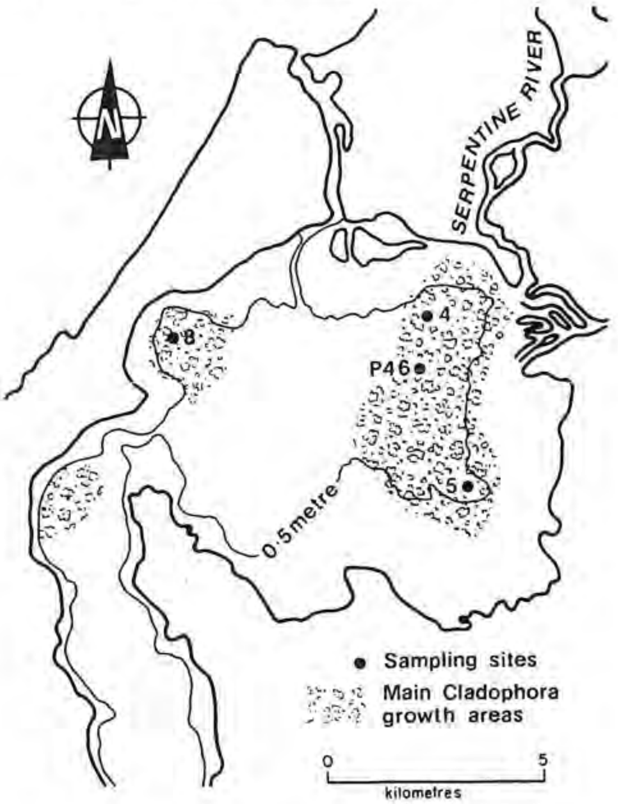


Figure 8.2 Principal *Cladophora* growth areas.

RELATIONSHIP OF GROWTH TO ENVIRONMENTAL VARIABLES

Monthly biomass in the algal bed at Post 46 is poorly correlated with the available set of measured environmental variables, mainly because the standing stock at a site at any time is the net effect of import, export, decompositional and grazing losses, as well as growth of the alga. Determining the response of *Cladophora* growth to environmental variables therefore required measurements of imprisoned populations in the bed coupled with laboratory experiments under controlled conditions.

The measurements of imprisoned populations in Peel Inlet showed that growth rates were highest in summer and lowest in winter (Fig. 8.4). Weight loss of algae in the flasks in winter was presumably due to decomposition and respiration. Seasonal changes in growth rate were well correlated with light, temperature and salinity. This was supported by laboratory studies which showed that the alga grows best in the levels of light and temperature found at the surface of algal beds in summer, i.e. 10% full sunshine (>200 uE m-^{2} sec -^{1}) and 20-25°C (Fig. 8.5 a, b). Rapid light attenuation by self-shading causes light limiting conditions at all times in the beds below about 0.5cm (Fig. 8.5 d). Salinity experiments confirmed that *Cladophora* is euryhaline and grows almost equally well over the range of 2.5 ppt — 50 ppt observed in the estuary (Fig. 8.5 c). Therefore, growth correlations with salinity are due to the colinearity of salinity with light and temperature.

NUTRITION STUDIES

Nutrient studies of *Cladophora* indicate that levels of at least 0.1 — 0.2mg L-^{1} inorganic nitrogen and 0.02 — 0.03mg L-^{1} inorganic phosphorus are required for maximum growth when no other factors are limiting (Fig. 8.6). These concentrations are only observed briefly in Peel Inlet water in winter during high river flow (Fig. 8.7) or at depth in the 'inter-algal' water within the self-shaded portion of the beds. When light and temperature conditions are favourable for growth, at the surface of the bed and above about 20°C, then the nutrient levels are low. *Cladophora* partially overcomes this temporal and spatial nutrition problem by drawing on cellular reserves created primarily in winter. Utilization of these reserves causes a reduction in tissue nutrient concentrations in summer as is illustrated in Figure 8.8.

Storage of nutrients in winter is made possible by direct uptake from estuary water which is rich in nutrients at this time and subsequently from decomposing phytoplankton blooms, as described in Chapter 7. However, storage in winter is less than the full capacity of the plant, in part because uptake rates are reduced under low light and temperature, and also because of the brief period in which nutrient concentrations are high. This particularly applies to phosphorus; tissue concentrations of *Cladophora* in the field have never exceeded the 'critical concentration' found to be necessary for maximum growth rate (Fig. 8.9). In contrast, tissue nitrogen is almost always above the critical concentration of 21mg N g-^{1}(Figs. 8.8 and 8.9). Thus *Cladophora* is always deficient in phosphorus but rarely deficient in nitrogen, and in summer, when most growth takes place, the growth rate of *Cladophora* in the actively photosynthesizing surface of beds is primarily limited by phosphorus because of inadequate cellular reserves and low supply from other sources. The nutrition studies therefore show that phosphorus availability is a key factor in controlling the biomass in the estuary at present.

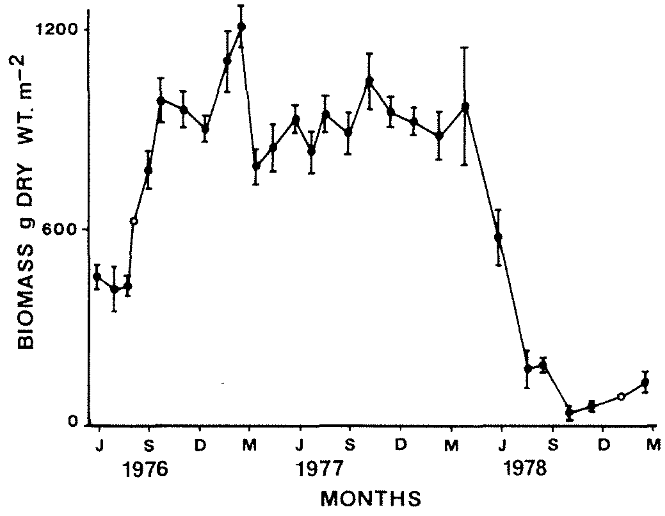


Figure 8.3 Biomass of *Cladophora* at post 46, Peel Inlet. Each point is the mean of 20 replicates ± standard error.

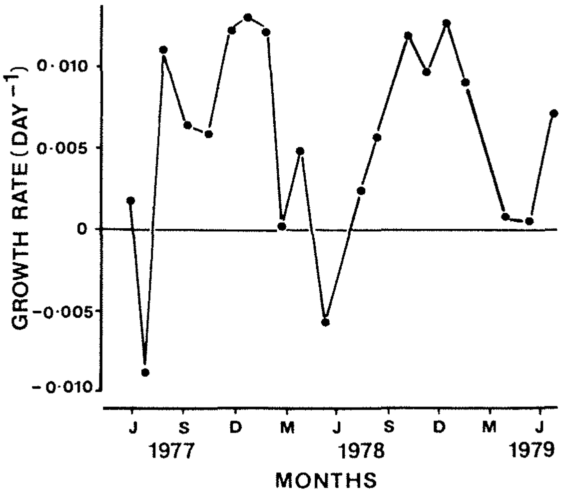


Figure 8.4 Growth rates of imprisoned populations of *Cladophora* at site 4, Peel Inlet.

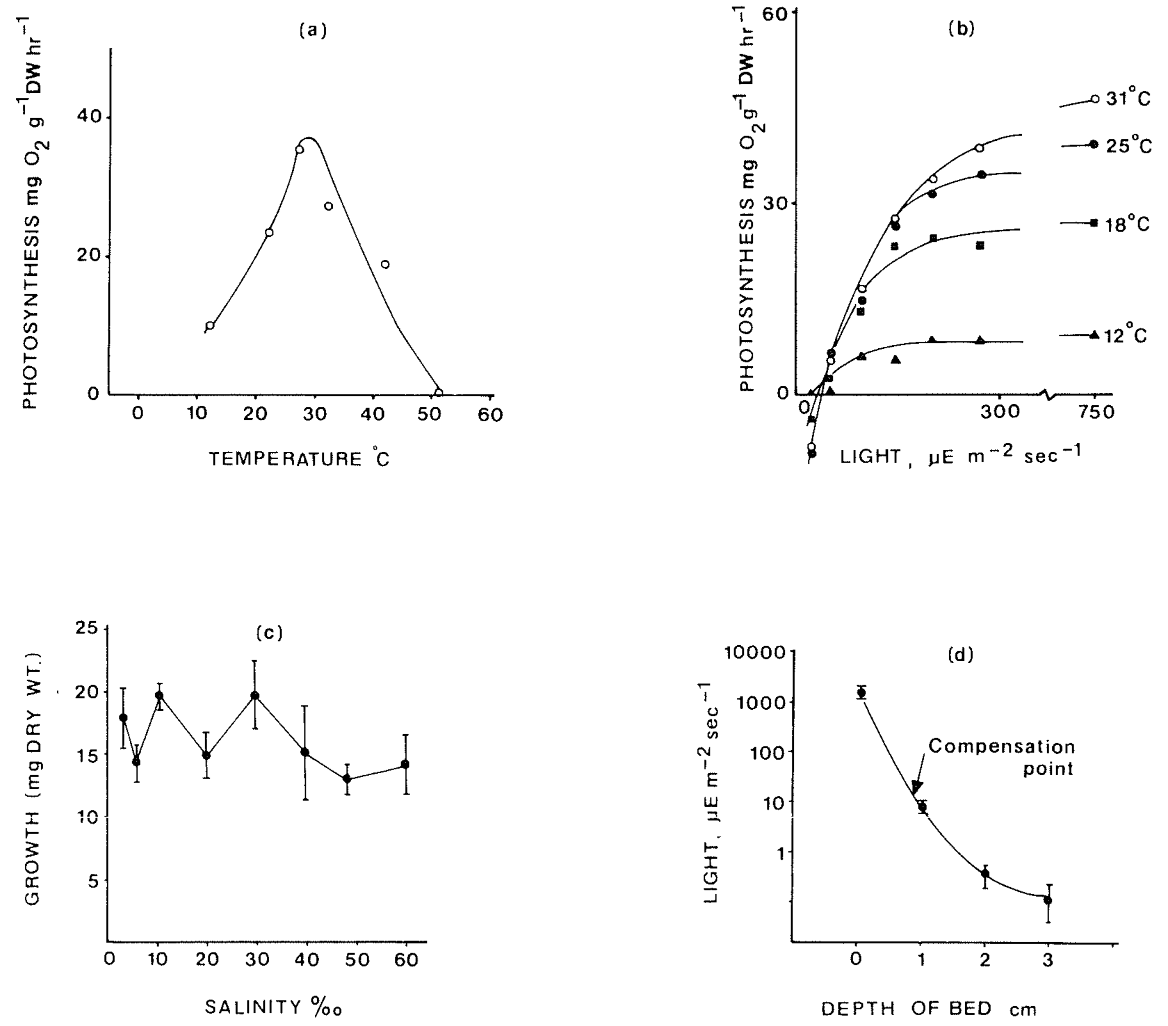


Figure 8.5 Effect of (a) temperature, (b) light, (c) salinity on photosynthetic rates and growth of *Cladophora* and (d) effect of algal bed depth on attenuation of light.

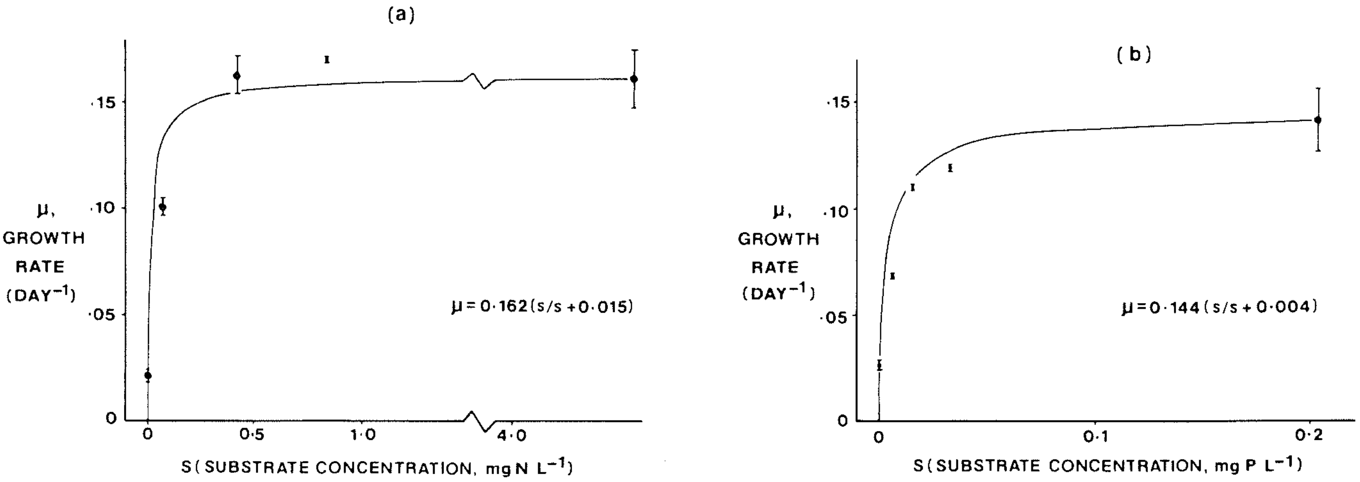


Figure 8.6 Relative growth rates of *Cladophora* as a function of (a) inorganic nitrogen concentration and (b) inorganic phosphorus concentration.

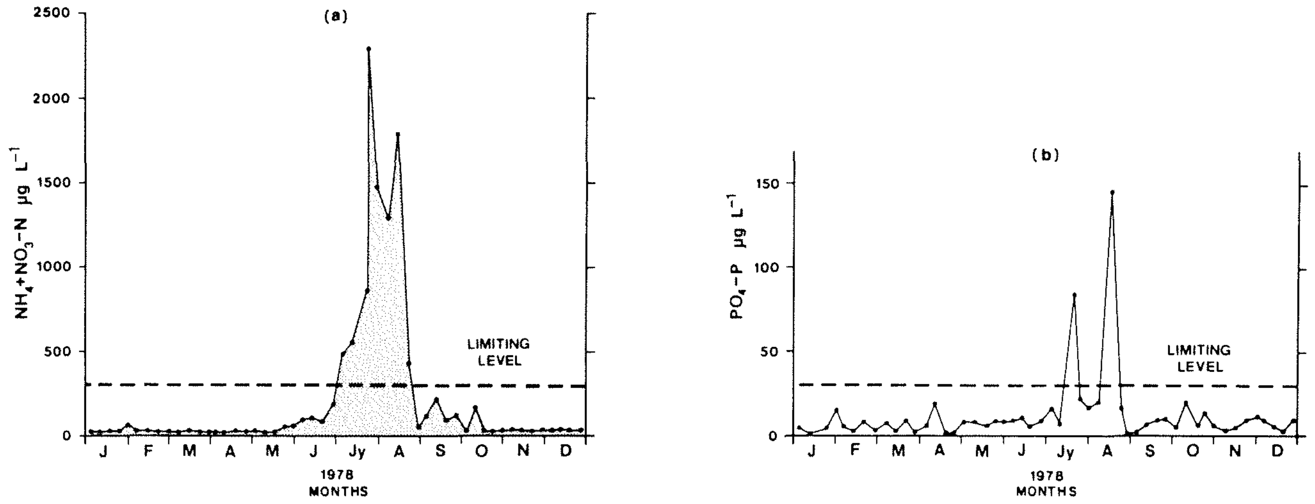


Figure 8.7 Concentrations in bottom water of (a) inorganic nitrogen and (b) inorganic phosphorus at site 4 during 1978. Limiting levels for *Cladophora* growth are plotted.

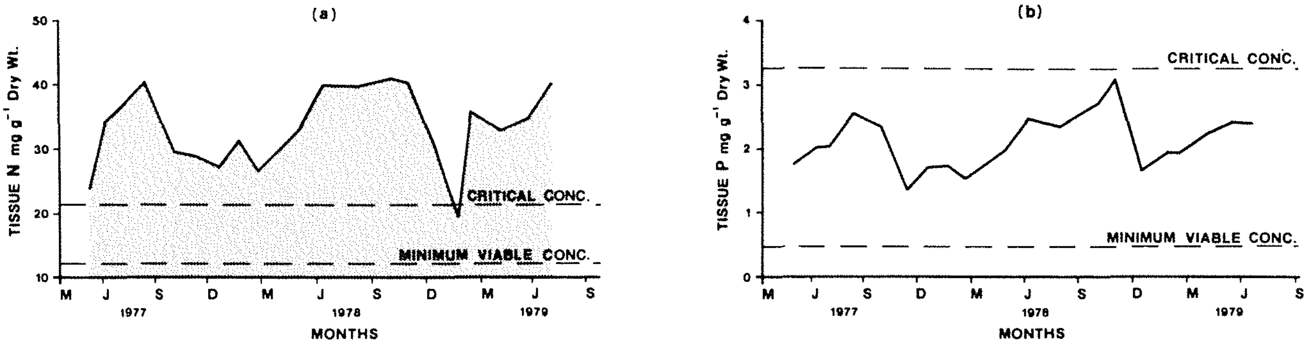


Figure 8.8 Concentrations of (a) tissue nitrogen and (b) tissue phosphorus in *Cladophora* at site 4. Critical concentration: the minimum tissue concentration associated with maximum growth rate. Minimum viable concentration: the tissue concentration at which there is zero growth.

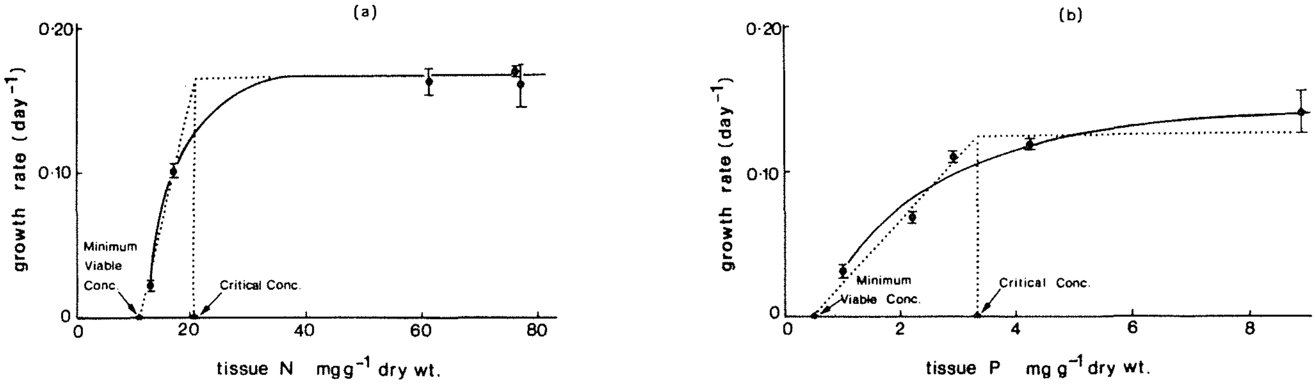


Figure 8.9 Growth rate of *Cladophora* as a function of (a) tissue nitrogen and (b) tissue phosphorus concentration.

CHAPTER NINE

MODELLING *CLADOPHORA* PRODUCTION AND ABUNDANCE

There are two main reasons for attempting to model the *Cladophora* growth processes and variations in *Cladophora* standing crop.

(a) To integrate the field and laboratory experimental data with a conceptual model of *Cladophora* growth, so that any anomaly in that integration may be understood and corrected.

(b) To extrapolate the model to both observed and simulated field situations, in order to assess the effect on *Cladophora* of possible alterations to the estuarine system.

The present *Cladophora* modelling has evolved through several stages of increasing sophistication. A speculative simulation analysis of *Cladophora* growth (in terms of phosphorus) was carried out early in the study. This preliminary analysis provided a valuable initial assessment of the planned experimental and monitoring programme for *Cladophora.*

In contrast to the differential equation formulation of this earlier model, subsequent attempts have developed simpler algebraic models which use relationships fitted to measured growth data (Fig. 9.1). The major simplifying assumption in all the *Cladophora* modelling is that nitrogen and phosphorus do not interact in their effects on growth.

CLADOPHORA MODELS

There are three major *Cladophora* models currently in use in the study.

PROGRAM A

This program computes instantaneous *Cladophora* growth rate on a nominated day of the year using radiant energy at mid morning or afternoon, temperature, inorganic nitrogen and inorganic phosphorus concentrations. The growth rate made possible by each of the above is assessed in turn, the minimum rate determined, then the minimum growth rate and the growth-limiting factor printed.

PROGRAM B

This program computes daily rather than instantaneous growth rate, taking into account changes in light during the day, and adjusting the computed rate by the night time respiratory loss.

GROWMOD

GROWMOD is a suite of programs which model *Cladophora* biomass variation in the field, using various assumptions and spatial scales to which the models apply. The basic logic of the GROWMOD models is shown in Figure 9.2. GROWMOD permits a light-temperature interaction with growth rate. Nutrient — growth interactions are treated in a similar fashion to previous models.

Other differences are:

1. GROWMOD is solved with a weekly, rather than hourly/daily time-step, because the available field-collected time series of *Cladophora* and environmental variables was only collected weekly.
2. Loss processes (decomposition and export) as well as importation of biomass to a growth area are considered.
3. Sections of bed, or whole beds are simulated, rather than isolated *Cladophora* fragments. The important consequences of self-shading and decomposition of buried *Cladophora* balls on total biomass are accounted for.
4. A most important property of some GROWMOD models is that of stochastic (Monte Carlo) simulation. This technique enables all of the uncertain model parameters to be randomly varied within predetermined limits, and provides an objective method of model sensitivity analysis.

In shallow water, wave action appears to prevent successful *Cladophora* colonization, but not beaching and accumulation. All models predict good growth in the well-lit shallows under most conditions.

The major GROWMOD programs are outlined below:

GROWMOD, TISMONT. This program computes growth rate on the basis of observed field tissue nutrient concentrations, and is run as a Monte Carlo simulation, in which all model parameters are permitted to vary at random between runs. The model applies to 1m^2 of *Cladophora* bed at any estuarine site supporting a viable *Cladophora* population.

GROWMOD, MONTE. This program is substantially similar to TISMONT, and incorporates the added refinement of a substrate-to-tissue nutrient incorporation step. This refinement permits simulations of potential *Cladophora* growth with 1m² at any site in the estuarine system for which a weekly nutrient and water column light time-series are available.

GROWMOD, COMP. Computes *Cladophora* biomass variation, migration and loss for all sites within the estuarine system, thus simulating the total estuarine population of *Cladophora*. This model incorporates a site-to-site biomass interaction matrix, which estimates biomass transfer by floatation and drift from one site to another, and its eventual loss, if appropriate.

Each of the above Monte Carlo models also exists in a simpler, deterministic form, which is used for the testing of modifications to the models.

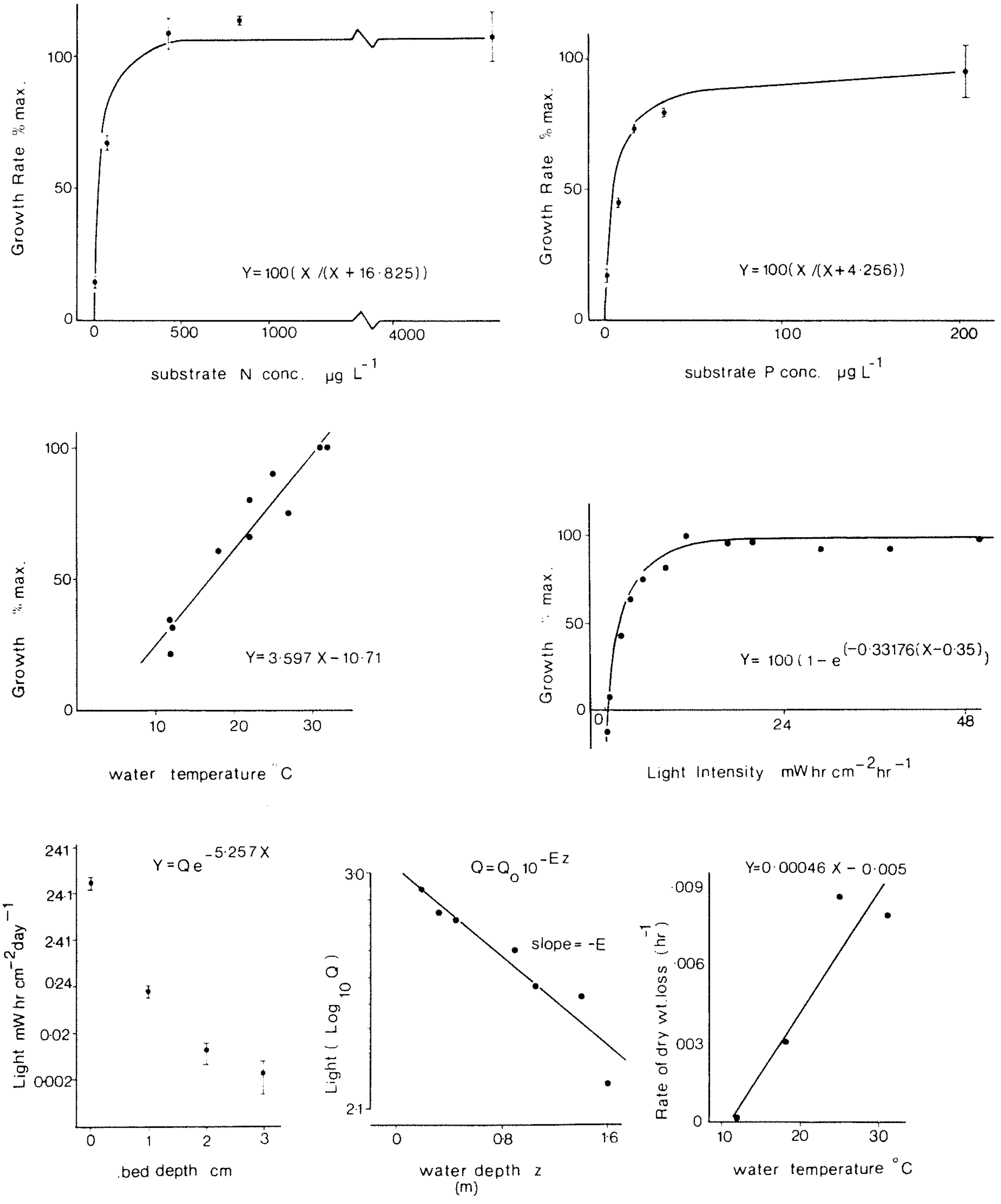


Figure 9.1 Functional fits to experimental data as used in *Cladophora* simulation models.

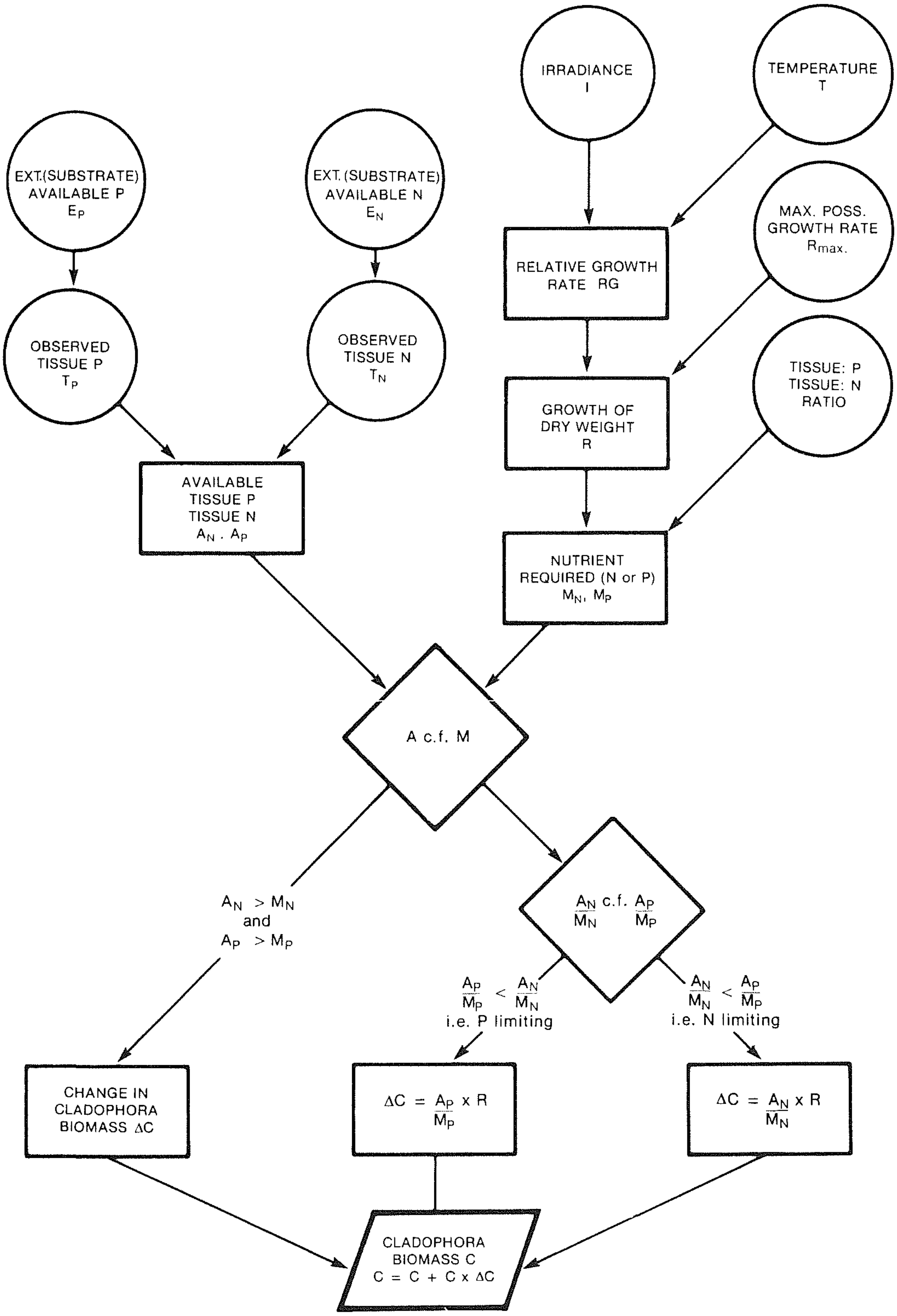


Figure 9.2 Flow chart of the algebraic *Cladophora* growth model GROWMOD.

RESULTS

Results of the modelling exercises have confirmed the conclusions summarized in Chapter 8; those of chronic phosphorus-limitation of growth, and the importance of adequate levels of light and temperature for growth. The models support the importance of the winter nutrient input to the *Cladophora* beds of eastern Peel Inlet. In the absence of such inputs, tissue nitrogen and phosphorus concentrations run down, and growth during the following spring and summer is limited. The GROWMOD simulations indicate that decomposition and high export rates of *Cladophora* to the beaches and sea led to the decline of biomass observed during the study. This finding suggests that under conditions of prolonged turbidity (and low water temperature) *Cladophora* losses exceed gains, particularly when nutrient deficiency reduces the alga's ability to respond when conditions for growth ameliorate.

Sample model outputs are shown in Figures 9.3 and 9.4.

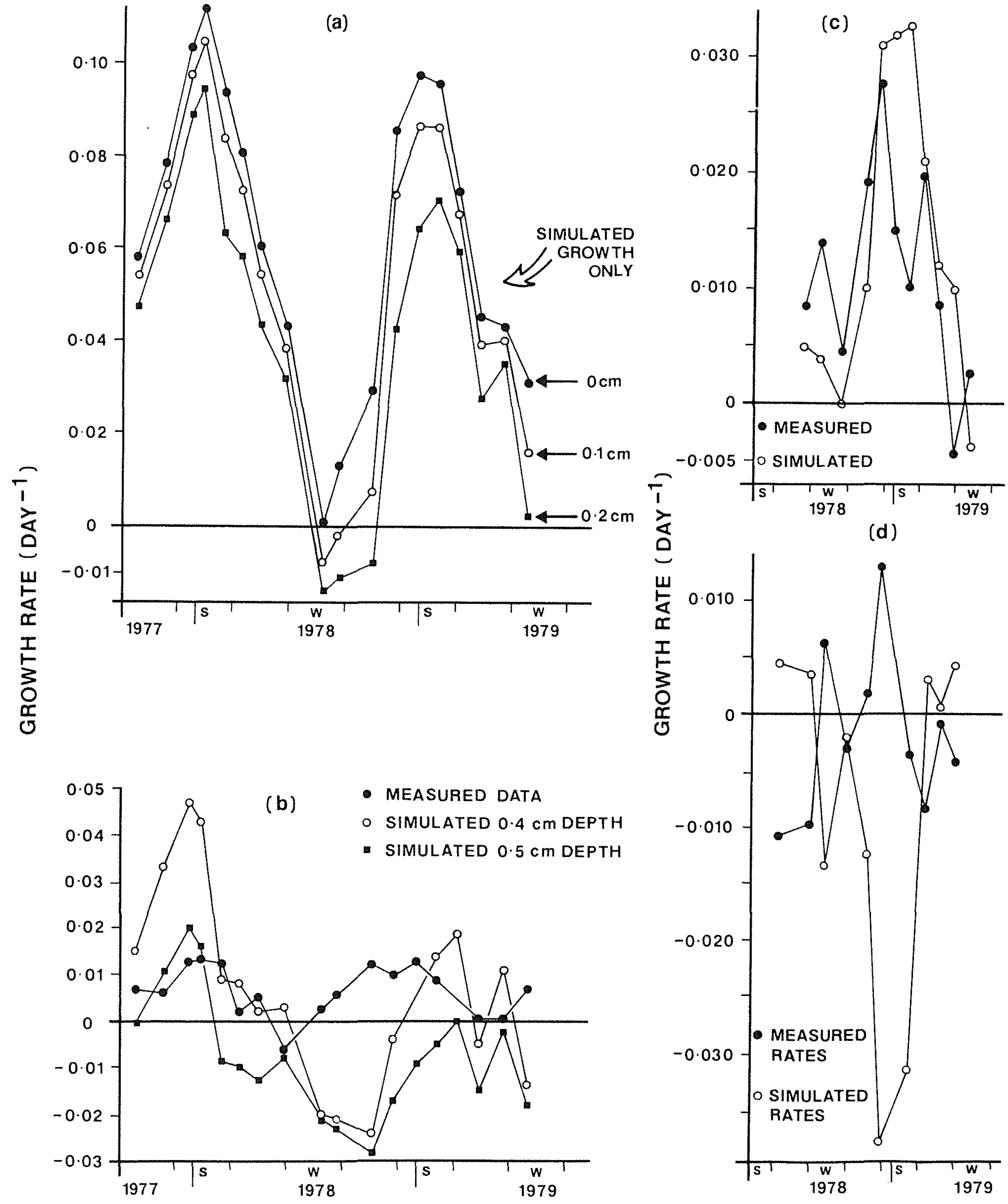


Figure 9.3 Simulated and measured *Cladophora* growth rates from Program B. Site 4 is (a) and (b); Coodanup shallows (Peel Inlet) is (c); Site 1 (Harvey Estuary) is (d).

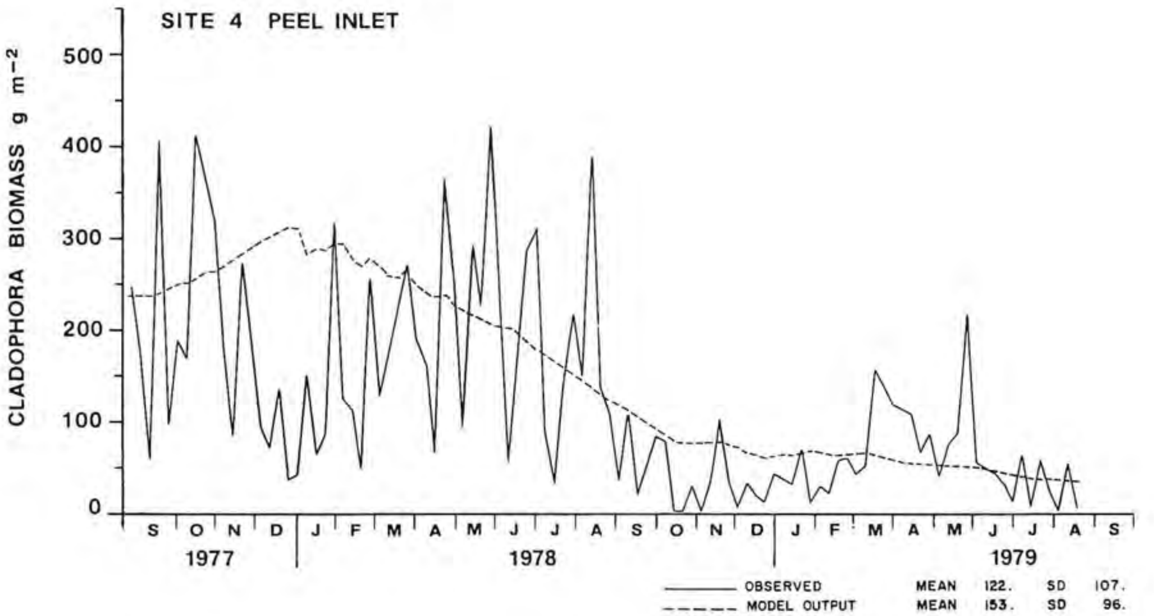
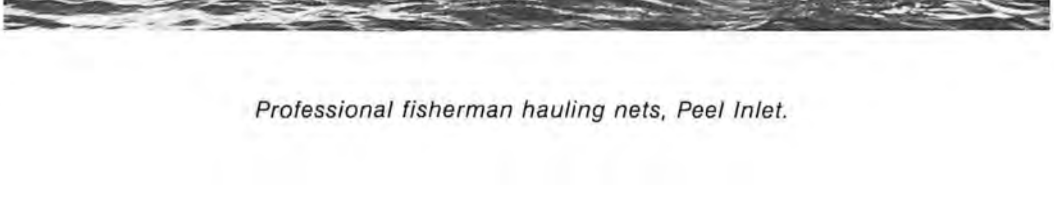


Figure 9.4 Comparison of observed and GROWMOD simulated biomass variation over two years at site 4.



Professional fisherman hauling nets, Peel Inlet.

CHAPTER 10

PLANT NUTRIENTS: SOURCES, SINKS AND STORAGE

NUTRIENT CYCLES IN THE ESTUARIES

The important nutrients nitrogen (N) and phosphorus (P) may be made available for plant, and subsequently animal growth by two mechanisms. The first is by external inputs, and the second by recycling nutrients already within the system. Considerable effort has been expended in attempts to measure the importance of various parts of the nitrogen and phosphorus cycles (Fig. 10.1), and the sizes of nutrient pools within the estuarine system. This effort has been of major importance in the integration of the study, and all study groups have provided inputs, either as data, or as models of nutrient behaviour.

Figure 10.1 shows the major storage pools and indicates mechanisms of transfer among these pools of N and P. It has not been possible to measure all transfer rates or pool sizes adequately, but the nutrient budget discussed in Section 10.3 attempts to summarize the important nutrient fluxes within the estuaries, and across their boundaries, at the aggregate level.

Figure 7.1 is a simplified food web of the estuarine system, in which the major pathways of nutrient flux through the biota are shown, but from which the return of inorganic nutrients to the primary producers, and loss to the sediments, sea and atmosphere is omitted.

The importance of nutrient recycling within the estuary cannot be over-emphasised. The Peel-Harvey estuarine system differs significantly from many aquatic systems so far studied in two important ways:

1. The estuarine water bodies are relatively well-mixed vertically and a stratified, two layered water column exists for only short periods of time. This lack of prolonged stratifcation permits direct interchange between water column, biomass, and sediment nutrient pools.

2. The estuarine water bodies are both very shallow, with a high area : volume ratio. Since the rate of sediment nutrient release or uptake depends substantially on this ratio, interaction between sediment and water is of great importance.

The aim of the nutrient cycling and budget studies is to predict concentrations of nutrients in various pools within the system and sizes of the pools themselves. A more important aim is to be able to predict the magnitude and direction of changes due to altered nutrient loading into the system, as might result from some attempt to control *Cladophora.*

NUTRIENT INPUTS

River nutrient inputs

Each of the three rivers was sampled weekly for the two years of the study. In addition, there was sufficient sampling of drains discharging direct to Peel Inlet and Harvey Estuary to enable estimates of drain nutrient loads to be made from Harvey River loadings after drain gauging ceased at the end of 1978. Tables 10.1 and 10.2 show the annual flow, total nitrogen, and total phosphorus loading of the rivers. The most significant feature of these data is the very high percentage of the annual N and P load that occurred during only ten key weeks of winter

TABLE 10.1 PEEL INLET AND HARVEY ESTUARY: STATISTICS OF NUTRIENT LOAD FROM RIVERS, WINTER 1978

Data		River Systems		
		Murray	Serpentine	Harvey
Annual discharge 1977/78	$m^3 \times 10^6$	289	65	206
Discharge 23/6 to 25/8	$m^3 \times 10^6$	240	39	144
	% annual	*83*	*60*	*70*
Annual N load (tonnes)		1153	116	317
N load 23/6 to 25/8	tonnes	1109	89	269
	% annual	*96*	*77*	*85*
Annual P load (tonnes)		25	22	73
P load 23/6 to 25/8	tonnes	23	18	62
	% annual	*92*	*82*	*85*

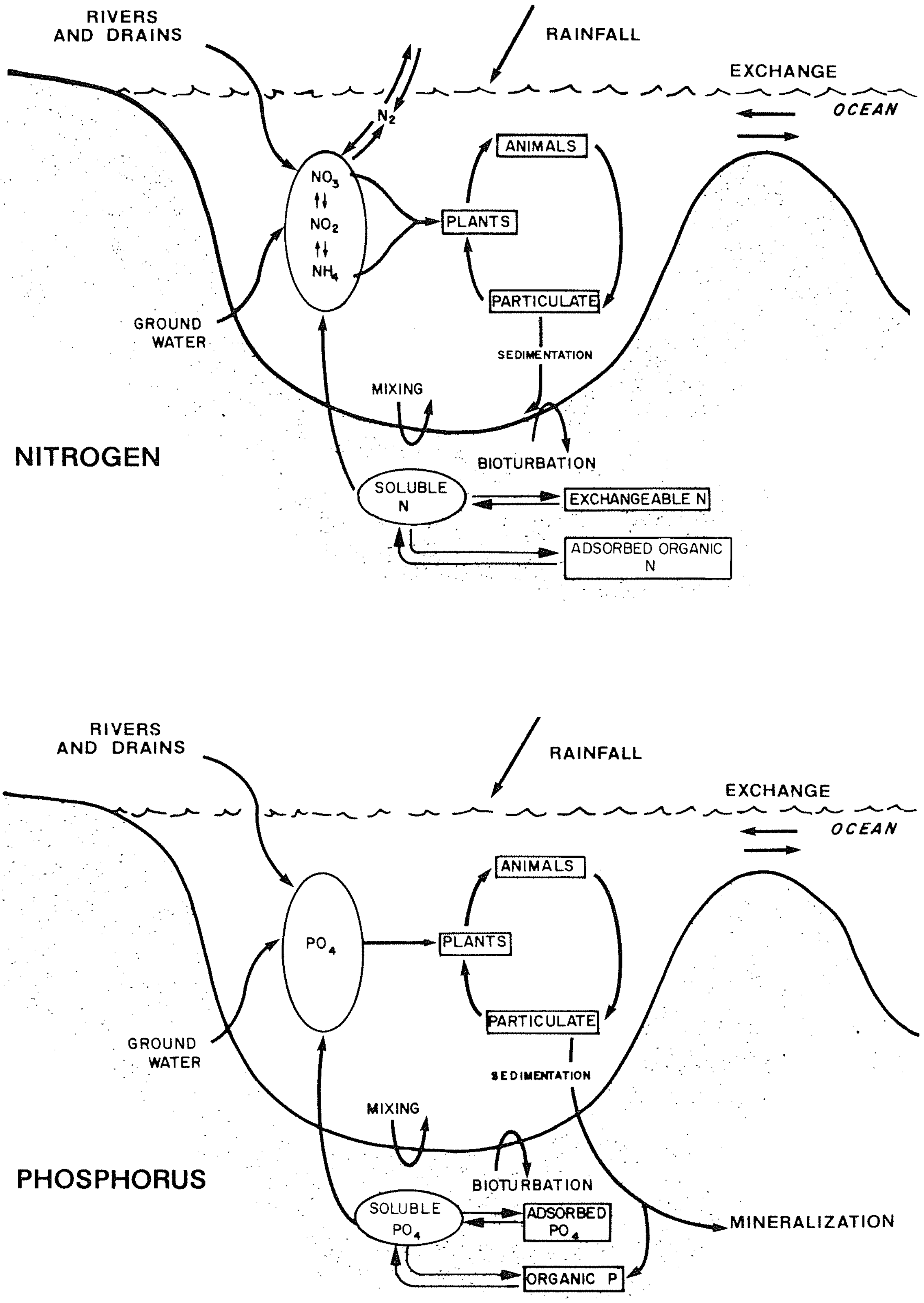


Figure 10.1 Schematic model of the nitrogen and phosphorus cycles.

flow. This is especially pronounced in 1977/78 and particularly in the Murray River. The very low flow of the Murray in 1978/79 resulted in a greatly reduced impact of the "First Flush".

The **relative** contributions of the three river systems in terms of N load and P load are shown in Table 10.3 and Figure 10.2. From these it will be seen that the coastal plain drainage systems of the Harvey and Serpentine provide the bulk of the phosphorus load in both years. In 1977/78, a year of near average flow, the Murray dominated nitrogen inputs (73%), but with very low flow in 1978/79, its nitrogen contribution fell to only 22%.

Observations in the winter of 1978 showed that the first flush of nutrients was of such importance that an attempt was made to sample all rivers on a daily basis for the first few weeks of winter 1979. For the Harvey River, where the time of rise of the usual flood hydrograph is of the order of 12-24 hours, this was done every two hours and consistently high concentrations of N and P were recorded (Fig. 10.3). However, flows on the Murray system were never of sufficient magnitude to record anything approaching the large N pulse of July 1978.

Rainfall Nutrient Inputs

Average concentrations estimated for nitrogen and phosphorus in rainfall direct to the estuary were respectively 41 ug L^{-1} and 8 ug L^{-1} in 1977/78. The Thiessen weighted rainfall volume in the system in that year was 99 x $10^6 m^3$. This results in a total load of approximately 4 tonnes of N and 0.8 tonne of P from this source, which is only 0.25% and 0.67% of river nutrient input in 1977/78.

Groundwater Nutrient Inputs

Unconfined groundwater constitutes 1% of total input to the estuary. However, nutrient concentrations in groundwater samples are generally much higher than those of surface water (with the exception of some of the Harvey drains). In the case of phosphorus, groundwaters have generally about twice the P concentrations of the Harvey and Serpentine Rivers and ten times that of the Murray. Figures 10.4 and 10.5 show groundwater concentrations of N and P for the range of bores in the Harvey Estuary area. Based on the estimated annual groundwater input of 2 x $10^6 m^3$ (Chapter 6), it seems that 1% can be regarded as an upper limit for groundwater nutrient input to the estuary.

TABLE 10.2 PEEL INLET AND HARVEY ESTUARY STATISTICS OF NUTRIENT LOAD FROM RIVERS, WINTER 1979

Data		River Systems		
		Murray	Serpentine	Harvey
Annual discharge 1978/79	$m^3 \times 10^6$	86	55	150
Discharge 29/6 to 31/8	$m^3 \times 10^6$	39	23	88
	% annual	*45*	*42*	*59*
Annual N load (tonnes)		110	108	292
N load 29/6 to 31/8	tonnes	60	60	238
	% annual	*55*	*56*	*82*
Annual P load (tonnes)		4	12	51
P load 29/6 to 31/8	tonnes	2	8	42
	% annual	*50*	*67*	*82*

TABLE 10.3 PEEL INLET AND HARVEY ESTUARY — RELATIVE CONTRIBUTION OF INPUT RIVERS 1977/78; 1978/79

Data		River Systems			
		Murray	Serpentine	Harvey	Total
1977/78	$m^3 \times 10^6$	289	65	206	560
Discharge	% total	*51*	*12*	*37*	*100*
N	tonnes	1153	116	317	1586
	% total	*73*	*7*	*20*	*100*
P	tonnes	25	23	73	121
	% total	*21*	*19*	*60*	*100*
1978/79	$m^3 \times 10^6$	86	55	150	291
Discharge	% total	*29*	*19*	*52*	*100*
N	tonnes	110	108	292	510
	% total	*22*	*21*	*57*	*100*
P	tonnes	4	12	51	67
	% total	*6*	*18*	*76*	*100*

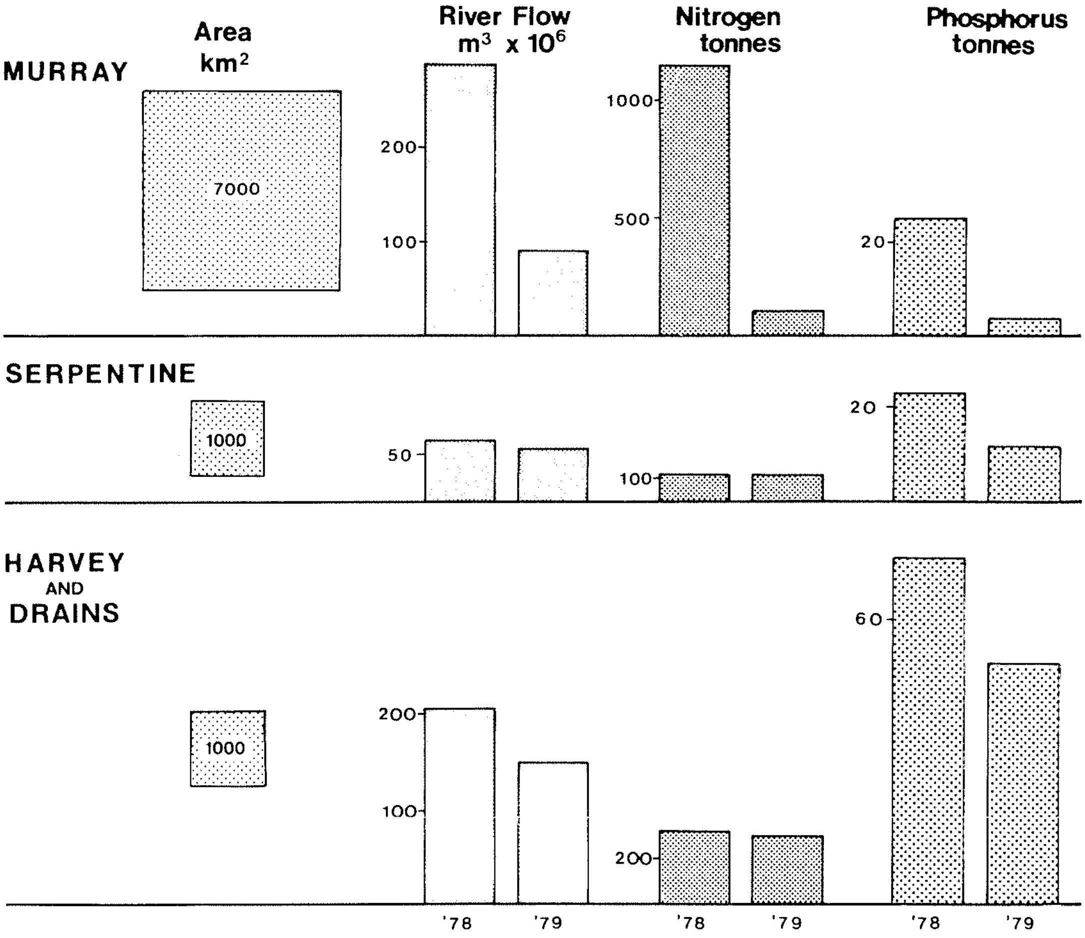


Figure 10.2 Relative nutrient contribution of the three rivers.

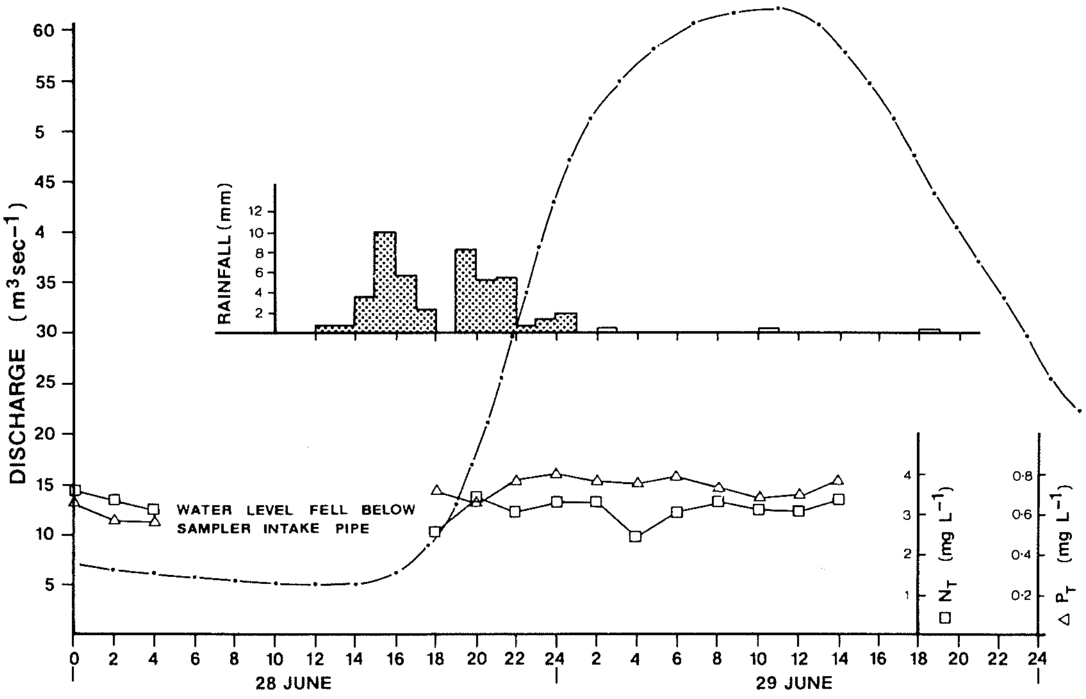


Figure 10.3 Harvey River 'first flush' hydrograph, 28-29 June 1979.

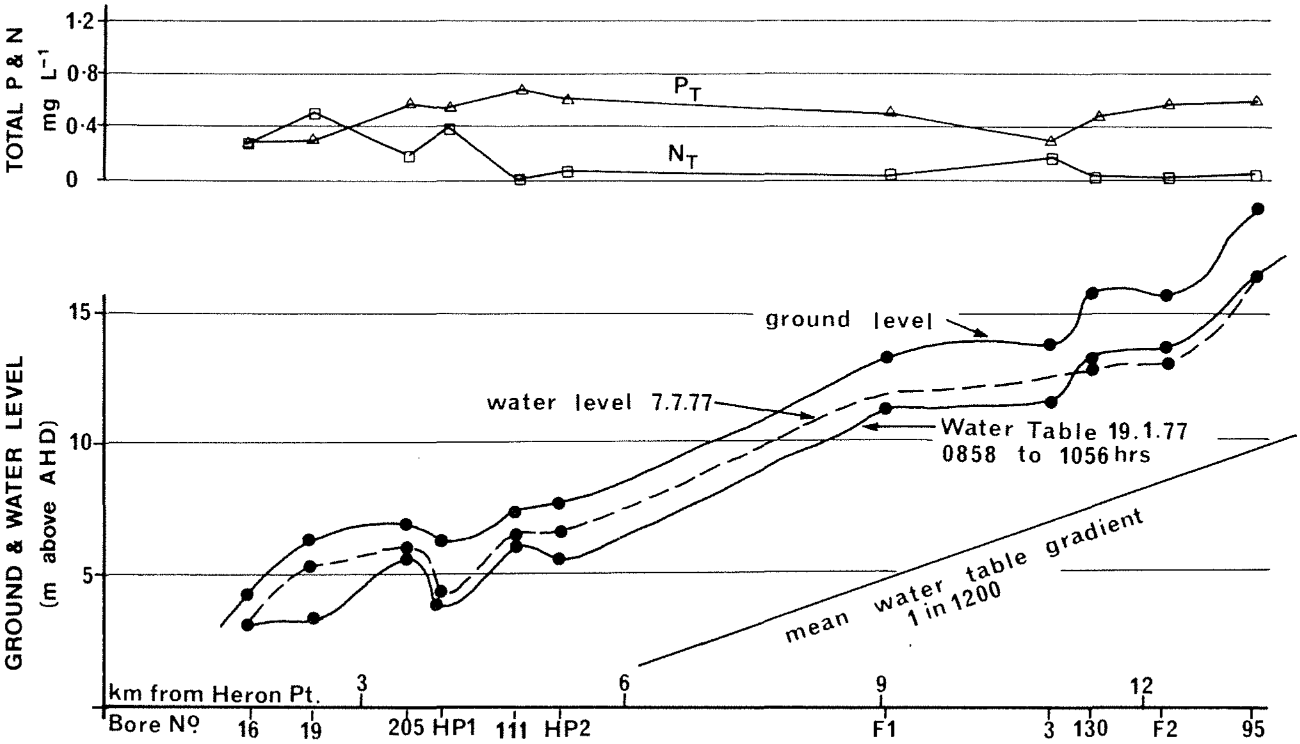


Figure 10.4 Groundwater survey, Herron Point Road transect.

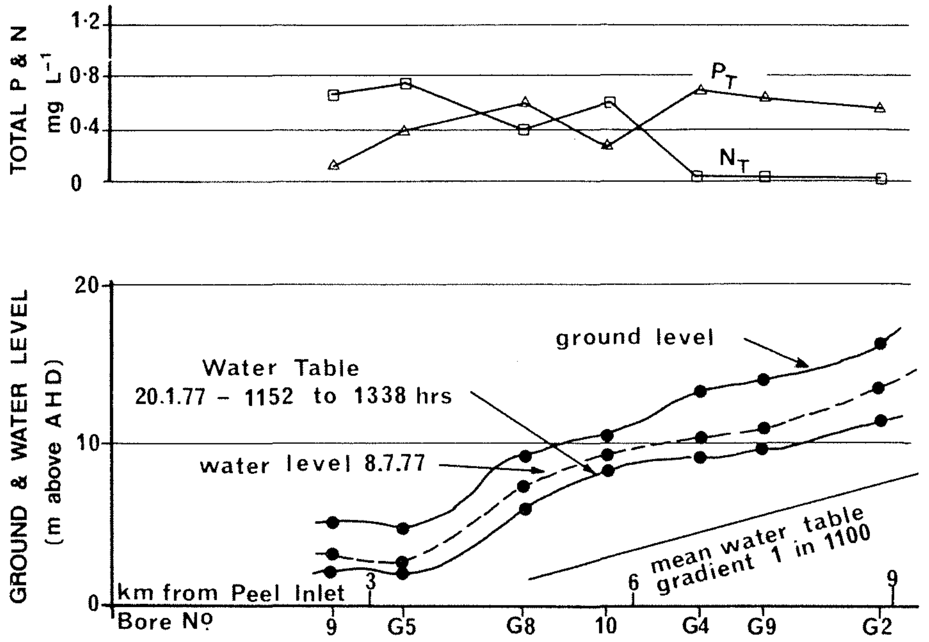


Figure 10.5 Groundwater survey, Greenlands Road transect.

Nutrient Inputs From the Sea

The ocean can be an important source, as well as a sink, for nutrients. Concentrations of nitrogen and phosphorus around 500 ug L^{-1} and 25 ug L^{-1} respectively are half those in estuary water during the greater part of the year (Table 10.4).

Direct measurements of nutrient exchange were made at 3 hourly intervals at Mandurah Bridge (Fig. 6.5) during the February and August exercises in 1978. On both occasions there was a considerable net gain of water by the system, however not all nutrients measured recorded gains over the exercise period as Table 10.5 shows. The volume of water gained by the estuary was approximately the same for the two study periods. In summer (February), when nutrient concentrations in ocean and estuary water were similar, the estuary gained ammonia, nitrate and phosphate. In winter (August) when estuary concentrations of nutrients were much higher, considerable losses took place; 10 tonnes of nitrate was lost in the 5 days of the exercise. The flux for nitrate is shown in Figure 10.6 and it can be seen that most of the loss took place in surface water. In the case of phosphate there was, by contrast, a small gain because of the very low levels present in the estuary. Table 10.6 shows the surface and bottom net fluxes for the August exercise period.

Air

The air may act as an ultimate source or sink for nitrogen. Loss of nitrogen by denitrification of nitrate to nitrogen gas occurs under conditions of low oxygen tension, and therefore would mostly be restricted to the sediments. Denitrification has not been measured.

Atmospheric nitrogen may be fixed under aerobic conditions by some bacteria, and by nitrogen-fixing blue-greens. It is estimated that during the 1978-79 bloom of *Nodularia spumigena* about 300 tonnes of nitrogen was contributed to Harvey Estuary.

Sediments

The sediments (including black ooze underlying the algal beds) are an important nutrient pool within the estuarine system, containing an estimated 1,200 tonnes of nitrogen and 130 tonnes of phosphorus in the top 1cm layer alone. These figures approximate the total N and P inputs from rivers during the 1977/78 water year (Table 10.7).

Although the sediments are probably a net sink for both nitrogen and phosphorus, there is ample evidence that release of these nutrients from the sediment is important in the maintenance of water column concentrations above marine values (Table 10.4) and as a relatively short-lived source of nutrients for *Cladophora*, other benthic plants, and for phytoplankton.

The sediments take up nutrients during periods of high external nutrient loading into the estuary, and subsequently release part of that uptake to the biota and the water column. Evidence for this cycle is shown in Figures 7.2, 7.3 and 7.4, as well as by the nutrient budget computation discussed in section 10.3.

Figures 7.2 and 7.3 show a major secondary phytoplankton bloom during September-November 1978 which was presumably initiated by nutrients of sedimentary origin, because external nutrient inputs and water column nutrient concentrations were insufficient to explain the chlorophyll *a* levels measured. Persistence of the bloom was probably

TABLE 10.4 COMPARISON OF MEAN NUTRIENT CONCENTRATIONS IN MARINE AND PEEL INLET WATER BASED ON SEVEN SAMPLINGS

	Total N (ug L^{-1})	NO_3-N (ug L^{-1})	NH_4-N (ug L^{-1})	Total P (ug L^{-1})	PO_4-P (ug L^{-1})
Peel Inlet (estuary)	971	15	49	50	5
Mandurah bay (marine)	482	3	12	26	6
Ratio Peel: Mandurah bay	2	5	4	2	0.9

TABLE 10.5 NET FLUXES FOR FEBRUARY AND AUGUST 1978; +VE VALUE INDICATES A NET GAIN, -VE VALUE INDICATES A NET LOSS

	February	August
Volume	+3.72 x 10^{7} m^{3}	+3.26 x 10^{7} m^{3}
Salt	+1.38 x 10^{9} kg	+1.62 x 10^{9} kg
NH_4-N	+403 kg	-1,974 kg
NO_3-N	+223 kg	-10,195 kg
PO_4-P	+197 kg	+ 74 kg
Chlorophyll *a*	+23 kg	-1,001 kg

TABLE 10.6 SURFACE AND BOTTOM NET FLUXES FOR AUGUST 1978. +VE VALUE INDICATES A NET GAIN. -VE VALUE INDICATES A NET LOSS.

	Surface	Bottom
Volume	+1.12 x 10^{7} m^{3}	+2.14 x 10^{7} m^{3}
Salt	+7.18 x 10^{8} kg	+8.99 x 10^{9} kg
PO_4-P	-35 kg	+109 kg
Total Phosphorus Dissolved	-1,224 kg	-675 kg
Total Phosphorus	-3,344 kg	-1,146 kg
NO_3-N	-8,104 kg	-2,071 kg
NH_4-N	-1,226 kg	-748 kg
Organic Nitrogen	-14,179 kg	-4,694 kg
Chlorophyll *a*	-810 kg	-191 kg

TABLE 10.7 COMPARISON OF MEAN SEDIMENT NUTRIENT STORAGE WITHIN THE TOP 1cm - WITH RIVER NUTRIENT INPUT DURING THE STUDY

	Sediment $\bar{X}$ (top 1cm) tonnes	River input 1977/78 tonnes	River input 1978/79 tonnes
TOTAL NITROGEN	1,188	1,586	510
TOTAL PHOSPHORUS	130	120	67

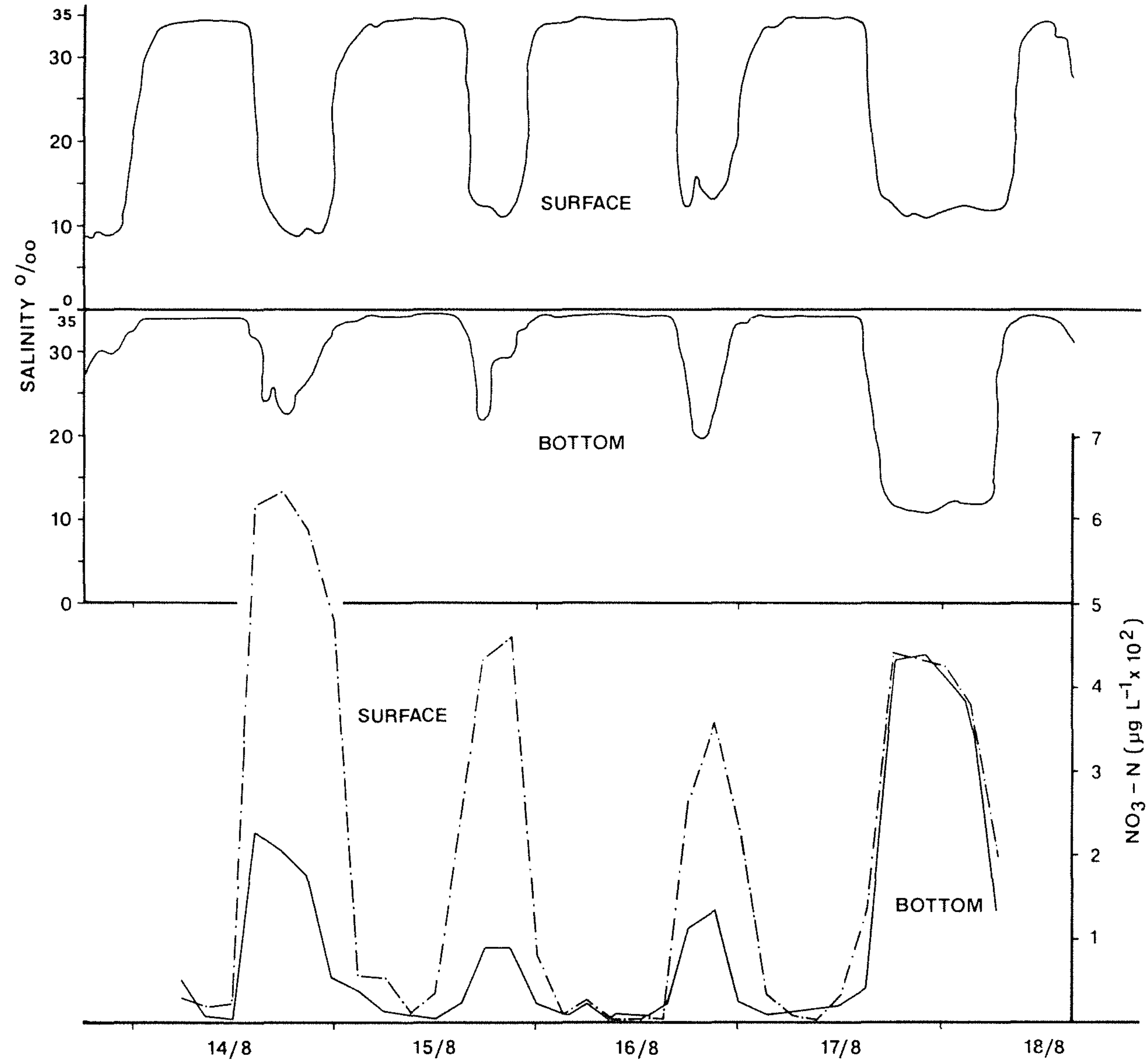


Figure 10.6 Mandurah channel salinity and NO_3-N, August 1978.

due to nutrient transfer from sediment to water column, and internal water column nutrient recycling. Figure 7.5 shows the same chlorophyll *a* data expressed in terms of apparent water column nutrient availability.

The sediments show marked variations in concentration of extractable nitrogen and phosphorus (Table 10.8), with high values corresponding with known periods of high external loading into the estuary, either from river flow, or from the *Nodularia* bloom mentioned above.

The equilibrium point concentration (EPC), for PO_4 adsorption/desorption has been determined for a range of sediment types within the estuary. The adsorption/desorption characteristics indicate that the sediment would tend to maintain 5-20 ug PO_4-P L^{-1} concentrations in the water, with release rates between 0-4 mg P m^{-2} day^{-1}, with higher rates occuring at low oxygen tensions. The black ooze is a highly enriched source of N and P, with a potential, at present not fully understood, to supply nutrients to the overlying water and *Cladophora* beds.

The role of the sediments in the nutrient supply of *Cladophora* is still unclear, but the annual tissue N and P cycles shown by *Cladophora* populations in eastern Peel Inlet (Fig. 8.8) indicate the seasonal pattern of high external nutrient input. Active sediment release and water column recycling are critical in the growth cycle of the plant. Figure 8.8 indicates that the combined rates of nutrient (particularly phosphorus) supply from sediment and water are inadequate to prevent seasonal depletion of tissue P stores.

Biomass

The biomass is difficult to quantify, but is clearly an important nutrient pool within the estuary. *Cladophora* biomass and suspended chlorophyll *a* measurements enable us to estimate variation in nutrient storage within those compartments. The storage and turnover of nutrients in fish, estuarine invertebrates, the estuarine microflora exclusive of suspended phytoplankton, and littoral flora is largely unkown. Where possible, crude estimates of biomass, and hence biomass nutrient pool sizes have been made, and are presented for comparative purposes in Table 10.9.

TABLE 10.8 ESTIMATED SEDIMENT BANK OF NITROGEN AND PHOSPHORUS IN THE ESTUARIES, SHOWING SEASONAL VARIATION IN POOL SIZE

		tonnes of N or P in 2cm layer				
		March 1978	Aug. 1978	March 1979	Sept. 1979	Mean
Total N	Peel	1,470	1,410	1,439	1,178	1,374
	Harvey	1,100	1,180	959	774	1,003
	TOTAL	2,570	2,590	2,398	1,952	2,377
Total P	Peel	132	146	152	157	147
	Harvey	104	125	114	106	112
	TOTAL	236	271	266	263	259
Extractable N	Peel	9.3	74.6	13.0	7.0	
	Harvey	8.5	55.8	15.6	7.1	
	TOTAL	17.8	130.4	28.6	14.1	
Extractable P	Peel	0.7	5.8	0.4	0.8	
	Harvey	0.9	5.0	0.3	0.8	
	TOTAL	1.6	10.8	0.7	1.6	

THE NUTRIENT BUDGET

Historical Changes in External Nutrient Loadings and their Causes

Historical analysis of river flows and nutrient concentrations (CSIRO, 1952-57) shows that at median flow rates, the Serpentine* and Murray Rivers delivered, respectively, 9 and 50 times more phosphorus, in 1972-78 than in 1949-56. For inorganic nitrogen, there was a small (1.4 x) increase in the Serpentine River and a 3 fold increase in the Murray River over the same period (Fig. 10.7). Unfortunately there is no comparable data·for Harvey River flows or nutrient concentrations.

Increased nutrient input from Mandurah's septic tanks was also likely during the late 1960's and early 1970's before significant deep sewering took place. However, nitrogen and phosphorus inputs are unlikely to have exceeded 1% of the river inputs during either of the study years.

The present river inputs of phosphorus from the various coastal plain catchments are correlated with superphosphate use (Fig. 10.8). These catchments deliver about 90% of the phosphorus load to the estuary from soils that are naturally phosphorus deficient. Thus there can be little doubt that the recent increases in river inputs of phosphorus to the estuary have been caused by the marked increase in superphosphate use in coastal plain shires since 1945, particularly during 1964-73 (Fig. 10.9). However, it should be noted that the relation between amount of fertilizer applied to the catchment and the river input of phosphorus is not a simple one. The 1978 input was about ten times that of 1953 even though fertilizer application, and rainfall and river flow, were similar in the two years.

More than half the phosphorus input to the estuary is derived from catchments of the Harvey River and Mayfields Drain (Table 10.10). These are the most heavily fertilized coastal plain catchments because of relatively high application rates on pasture land between Harvey and Waroona. Much of this land is under irrigation (Fig. 3.2). Of the remaining phosphorus sources, the Serpentine River catchment is the most important, contributing about 20% of the total.

The increased load of nitrogen in the Murray River is believed to be due mainly to mineralization of nitrogen from pasture legumes in the eastern agricultural portion of the catchment, although some of the increase was probably caused by increased use of nitrogenous fertilizers.

Comparison of total phosphorus concentrations reveals a 3 to 4 fold increase of total P in some parts of Peel Inlet between 1949-56 and 1972-78. This increased concentration appears to have been caused by increased river loadings of phosphorus.

If we are correct in attributing the increased river input and estuary water concentrations to the increased use of superphosphate, then the loading of phosphorus may now be declining in response to the price-related halving in fertilizer use in this region since 1975 (Fig. 10.9). However, the series of

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* Flow data for the Serpentine River are best estimates only (see Chapter 4).

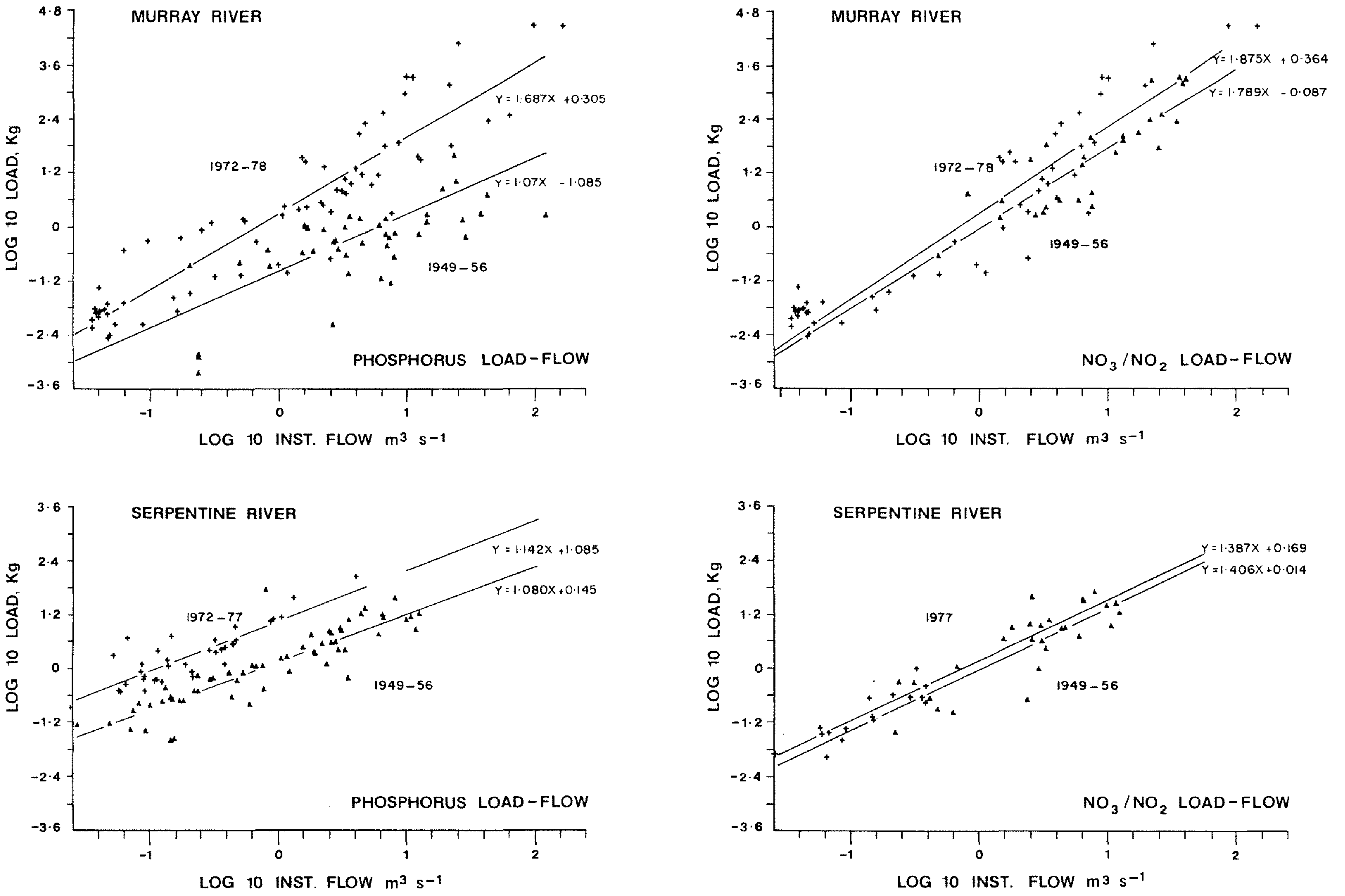

Figure 10.7 Comparison of 1949-56 and 1972-78 load-flow relationships of phosphorus and nitrogen in the Murray and Serpentine rivers.

dry years since 1976 and consequential reduced runoff must also be considered. A high flow year may still produce high nutrient loads despite recent reductions in fertilizer application rates. Only further monitoring and catchment research will clarify the situation.

Calculating the Nutrient Budget

The weekly budget of total nitrogen (N in tonnes) and total phosphorus (P in tonnes) is computed as shown in Figure 10.10. Observed weekly data sets are as follows:

1. River flow (Murray, Serpentine, Harvey + drains) in m^3 x 10^3 and river nutrient concentration in ug L^{-1} combine to produce total nutrient input from rivers.

2. Rainfall volume in m^3 x 10^3, rainfall nutrient concentration in ug L^{-1} (assumed constant). These combine with river nutrient load to produce N and P loads into the estuary (Figs. 10.12 and 10.16).

3. Estuary sector weighted water volume in m^3 x 10^3 (from tide heights, Fig. 10.11), combined with estuary water column nutrient concentration by sector in ug L^{-1}, produce estuary water column nutrient loads (Figs. 10.13 and 10.17).

4. Estuary sector flushing rate per week (as calculated from salinity observed and using the CRES flushing model, section 6.3 above) — in m^3 x 10^3.

TABLE 10.9 ESTIMATED MEAN NUTRIENT POOL SIZE (TONNES) FOR VARIOUS COMPONENTS OF THE PEEL-HARVEY ESTUARINE SYSTEM

	NITROGEN (tonnes)	**PHOSPHORUS (tonnes)**
Plants		
Cladophora[1]	640	55
Benthic macroalgae[1] (excluding *Cladophora*)	130	11
Seagrasses[2]	106	11
Phytoplankton[3]	12.1	1.7
Benthic microalgae[4]	139	20
Bacteria, fungi	no estimate	
Fringing marshes[5]	327	48
Animals		
Fish (commercial catch)[6]	20.9	1.3
Crabs[6]	0.7	0.04
Prawns[6]	0.7	0.04
Zooplankton	no estimate	
Benthic molluscs[7]	26.3	1.7
Other benthic invertebrates	no estimate	
Birds[8]	1.6	0.1
Water[9]	173	12
Sediment[10]	2 377	259

Notes:

[1] Mean of four grid studies and 1976-77 estimate.

[2] S. Carstairs, *pers. comm.*

[3] Mean of 110 weekly samples, Peel-Harvey Study.

[4] September 1979 estimate, R.J. Lukatelich, *pers. comm.*

[5] February 1980 estimate.

[6] Four year (1975-1979) mean of professional catch only. Data courtesy of R.C.J. Lenanton from Department of Fisheries and Wildlife catch statistics.

[7] Estimated from mean production estimates of the two major species from Wells, *et al.* (1980)

[8] Based on seasonal abundance data (1976-1977) courtesy of J.A.K. Lane and G. Pearson. Body weight data from G.M. Storr (W.A. Museum) and G. Pearson (W.A. Wildlife Research Centre).

[9] Mean of 110 weekly samples, Peel-Harvey Study.

[10] Mean of four grid studies, J.O. Gabrielson *pers. comm.* Top 2 cm of sediment layer only.

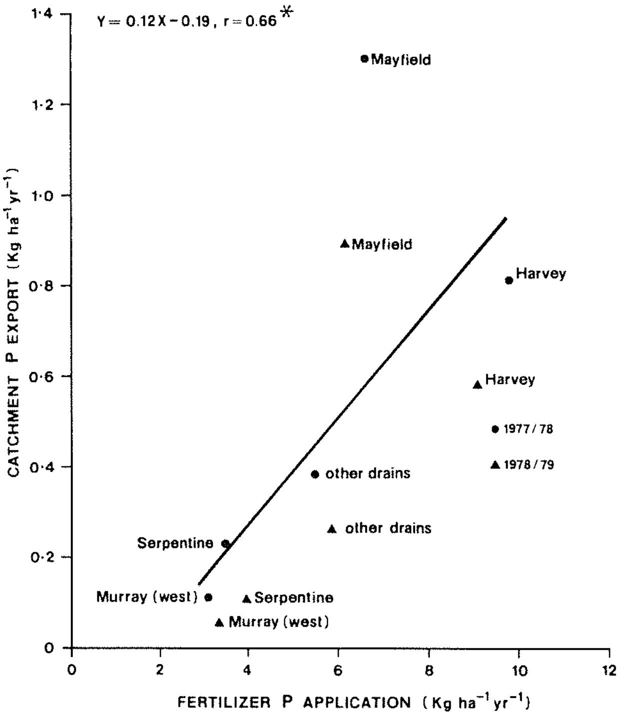

Figure 10.8 The relationship between fertilizer phosphorus application and catchment export rate of phosphorus from coastal plain catchments (see Fig. 4.1).

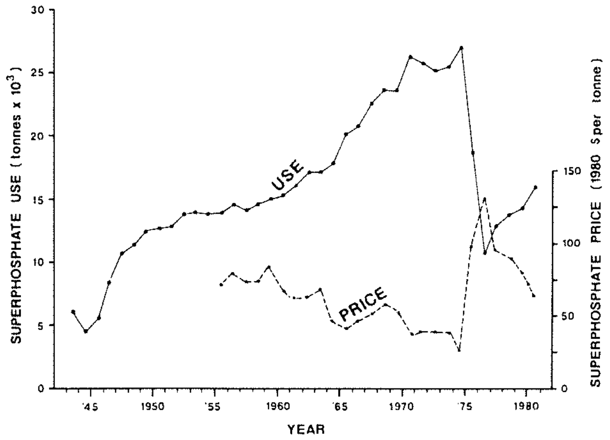

Figure 10.9 Superphosphate usage and price for coastal plain catchments (see Fig. 4.1), Shire contributions are: Kwinana (50%), Rockingham (70%), Serpentine - Jarrahdale (100%), Murray (100%), Waroona (100%), Harvey (33%). Price adjusted to 1980 dollar values.

TABLE 10.10 PHOSPHORUS FERTILIZER APPLICATION AND EXPORT FROM CATCHMENTS DRAINING INTO THE PEEL-HARVEY ESTUARINE SYSTEM, 1977/78

	Area km²	Phosphorus applied		Phosphorus exported		
		Tonnes	kg ha⁻¹ yr⁻¹	Tonnes	% of total	kg ha⁻¹ yr⁻¹
COASTAL PLAIN CATCHMENTS						
Harvey River	590	580	9.8	48	*40*	0.8
Mayfields Drain	110	73	6.6	14	*12*	1.3
Other drains	290	160	5.5	11	*9*	0.4
Serpentine R.	1000	350	3.5	23	*19*	0.2
Murray River[1]	700	220	3.1	8.5	*7*	0.1
Total	2700	1400	4.8	104	*86*	0.4
PLATEAU CATCHMENT[2]	6900	2500	3.9	17	*14*	0.02
TOTAL TO ESTUARY	9600	3900	4.3	121	*100*	0.1

Fertilizer data from Australian Bureau of Statistics

[1] west of Hughes Bridge gauging station 614006
[2] Murray River east of 614006

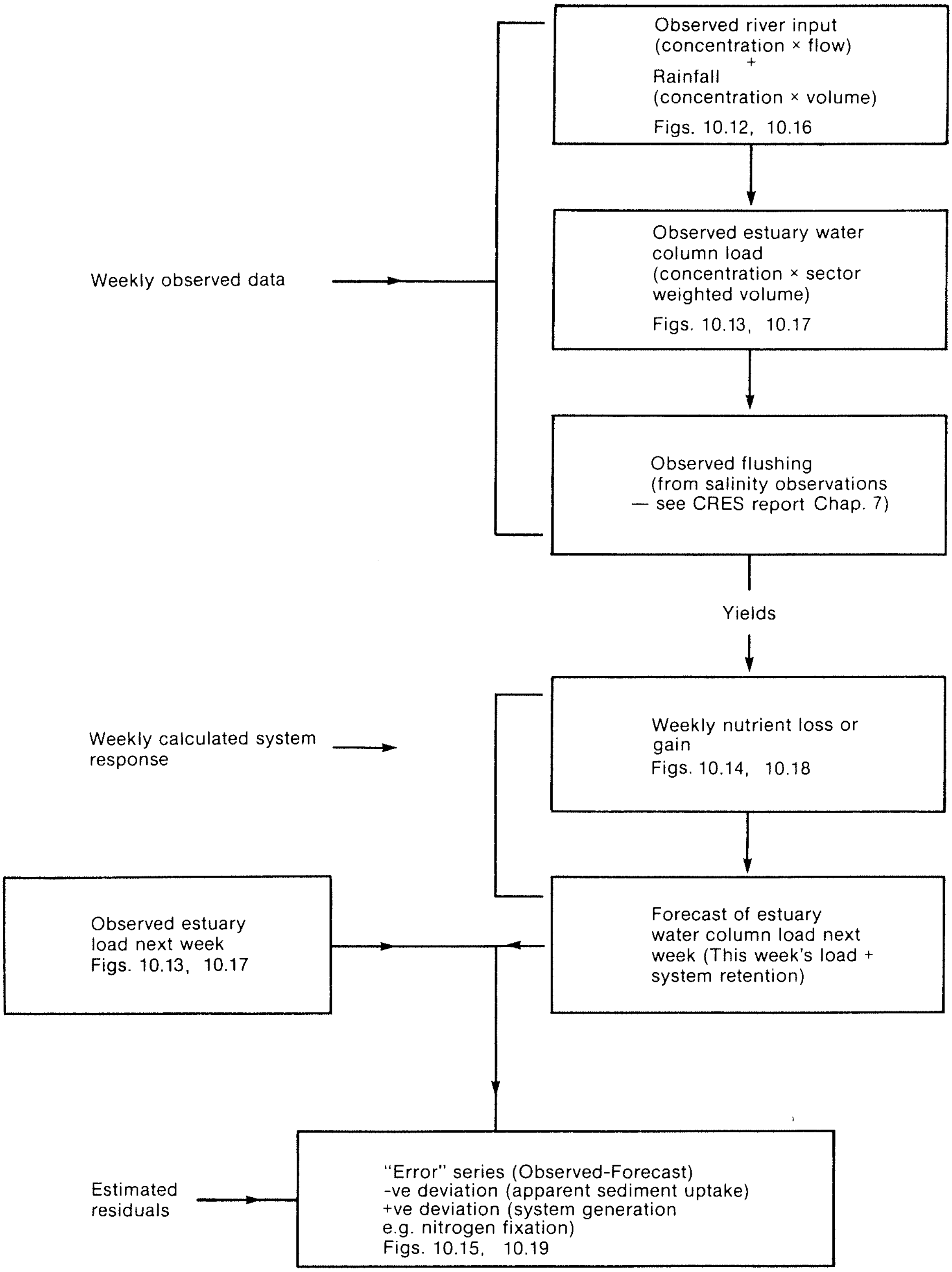

Figure 10.10 The nutrient budget calculation (nitrogen and phosphorus).

Weekly nutrient loss or gain to the system is calculated, from which a forecast is made of the *next week's* water column load. (See Figs. 10.14 and 10.18). The comparison of this load with that *actually observed in the water column* is a measure of the 'errors' in the budget calculation; i.e. sediment uptake or generation of nutrients, nitrogen fixation, marine nutrient input, as well as true measurement errors. For example, sediment uptake would result in a negative value of an observed minus forecast of water column load. (See Figs. 10.15 and 10.19.)

Results

Figure 10.15 shows a large negative 'spike' at around week 48. This coincides with the massive nitrogen input by the Murray River near the end of July 1978 and is a measure of an apparent large sediment uptake of nutrients.

An example of system generation of nitrogen; i.e. a large positive value for observed minus forecast load can be seen in Figure 10.15 at about week 65, which coincides with the observed bloom of nitrogen-fixing blue-greens in Harvey Estuary in November 1978.

The plot of phosphorus residuals in Figure 10.19 shows a more disturbed pattern than nitrogen. This is possibly associated with gross sediment phosphorus uptake and release, as well as with the marine inputs. Further work is in progress to analyse these changes, and preliminary results suggest that the marine input provides a low, and relatively stable input of N and P, to which is added river, sediment and other loadings.

Annual nutrient budget

An attempt has been made to estimate the net contribution of N_T and P_T from the sea. The logic of the computation, and the results are shown in Table 10.11. Input from the sea together with the

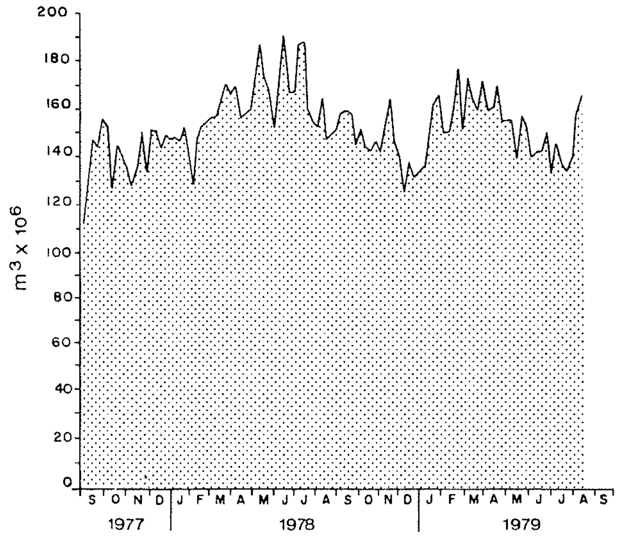

Figure 10.11 Total estuary volume. Mean 152 $m^3 \times 10^6$.

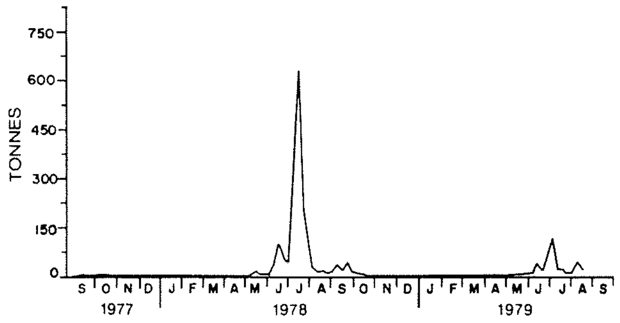

Figure 10.12 Total nitrogen input into the estuary.

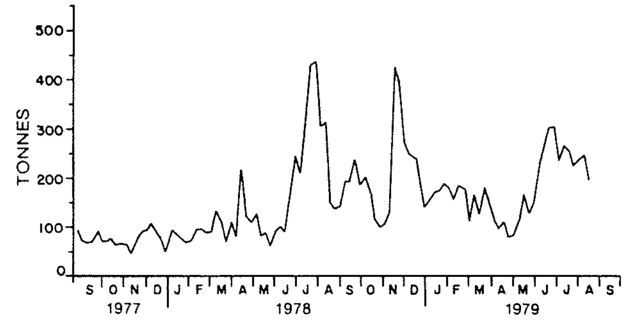

Figure 10.13 Total nitrogen load in the estuary water column.

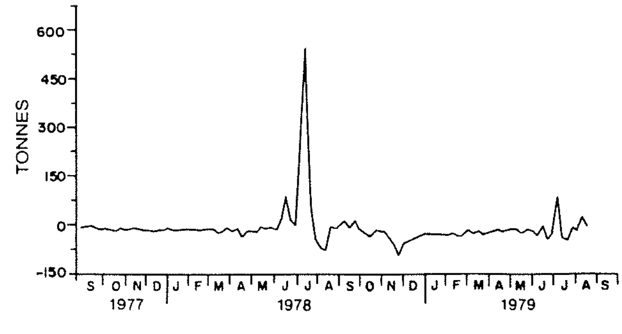

Figure 10.14 Total nitrogen load budget (gains - losses).

TABLE 10.11 ANNUAL NUTRIENT BUDGET*

NITROGEN - tonnes

1977/78		**1978/79**	
Marine input	873	Marine input	866
River & rain input	1615	River & rain input	595
	2488		1461
Flushed	1409	Flushed	1805
System gain	+ 1079	System loss	- 344
% gain	+ *43*	% gain	- *24*
(System in net *retention*)		(System in net *depletion*)	

PHOSPHORUS - tonnes

1977/78		**1978/79**	
Marine input	47	Marine input	46
River & rain input	113	River & rain input	92
	160		138
Flushed	110	Flushed	114
System gain	+ 50	System gain	+ 24
% gain	+ *40*	% gain	+ *17*
(System in net *retention*)		(System in net *retention*)	

* Assuming (i) net system volume change over 1 year is zero.
(ii) marine N and P concentrations are constant.

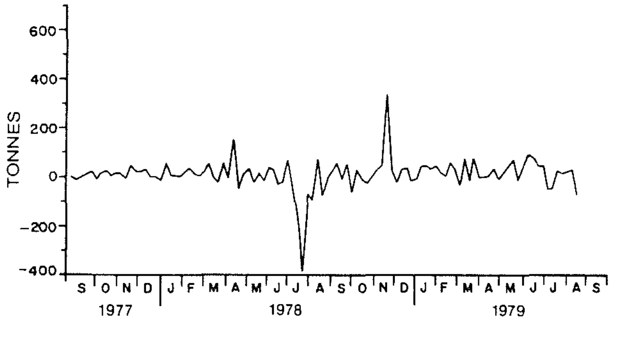

Figure 10.15 Total nitrogen load in estuary water column (observed - estimated).

continuous contribution from the sediments and other sources results in a 'base' level of nutrients in the system estimated at about 75 tonnes N and 5 tonnes P (from 1977 data. Figs. 10.13 and 10.17).

Nutrient loads

(i) ≥observed weekly water column load (concentration x system volume)

(ii) ≥weekly gross losses (concentration x system volume x flushing rate ($\bar{F}$)).

∴Mean annual flushing rate =

$$\frac{\geq \text{gross losses}}{\geq \text{obs. weekly load}} = (\bar{F})$$

1977/78 $\bar{F}$ = 0.23 per week
1978/79 $\bar{F}$ = 0.19 per week

Volume flushed

Annual ≥system volume x $\bar{F}$ =≥ estuary water flushed, which is replaced (in a year) by the same volume of marine water, having a mean concentration of N=482 ug L^{-1}; P=26 ug L^{-1}.

Marine input load to estuary

Mean marine concentration x mean marine volume flux = mean marine load of N and P.

Important consequences for nutrient management of the system may be drawn from the Table. The nitrogen balance of the system is critically dependent upon river flow from the eastern Murray catchment. In the very dry 1978/79 water year, the estuary appeared to have a negative nitrogen balance, with losses exceeding gains, in contrast to 1977/78.

Phosphous input is much less affected by river flow because flow from the coastal plain is much more reliable than that from the Murray River catchment. A large reduction in phosphorus loading to coastal plain soils is necessary to substantially reduce P input to the estuary.

SPECULATIVE NUTRIENT MODELLING

It is desirable to be able to estimate the consequences of changes to the estuaries or their catchments on nutrient status of the water, biomass and sediments. This is difficult to achieve in practice, particularly with the available data and the remaining critical uncertainties in the knowledge of nutrient cycling within the system. Work is still in progress in these areas, but we are presently hampered by a lack of data. The position will undoubtedly improve as further work is completed, especially on the role of the sediments.

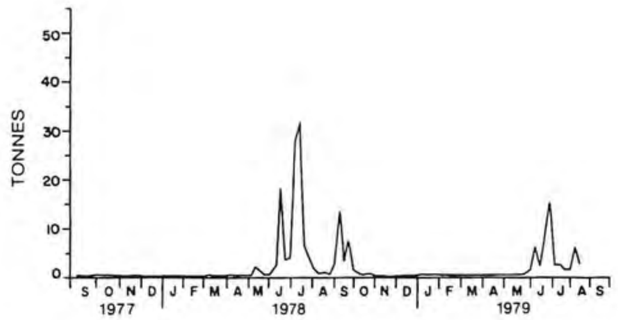

Figure 10.16 Total phosphorus input into the estuary.

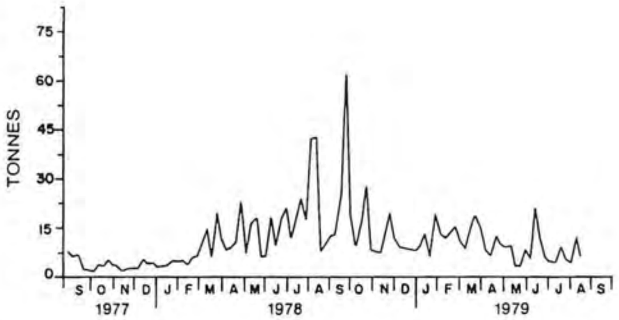

Figure 10.17 Total phosphorus load in the estuary water column.

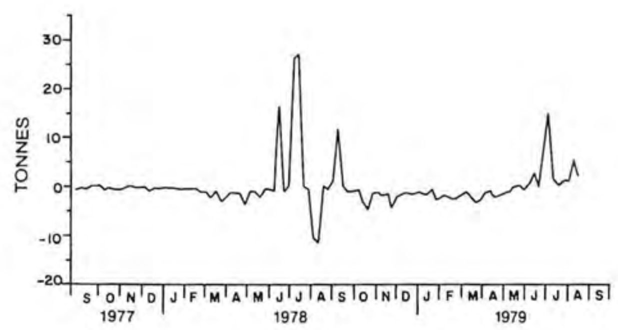

Figure 10.18 Total phosphorus load budget (gains - losses).

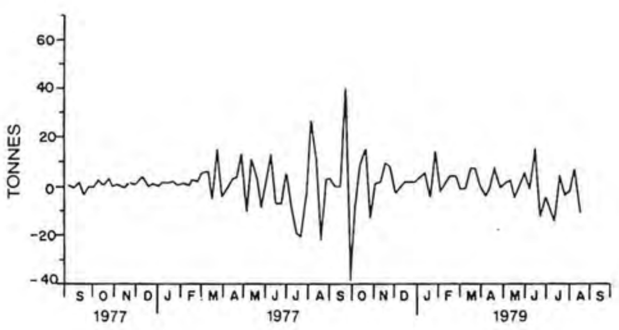

Figure 10.19 Total phosphorus load in estuary water column (observed - estimated).

CHAPTER 11

POSSIBLE MANAGEMENT SCENARIOS

INTRODUCTION

This chapter is concerned primarily with management as it relates to the algal problem. Nevertheless, although this is now the pressing problem, it must be remembered that there are other aspects of management with which the Peel Inlet Management Authority (PIMA) has to concern itself and on which it may wish to be advised by EMAC, on the basis of the findings of the study. For example PIMA is under pressure to make decisions about proposals for marinas on both sides of the inlet channel and on the banks of the Murray and Serpentine Rivers.

Discussion here is restricted to examination of the general principles under which management of the algal problem can be achieved and it does not attempt to evaluate the relative merits of possible practical measures. These will have to be decided after study of relevant engineering, economic and social considerations, as well as on the findings of the study.

SUMMARY OF FINDINGS RELEVANT TO *CLADOPHORA* MANAGEMENT

The following points from earlier chapters may usefully be reiterated here:

1. *Cladophora* growth rates in algal beds in the estuary are always much less than rates measured in the laboratory under optimal conditions (a doubling time of five days). Growth limiting factors are temperature, light, and plant nutrients. Salinity is not a limiting factor within the range observed in Peel Inlet. Water temperature averages about 15°C for some months in winter, thus limiting growth. Light limits growth during much of the year, especially when nutrient levels and turbidity are high during and following river flow, and intense self-shading within the algal bed allows maximum growth only at the surface of the bed at any time. The growth rate is also related to availability of nutrients, but it is only in summer-autumn and in the top few millimetres of the algal bed that the growth potential of *Cladophora* is limited by the nutrient supply. Thus, much of the time the supply of nitrogen and phosphorus is in excess of the capacity of the alga to use them.
2. Of the two key nutrients it is phosphorus rather than nitrogen which limits *Cladophora* growth when light and temperature are adequate.
3. *Cladophora* is able to take up and store nitrogen and phosphorus even when light and temperature are inadequate for growth. Such stores are sufficient for about a doubling of biomass when growth is again possible and partially make up for the low rate of supply of these nutrients during summer.
4. In an algal bed the compensation point below which respiration exceeds photosynthesis is only about 1 cm beneath the surface and below this algae die and decompose. Decomposition, with the release of nutrients is relatively slow (60%—70% weight loss and release of N and P in six months).
5. The nutrient store in surface sediment is resupplied from: the brief external annual river input (via phytoplankton, flocculation and sedimentation); decomposition of benthic algae; decomposition of blue-green 'algal' blooms. The store is limited and losses to the underlying true sediment and to be overlying water may greatly exceed the amount available to benthic algae for growth.
6. At present, septic tank and other wastewater effluent make a relatively small contribution to nutrient input to the estuary. However, the many proposed developments around the estuary could add greatly to this contribution, unless provision is made to dispose of wastewater and the contained nutrients away from the estuary.
7. The *Cladophora* problem has decreased over the last four years, but it is not possible to say with any confidence what has caused this decrease or whether the problem will or will not continue to decline; there are not the long term data on which to base a judgment. It is unlikely that the weed and ooze harvesting has been a major cause of the decline, though this may well have contributed to it. The phosphorus input to the system may have decreased as a result of the succession of dry years or of the reduced application of superphosphate to coastal plain catchments since 1974. However, there is no certainty that the recent reduction in superphosphate application has yet resulted in lower input rates to the estuary, or that a wet winter will not rapidly restore phosphorus loads to former high levels. It may be that phytoplankton, and especially *Nodularia*, blooms have been more frequent and more extensive, with the resulting increased turbidity reducing benthic light during the main *Cladophora* growth season. Lastly, it is possible that there has been some unknown biological factor inimical to *Cladophora*.

MANAGEMENT OPTIONS

It will be clear from the foregoing that radical management of the algal problem resolves itself into manipulation of one or more of the growth-limiting factors listed above, or a direct attack on the alga itself. The reduction of nitrogen and phosphorus availability offers the only permanent solution to the problem of excessive algal growth.

The following possible management options should be considered for implementation singly or in combination of two or more.

Option 1

Continue the present weed removal and extend it to remove algal accumulations further from the shore. As well as reducing the algal nuisance, this will ensure that piles of algae are removed before they have time to decompose and release nutrients to the water.

An alternative to the present practice of weed raking, suggested by consultants Kinnaird Hill De Rohan & Young Pty. Ltd. and independently by others, is to harvest algae before they come ashore. This has several attractions; it prevents accumulation and decomposition onshore and a commercial use may be found for clean algae; moreover it would deplete the system of a small proportion of the plant nutrients. However, it is unlikely that the weed problem could be eliminated by this option, although with the present lower levels of superphosphate application it is possible that the nutrient stores could be sufficiently reduced for the nuisance to be contained.

Option 2

Reduce the amount of available nitrogen.
Most of the nitrogen entering the estuary comes from the plateau (73% in 1978) and although the source has not been identified it is believed to be derived mainly from pasture legumes. Thus it comes in saline water from agricultural areas, rather than in fresh water from the forested part of the catchment. Although there appears to be little prospect of being able to reduce input from this source, the source of nitrogen does warrant further investigation because nitrogen availability may limit phytoplankton growth and sedimentation in winter and hence nutrient retention in the estuary.

The atmosphere is an important source of nitrogen which cannot be directly controlled. The *Nodularia* blooms of 1978-79 and 1980-81 occurred in situations of a low N : P ratio in Harvey Estuary and release of nutrients from this nitrogen-fixing organism in turn stimulated *Cladophora* production in western Peel Inlet. It must be assumed that atmospheric nitrogen will be trapped if its input from other sources is inadequate and phosphorus availability is high, and if water temperature is above about 18°C.

Ocean water levels of nitrogen are well below those of estuary water (Chapter 10) so that improved exchange with the sea will reduce nitrogen availability in the system; however, it is unlikely that it could reduce it to a level at which N was limiting rather than P.

Option 3

Reduce the input of phosphorus to the estuary. This could be achieved in one of the following ways:

(a) *By reducing the discharge of phosphorus to drainage to the estuary.* To achieve this it will be necessary to modify present techniques of superphosphate application to coastal plain farmland. The problems of relating soil types, phosphorus chemistry, and farming practices to loss of phosphorus from the land are complex and require further investigation before decisions can be made about the best methods by which phosphorus discharge to drainage can be reduced.

(b) *By diverting phosphorus-rich water away from the estuary.* Some 60% or more of phosphorus entering the estuary does so via the Harvey River and Mayfields Drain. These could be diverted direct to the sea. A further 20% of phosphorus input enters the estuary via the Serpentine River.

(c) *By introducing a 'biological filter' into the coastal plain drainage system.* Irrigated swamplands have been used successfully in other parts of the world to remove nutrients from urban wastewater drainage and in many cases profitable agricultural or forestry crops have been produced.

Option 4

Reduce nutrient retention, by improved flushing. The principal objective here is to increase the mean flushing rate of the estuary water and hence the time during which nitrogen and phosphorus can be retained by phytoplankton or flocculation and sedimentation.

Assuming the behaviour of salt and nutrients are the same, whilst acknowledging that the latter are not conservative, then:

(a) a 50% increase in the flushing rate will be expected to increase losses by only about 10%.

(b) a 100% increase in the flushing rate will be expected to increase losses by about 15%.

Greater increases in the flushing rate only marginally improve these figures (Technical Report No. 100).

Reduced nutrient retention would certainly drive the system *towards* equilibrium with the sea, but sediment release of nutrients would be expected to compensate for the increased loss until the 'active' zone of the sediments (not accurately defined) became nutrient depleted to equilibrium with the water and biomass.

A possible future dam or dams on the Murray River, which retained the potable water and allowed discharge of nitrogen-rich saline water to the estuary, might worsen eutrophication of Peel Inlet. The benefit of the low nutrient water from the forested section of the Murray catchment, which currently serves to dilute nutrient concentrations in both river and estuary, would be lost. To some extent this problem already exists due to dams on the two major tributary rivers, the North and South Dandalups.

Option 5

Deplete the sediment store of phosphorus.
During the major algal growth season phosphorus concentration in the ambient water is low and the plant is dependent on the additional phosphorus released from the black ooze. A proportion of this released phosphorus is lost to the sea by tidal exchange, although it is not possible to determine with any accuracy how much is lost. The practical proposal for reducing the sediment store is to remove it by some form of dredging.

The above options all aim to solve the algal problem, by reducing the present nutrient enriched condition of the estuary. However, other possible options may merit consideration even though they offer no prospect of achieving a long term solution.

Option 6

Reduce benthic light. Absence of a *Cladophora* problem in the greater part of Harvey Estuary is believed to be because benthic light is inadequate most of the time. In Peel Inlet light is also limiting during and following river flow. Light limitation is attributable to: dissolved organic matter (tannins) in river water, phytoplankton, suspended and resuspended fine particulate matter.

Light could be used as a tool to limit growth of benthic algae in Peel Inlet, in one of the following ways:

(a) Deepen the estuary, to say 3m.

(b) Addition of a light absorbing chemical. Such a chemical (Aquashade) is marketed commercially.

(c) Encourage growth of phytoplankton. This was suggested at one stage of the study because of the absence of *Cladophora* from most of Harvey Estuary. However, it would involve increasing the eutrophic condition of the estuary, with unpredictable effects on the ecosystem.

Option 7

Application of an algicide.
A low-cost, low-toxicity commercial algicide, Simazine (2-chloro-4,6-bis (ethylamino)-s-triazine) is now available. It could be adsorbed onto granules and applied directly to a *Cladophora* bed. Treatment costs are estimated to be 2-3 cents per 1000 litres of treated volume. This compound may warrant further investigation. However both beneficial and deleterious environmental side effects can be foreseen and these will need to be investigated, as well as methods of application and the effectiveness of the algicide to reduce weed growth.

Option 8

Introduction of weed eating fish.
The introduction of exotic species is not favoured and a lengthy investigation would certainly be required in order to assess the merits of such an introduction and its achieving the desired result.

Option 9

Cultivation and harvesting of a useful algae;
an agar producing species such as *Gracilaria*. Here again it would be necessary to undertake a lengthy investigation before a recommendation could be made.

In conclusion, it must be stressed that any modification of the estuarine environment, whether it be by reducing the input of nutrients, by modifying river drainage, by dredging, or by any other means, will produce complex changes in the ecosystem, not all of which are easily foreseen. Before decisions are made about practical measures for eliminating the algal problem careful consideration must be given to other possible consequences of the action, as well as to the social and economic implications.

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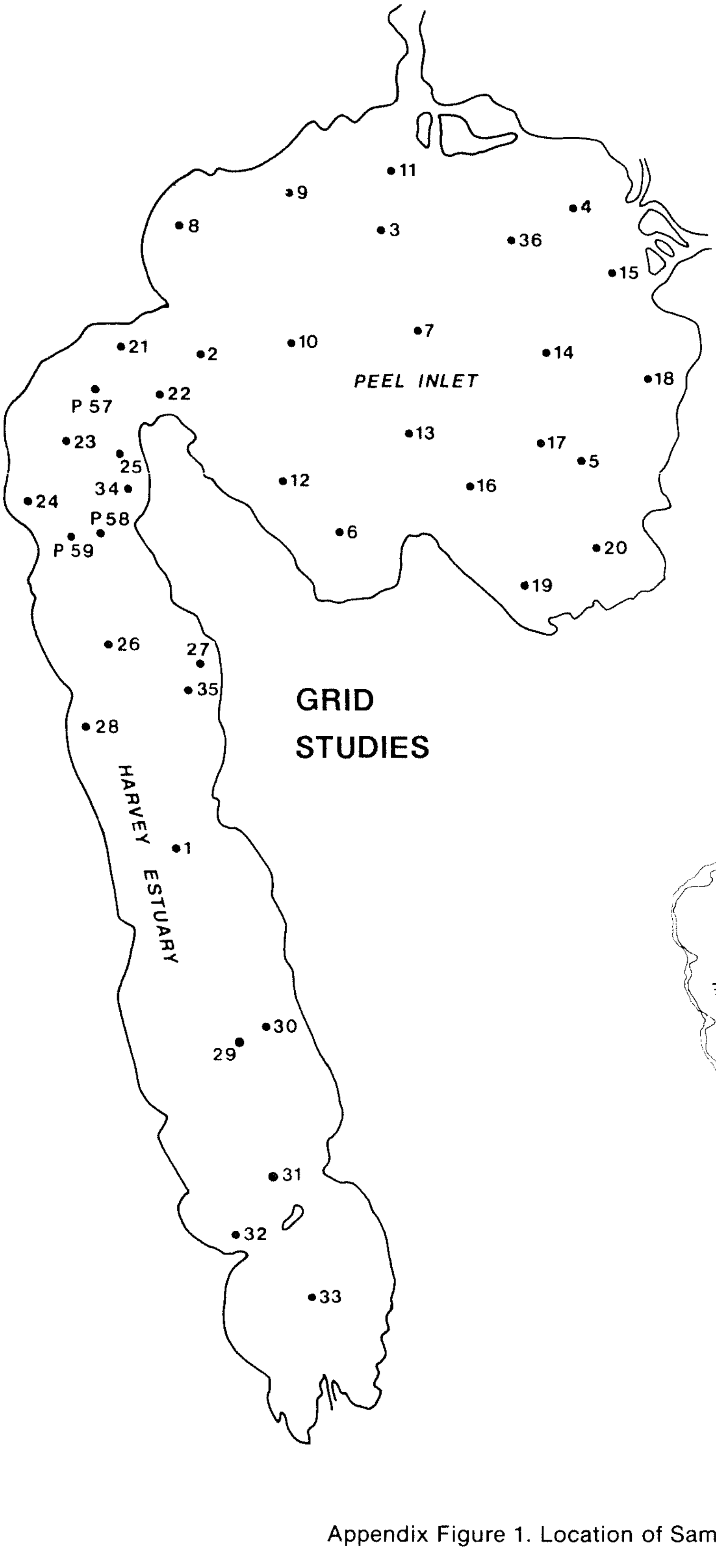
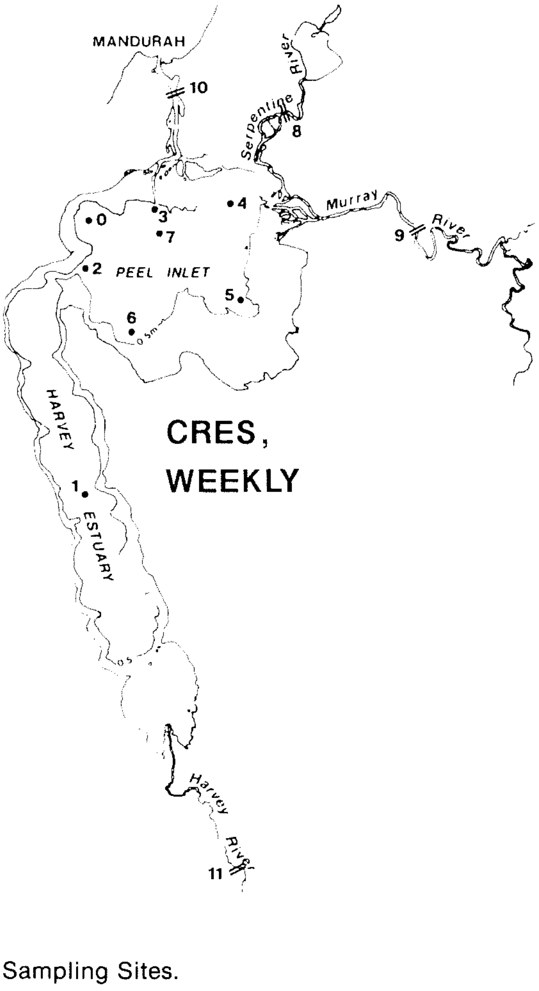
APPENDIX I

A guide to the data collected during the study.

1. Measurement of Physical Variables
2. River and Drain Sampling Programme
3. Estuary Sampling Programme
4. Supplementary Estuary Sampling
   - (a) Continued monitoring
   - (b) Sediment studies
   - (c) Grid studies
   - (d) Phosphatase study
   - (e) Blue-green bacteria





Appendix Figure 1. Location of Sampling Sites.

1. MEASUREMENT OF PHYSICAL VARIABLES

VARIABLE	LOCATION	LENGTH OF RECORD	TIME INTERVAL	COLLECTED BY	REMARKS
River flow (m^3 x 10^3)	Murray River (614006)	1940 — present	mean daily	PWD	Routed from 614006 to Pinjarra Weir
River flow (m^3 x 10^3)	Serpentine River (614072)	1911 — present	mean daily	PWD	Peel Inlet flows estimated to be 6 x gain
River flow (m^3 x 10^3)	Serpentine Drain (614030)	April 1979 — present	mean daily	PWD	At Dog Hill — not used in study
River flow (m^3 x 10^3)	Harvey River Main Drain	1977 — Oct 1979	mean daily	P-H Study	At railway bridge
River flow (m^3 x 10^3)	Harvey Estuary drains	1977 — Oct 1979	weekly	P-H Study	Estimated from Harvey River record
Rainfall (mm)	Robert Bay (Gauge No. 1)	Mar 1977 — Oct 1979	hourly	P-H Study	Casella natural siphon pluviometer
Rainfall (mm)	Harvey Estuary (Gauge No. 2)	July 1977 — October 1979	hourly	P-H Study	See Black & Rosher (1980) for locations
Rainfall (mm)	Mandurah (Gauge No. 3)	July 1977 — Oct 1979	hourly	P-H Study	
Rainfall (mm)	Mandurah P.O.	1889 — present	monthly	CBM	
Rainfall (mm)	Waroona	1935 — present	monthly	CBM	
Rainfall (mm)	Pinjarra P.O.	1877 — present	monthly	CBM	
Temperature (°C)	Robert Bay	Jan 1977 — Oct 1979	mean monthly	P-H Study	From continuous trace thermograph
Humidity (%)	Robert Bay	Jan 1977 — Oct 1979	mean monthly	P-H Study	From continuous trace hygrograph
Wind speed (m sec^{-1}) and direction	Robert Bay	Sept 1976 — Oct 1979	4 hourly — weekly	P-H Study	
Evaporation (mm)	Robert Bay	Jan 1977 — Oct 1979	mean weekly	P-H Study	From U.S. Class A pan evaporimeter
Global radiation (mW cm^{-1})	Guildford Aerodrome	Sept 1977 — Oct 1979	mean monthly	CBM	
Barometric pressure (mb)	Rossmoyne	Aug 1977 — Oct 1979	12 hourly	P-H Study	From continuous trace barograph
Tidal flux (m sec^{-1})	Mandurah bridge	2 x 5 day periods Feb & Aug 1978	hourly	P-H Study	
Tide height (cm)	Mandurah jetty	August 1977 — present	hourly	PWD	
Tide height (cm)	Chimneys	Sept 1977 — Feb 1980	5 min — ¼ hrly	PWD	
Tide height (cm)	CRES site 0	Oct 1977 — Apr 1978	5 min — ¼ hrly	PWD	
Tide height (cm)	Coodanup	Oct 1977 — Apr 1978	5 min — ¼ hrly	PWD	
Tide height (cm)	Robert Bay	Oct 1977 — Apr 1978	5 min — ¼ hrly	PWD	
Tide height (cm)	Dawesville	Oct 1977 — Apr 1978	5 min — ¼ hrly	PWD	
Tide height (cm)	Harvey Ford	Oct 1977 — Apr 1978	5 min — ¼ hrly	PWD	

2. RIVER AND DRAIN SAMPLING PROGRAMME

VARIABLE	CRES *LOCATION (FIG. 1)	**LENGTH OF RECORD	TIME INTERVAL	COLLECTED BY	REMARKS
NO3/NO2—N (ug L^{-1})	8, 9, 11	2 Sept 1977 — 28 Sept 1979	weekly	P-H Study	N.B. Surface samples only for all nutrient measurements
NH4—N (ug L^{-1})	"	" "	"	"	
Kjeldahl—N (ug L^{-1})	"	" "	"	"	
Total N (ug L^{-1})	"	" "	"	"	Estimated by the addition of the three forms of N above
PO4—P (ug L^{-1})	"	" "	"	"	
Other—P (ug L^{-1})	"	" "	"	"	
Total—P (ug L^{-1})	"	" "	"	"	Estimated by difference Total—P – PO4—P

* Limited sampling was carried out on various agricultural drains entering the estuaries. The input from these drains was subsequently estimated from Harvey River (site 11) concentration and flow data. See Black and Rosher (1980).

** Sampling was discontinued at sites 8 and 9 during the period 12 January 1979 — 29 June 1979.

3. ESTUARY SAMPLING PROGRAMME

VARIABLE	CRES LOCATION (FIG. 1)	*LENGTH OF RECORD	TIME INTERVAL	COLLECTED BY	REMARKS
Depth (cm)	sites 0—7, 10	31 Aug 1977 — 25 Sept 1979	weekly	P-H Study	Surface and bottom profile data collected from Nov 1977 onwards
Temperature (°C)	"	" "	"	"	
Photosynthetically active radiation ($uE\ m^{-2}\ s^{-1}$)	"	" "	"	"	
PAR extinction coef	"	" "	"	"	
Dissolved oxygen ($mg\ L^{-1}$)	"	" "	"	"	
Salinity (ppt)	sites 0—7, 10 and posts 26, 46, 58	" "	"	"	
Cladophora biomass ($g\ m^{-2}$)	sites 0, 4, 5, 6, 7	" "	"	"	Expressed as dry weight. Mean of 5 replicate samples per site.
Other benthic plant biomass ($g\ m^{-2}$)	"	" "	"	"	
Phytoplankton — numbers and species composition	sites 1, 4, 7	April 1978 — Dec 1980	"	"	Surface sample only — reported by R.J. Lukatelich — Tech. Rep. 93
Chlorophyll *a* ($ug\ L^{-1}$)	sites 0—7, 10	31 Aug 1977 — 25 Sept 1979	"	"	surface sample only
Phaeophytin ($ug\ L^{-1}$)	"	" "	"	"	
NO3/NO2—N ($ug\ L^{-1}$)	"	" "	"	"	N.B. all nutrients were sampled at both surface and bottom, but the bottom series is incomplete
NH4—N ($ug\ L^{-1}$)	"	" "	"	"	
Kjeldahl—N ($ug\ L^{-1}$)	"	" "	"	"	
Total—N ($ug\ L^{-1}$)	"	" "	"	"	Estimated by the addition of the three N forms above
PO4—P ($ug\ L^{-1}$)	"	" "	"	"	
Other—P ($ug\ L^{-1}$)	"	" "	"	"	Estimated by difference; total-P — PO4-P
Total—P ($ug\ L^{-1}$)	"	" "	"	"	

*Length of record variations: Sites 1—7 31 Aug 1977 — 25 Sept 1979
Site 0 15 Aug 1978 — 25 Sept 1979
Site 10 5 Dec 1978 — 25 Sept 1979

4. SUPPLEMENTARY ESTUARINE SAMPLING

VARIABLE	GRID LOCATION (FIG. 1)	LENGTH OF RECORD	TIME INTERVAL	COLLECTED BY	REMARKS
		(a) CONTINUED MONITORING			
Depth (cm)	1, 2, 4, 7, 31, post 58	Sept 1979 — Sept (Dec) 1980	fortnightly	R.J. Lukatelich (see Tech. Rep. 93 and Ph.D thesis)	Surface and bottom samples
Secchi depth (cm)	" "	" "	"		" "
Salinity (ppt)	" "	" "	"		" "
Phytoplankton — numbers and species composition	1, 4, 7	" "	"		Surface sample only
Periphyton — Chlorophyll *a* species composition	1, 4, 7, 31	" "	"		Sampled with artificial substrate
Chlorophyll a (ug L-¹)	1, 2, 4, 7, 31, post 58	" "	"		Surface sample only
Phaeophytin (ug L-¹)	" "	" "	"		" "
Sediment chlorophyll *a* (ug L-¹)	" "	" "	"		Surface 1cm of sediment
NO3/NO2-N (ug L-¹)	" "	" "	"		Surface and bottom samples
NH4-N (ug L-¹)	" "	" "	"		" "
Kjeldahl-N (ug L-¹)	" "	" "	"		" "
Total N (ug L-¹)	" "	" "	"		" "
PO4-P (ug L-¹)	" "	" "	"		" "
Other-P (ug L-¹)	" "	" "	"		" "
Total P (ug L-¹)	" "	" "	"		" "
		(b) SEDIMENT STUDIES (SEE ALSO SECTION C)			
Extractable — PO4-P (ppm dry)	1, 4, 5, 6, 7, 8, 31, post 46	Dec 1978 — March 1980	every 2 — 4 weeks	J.O. Gabrielson (See Tech. Rep. 96 and Ph.D. Thesis)	surface sediments and black ooze,if present
NH4-N (ppm dry)	" "	" "	"		
NO3-N (ppm dry)	" "	" "			
Total P (ppm dry)	" "	" "	"		
Total N (ppm dry)	" "	" "	"		
Organic matter (%)	" "	" "	"		
Water content (%)	" "	" "	"		
Sedimentation rate of:	1, 4, 7, 31	June 1979 — Dec 1980	every 2 — 4 weeks	J. O. Gabrielson and R.J. Lukatelich (see Tech. Reps. 93 and 96 and Ph.D. Thesis)	Collected by sediment traps suspended 0.5 m above bottom
Total mass (g m-² day-¹)	" " " "	" "	"		
Total P (g m-² day-¹)	" "	" "			
Total N (g m-² day-¹)			"		
Organic matter (g m-² day-¹)	" "	" "	"		
Chlorophyll a (ug m-² day-¹)	" "	" "	"		

4. SUPPLEMENTARY ESTUARINE SAMPLING (cont'd)

VARIABLE	GRID LOCATION (FIG. 1)	LENGTH OF RECORD	TIME INTERVAL	COLLECTED BY	REMARKS
		(b) SEDIMENT STUDIES (CONT'D)			
Sediment core profiles:	1—8, 24, 28, 31, post 46	1977 — 1980	Individual dates	J.O. Gabrielson (See Tech. Rep. 96 and Ph.D. Thesis)	Variables done on 1 cm slices down to 20—30 cm. Description of cores given.
Total P (ppm dry)	"				
Total N (ppm dry)	"				
Organic matter (%)	"				
Water content (%)	"				
		(c) GRID STUDIES			
Depth (cm)	1—36	March 1978 — Sept 1979	(One day every 6 months, March 1978, August 1978, March 1979, Sept 1979)	Peel Study Data on tape at Botany Dept. UWA (See also Tech. Reps. 91, 93, 95, 96)	Surface and bottom samples
Temperature (°C)	"	" "			"
Secchi depth (cm)	"	" "			"
Salinity (ppt)	"	" "			"
Cladophora biomass (g m^{-2})	"	" "			"
Other benthic plant biomass (g m^{-2})	"	" "			"
% plant cover on bottom	"	" "			"
Chlorophyll *a* (ug L^{-1})	"	" "			" "
Phaeophytin (ug L^{-1})	"	" "			"
NO2/NO3-N (ug L^{-1})	"	" "			"
NH4-N (ug L^{-1})	"	" "			"
Kjeldahl-N (ug L^{-1})	"	" "			"
Total-N (ug L^{-1})	"	" "			"
PO4-P (ug L^{-1})	"	" "			"
Other-P (ug L^{-1})	"	" "			"
Total P (ug L^{-1})		" "			
Phosphatase activity (ug released L^{-1} hr^{-1})	"	(not done Sept 1979)			"
Surface sediments: Total P (ppm dry)	"	March 1978 — Sept 1979			Surface sediments and black ooze, if present
Total N (ppm dry)	"	" "			"
Extr. PO4-P (ppm dry)	"	" "			"
Extr. NH4-N (ppm dry)	"	" "			"
Extr. NO3-N (ppm dry)	"	" "			"

4. SUPPLEMENTARY ESTUARINE SAMPLING (cont'd)

VARIABLE	GRID LOCATION (FIG. 1)	LENGTH OF RECORD	TIME INTERVAL	COLLECTED BY	REMARKS
			(c) GRID STUDIES (CONT'D)		
Surface sediments (cont'd)	1—36	March 1978 — Sept. 1979	(One day every 6 months, March 1978, August 1978, March 1979, Sept. 1979)	Peel Study Data on tape at Botany Dept. UWA.	
Organic matter (%)	"	" "			
Water content (%)	"	" "			
Organic-P (ppm dry)	"	March 1978	One day, March 1978	J.O. Gabrielson See also Tech Rep. 96	
Phosphatase activity (ug P released L^{-1} hr^{-1})	"	March 1978 — Sept 1979			
	"	" "			
			(d) PHOSPHATASE STUDY (EXCLUDING PHOSPHATASE COMPONENT OF GRID STUDIES)		
Phosphatase activity (ug P released L^{-1} hr^{-1})	1—7	Nov 1977 — April 1978	weekly	A.L. Huber (see Tech. Rep. 95 and Ph.D Thesis)	There were also three diurnal studies, two in Feb. 1978 and one in May 1978
			(e) BLUE-GREEN BACTERIA		
Blue-green species	1—8, 10, 31 and post 58	May 1979 — Oct 1980	weekly May 1979 — Sept 1979 fortnightly Sept 1979 — Oct 1980	A.L. Huber (see Tech. Rep. No. 94 and Ph.D Thesis)	Surface samples on cultured populations
Nodularia spumigena bloom	25 special sites in Harvey Estuary	Nov 1978 — Jan 1979	variable		