SWAN RIVER TRUST

Swan River - The Future

Workshop Proceedings

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BACKGROUND

The Swan-Canning Estuarine System is highly modified from its natural state. European settlement has influenced its hydrology and ecology and today frequent algal blooms, and occasional fish kills are a reminder of the pressures on water quality.

The Swan River Trust and its predecessors have long recognised the influence of industrial, urban and rural development upon the estuary. For many years these organisations have sought to monitor the physico-chemical parameters and the presence of pollutants in the estuary, its tributaries and contributing drains. As a consequence, point source pollution to the estuary has been considerably reduced. However, the influx of nutrients from non point sources remains as a fundamental problem for management and continues to threaten the future 'health' of the estuary.

Current methods in monitoring estuarine 'health' enable the condition of the estuary to be documented but the results are limited in their predictive capacity. Therefore, in establishing this workshop the Swan River Trust is seeking new approaches to monitoring which would enable managers to report on possible trends, establish guidelines and predict the effects of management action and proposed development on the estuary. The workshop was also aimed at addressing current waterways research in order to establish priorities for future study.

Key figures in waterway investigation were invited to present an overview of monitoring and research occurring in both the estuary and its catchment and to identify important parameters for future investigation. This was intended to provide a background to an open forum which would discuss future priorities in monitoring and research. Given the overall need for the integration of management and research, it was entirely appropriate that Dr Ernest Hodgkin should present the first of the papers, as his long and distinguished career has encompassed both waterway research and management. His account of the historical and present day physical status of the estuary, not only provides an introduction to the Swan-Canning Estuary, but to the workshop itself.

It is hoped that the outcome of the workshop and this volume will be to provide a direction for future research and monitoring as a basis for improved management of waterway in Western Australia, especially the Swan River.

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1.0
Introduction

INTRODUCTION TO WORKSHOP

by Bruce Hamilton

All of the participants are most heartily welcomed to the Workshop. You are a special group of people, because you represent the best accumulation of knowledge and the best minds in the State, when it comes to understanding and managing the Swan River. This is most important, because the workshop today is all about drawing our existing knowledge together and defining what needs to be done in the future to understand the Swan much better. In turn, this should lead to a better information base for more effective management.

I was amazed when I first came to the Waterways Commission in 1987 to find that the Swan had not been studied in a comprehensive manner and was not well understood from a systems point of view. Even though a lot of individual work has been done over the years we still do not know what makes the Swan work as a system, and we certainly do not know what causes and maintains the large algal blooms that are now starting to cause real problems.

The aim of this workshop therefore, is to set out a strategy, or an overall plan, so that over a reasonable time we will more fully understand and be better able to manage the Swan and Canning Rivers. We need to define the work that should be done to understand the dynamics and processes that drive the system; including the physical, biological and chemical elements and the interactions between them. But this must be done at practical level with the aim of applying the results to short and long term management.

We should ask the question at this stage as to why we are at this position, given the calibre and expertise of researchers in this State. There are probably a number of reasons, but the key lesson for me is that we must take a much more integrated approach. I believe that in the past our study and management of natural systems has been too fragmented, and that it is now vital that we all work together with a common vision and a common set of objectives.

This does not mean academic or research excellence need suffer. Rather there are strong reasons for us all to work together, academics and managers alike. Not the least of these is the shortage of funding for research.

In this context our responsibility is to bring people like you together to set out research plans which are comprehensive and far sighted, and on which we all agree. Your role should be to direct your research, as far as possible, towards that plan, so the bits add up over time to a comprehensive information base, a better understanding and better management.

We must also not forget the bigger picture. The Swan estuary is part of complex catchment, partly on the coastal plain but also extending many kilometres inland. At the other end the Swan empties into the ocean, carrying with it good and bad contributions from the catchment.

The challenge for the workshop is to come up with detailed research and management recommendations for the Swan-Canning system but not forget the bigger picture. It is also to provide a properly integrated approach and not forget any important bits.

I wish you well in your deliberations and look forward to your contributions.

THE SWAN-CANNING ESTUARY
COMPARED WITH
OTHER ESTUARIES OF THE SOUTHWESTERN AUSTRALIA

Ernest P Hodgkin

The Swan-Canning estuary is not a typical south west estuary — C Y O'Connor made sure of that 100 years ago when he blasted the rock bar at the mouth and dredged the extensive sand flats to make Fremantle Harbour. It is salutary to consider how it now fits into the wide spectrum of what we call estuaries.

In this talk I want to emphasise the following aspects of the estuaries of the south west and of the Swan in particular:

1. None are now textbook estuaries.
2. Hydrologically and ecologically they are 'seasonal estuaries'.
3. They vary greatly: in size, form, hydrology, ecology, trophic status, etc.
4. The Swan, unlike most south west estuaries, is tidal throughout the year.
5. Hydrologically it is more marine than any other south west estuary.
6. In consequence it has the most diverse (species rich) biota.

The textbook estuary

Pritchard (1967), an American physical oceanographer, defined an estuary as:

> "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage".

Day (1981) a South African biologist modified this to read:

"An estuary is a partially enclosed body of water which is either permanently or periodically open to the sea and within which there is measurable variation of salinity due to the mixture of sea water with fresh water derived from land drainage".

Moore (1988), a geographer, has a simpler definition:

> "The mouth of a river where tidal effects are evident and where fresh water and sea water mix".

Moore's estuary is a dynamic environment in which the tides mix river water with sea water to create a salinity gradient from fresh at the river end to marine outside the entrance, a gradient that moves up and down the estuary tidally throughout the year. Figure 1.

The plant and animal communities of the estuary change progressively from those dominated by species adapted to fresh water, through brackish water species, to sea water species; from stenohaline freshwater, through euryhaline (estuarine), to stenohaline marine organisms.

This textbook estuary is a northern hemisphere concept. The Hawkesbury River of NSW is such a estuary, but there are are none in Western Australia.

South west estuaries

Most south west estuaries were probably textbook estuaries when first flooded by the post galcial marine transgression 6000 years ago. They were tidal, and marine salinity water penetrated a long way inland. Now tidal exchange is restricted by narrow entrances and sand bars; they have changed radically. Table 1.

Table 1. Textbook estuaries and south west Australian estuaries compared.

	TEXTBOOK ESTUARY	SOUTH WEST ESTUARY
Morphology	Entrance wide open	Entrance narrow, with a bar
Ocean tides	Macrotidal or mesotidal	Microtidal
Hydrodynamics	Tidal dominated	Dominated by river flow
Hydrology	A salinity gradient moves along the estuary tidally	Salinity changes seasonally
Ecology	Diverse biota: freshwater, estuarine, marine	Restricted biota, dominated by estuarine species

The astronomic tide is small (40 cm MHHW to MLLW), and there is no river flow for half the year. Estuary water changes from nearly fresh to marine or greater, seasonally instead of tidally, once a year instead of once or twice a day. Hydrologically, they are 'seasonal estuaries'. Eologically, the estuaries are dominated by the very few species which can tolerate this extreme range of salinity.

The Swan is now the nearest approach to a textbook estuary there is in Western Australia. Oyster Harbour may be an estuary geographically, but hydrologically and ecologically it is a marine bay similar to Princess Royal Harbour.

There are more than 50 estuaries in the south west and they differ from one another almost as much as they do from the textbook estuary in many important respects. There can be no common model on which to base mangement, whether to prevent eutrophication or for any other purpose. Figure 2.

How do they resemble and differ from one another?
Where does the Swan fit in the picture?

Catchments vary greatly in size, but more importantly they differ in:

- **Geology and soil types** — rock, clay, loam, sand — their capacity for soil erosion and nutrient retention and release.
- **Land use** — urban, agriculture, forests, coastal bush — as sources of runoff to rivers, carrying sediments and nutrients.
- **Runoff and river flow** — volume and pattern, whether reliable or dominated by flood flow. Figure 3. Table 2.

Estuary size. The estuaries range in size from Peel-Harvey (130 km^2), the Swan (about 25 km^2 and 60 km long), to a number which are only 1 km^2 (e.g. Taylor). They also vary greatly in depth, the Swan is up to 20 m deep, Peel only 2 m and many south coast estuaries are <1 m deep. Evaporative loss is >1 m so that shallow estuaries with restricted tidal exchange become hypersaline and may dry up altogether.

Form and origin. There are four main geomorphic types of estuary. Table 3.

- **Riverine estuaries**, confined to narrow river channels, and

Estuaries with lagoons into which the rivers discharge:

- **Valley estuaries**, in valleys roughly perpendicular to the coast.
- **Basin estuaries**, in basins on the coastal plain or in bays on rocky coastlines.
- **Inter-dune estuaries**, in narrow depressions parallel to the coast.

Table 2. Catchment areas, areas cleared, river flows and runoff.

RIVER	CATCHMENT AREA km^2	RIVER FLOW m^3 x10^6 MEAN	MEDIAN	RUNOFF mm	AREA CLEARED per cent	Gauging station	Years
AVON	119 000	322	171	1 - 10	~65	Walyunga 616011	13
WUNGONG	136	28	25	209	5	Pipehead dam 616071	71
MURRAY	6 840	331	220	48	75	BP W'spout 614006	43
BLACKWOOD	20 500	659	519	32	85	Darradup 609025	26
WARREN	4 040	300	311	77	36	Barker Rd 607220	16
DEEP	906	172	173	190	5	Centre Rd 606032	18
FRANKLAND	5 800	179	166	31	85	Mt Frankland 605012	42
PALLINUP	3 600	20	7	0 - 30	85	Bull Crossing 602001	19

Source: W A Water Authority

Hydrology The hydrodynamics and hydrology of the estuaries depend on the small ocean tide range, the tidal prism, the volume and periodicity of river flow, evaporation, and the behaviour of the bars. The bars are:

- **Permanently open**; there is always tidal exchange; in summer the lagoons are marine while the riverine parts have a salinity gradient along them; in winter river flow overrides the tides and the surface water is fresh (deep water may remain marine).
- **Seasonally open/closed**; river flow breaks the bars in winter and there is tidal exchange; when river flow ceases the bars close and there is no tidal exchange for half the year. Salinity is low in winter and approaches marine in summer.
- **Normally closed**; the bars only break following the infrequent floods, at any time of year, and generally only stay open for a few weeks. Salinity ranges from nearly fresh to grossly hypersaline or the lagoon water may dry up altogether.
- **Permanently closed**; these are no longer estuaries, though they were sometime during the last 6000 years. Salinity ranges from nearly fresh to grossly hypersaline or the lagoon water dries up altogether. Table 3.

Table 3. Examples of the estuary types:

	RIVERINE	VALLEY	BASIN	INTER-BARRIER
PERMANENTLY OPEN	Gardner	**SWAN** Blackwood	Peel —— Nornalup	Harvey Leschenault
SEASONALLY OPEN/CLOSED	Donnelly Margaret		Wilson Broke	Greenough Vasse-Wonnerup
NORMALLY CLOSED		Beaufort Stokes		
PERMANENTLY CLOSED		Culham		Jerdacuttup (Lake Clifton)

Permanently open and seasonally open estuaries are in the high rainfall (>700 mm) area of the extreme south west. Normally closed and permanently closed estuaries are on the low rainfall (<600 mm) coastline where there is often no significant river flow for several years in succession.

Ecology. This is largely dictated by the hydrological and hydrodynamic conditions - the salinity extremes experienced and the frequency and duration of bar opening.

The biota of permanently open estuaries have to choose between staying put (plants and most benthic fauna) or nipping in while the salinity is favourable (most fish). It is an environment that favours a very few resident species of euryhaline invertebrates and fish and a relatively large number of migrant, more stenohaline species of fish.

The biota of seasonally open estuaries have a similar choice, but they only have access when the bars are open, when the bars are closed they are trapped and have to take what comes to them hydrologically.

The normally closed estuaries are a more hazardous environment, even for the benthic biota. Access for recruitment from the sea is infrequent, brief and not always at a favourable time of year. Once in there is no getting out and when the salinity gets too high a salty grave is the fate for fish and invertebrates alike.

The only recruitment to the permanently closed estuaries is from the saline rivers and the same fate awaits the biota as the water evaporates.

The Swan-Canning estuary

It should be clear where the estuary fits into this picture of the estuaries of the south west, but I will summarise the main features in which the Swan-Canning resembles and differs from other estuaries in the south west?

It is a permanently open, valley estuary; it has a long riverine reach through unconsolidated Pleistocene sediments; the large lagoon is shallow where the river discharges into it (Perth Water), but has a deep (20m) basin; it has a long deep entrance channel; there is no entrance bar. Figure 4.

It has a very large catchment with a large and relatively reliable river flow from the high rainfall part, but with more variable flow from the low rainfall part, most of which is cleared agricultural land on predominantly clay soils.

For more than 2000 years, until about 4000 years BC, the Swan resembled the textbook estuary. Then until Fremantle Harbour was constructed in 1892-97 it was probably a typical, seasonal estuary. The rock bar and tidal sand flats greatly restricted tidal exchange and the tide range was probably only about 10% of the small ocean tide.

Now the tide range is about 80% of the ocean tide and the Swan is more like a textbook estuary than is any other south west estuary. However tidal exchange is still restricted (by the narrow entrance, the bridges, and the long entrance channel) and it is still a seasonal estuary hydrologically.

The riverine part is fresh in winter and brackish to marine in summer. But the lagoonal part often remains brackish (10-15 ppt) and this allows some euryhaline-marine organisms (e.g. *Mytilus*) to survive there for several years between floods. The deep water in the lagoon remains marine salinity throughout the year and stratification can make it anoxic. The entrance channel is flushed tidally with high salinity water most winters and has a relatively rich invertebrate fauna.

In summary. The Swan-Canning was probably a fairly typical permanently open south west estuary last century. Now, tidal exchange is less obstructed, hydrologically and ecologically it is still a 'seasonal estuary' but is more marine than previously. Surrounded by a large urban sprawl it is a very different environment. While the estuary and its problems are unique in many respects, they need to be examined in the context of other estuaries of the south west and the 'textbook' estuaries of other parts of the world.

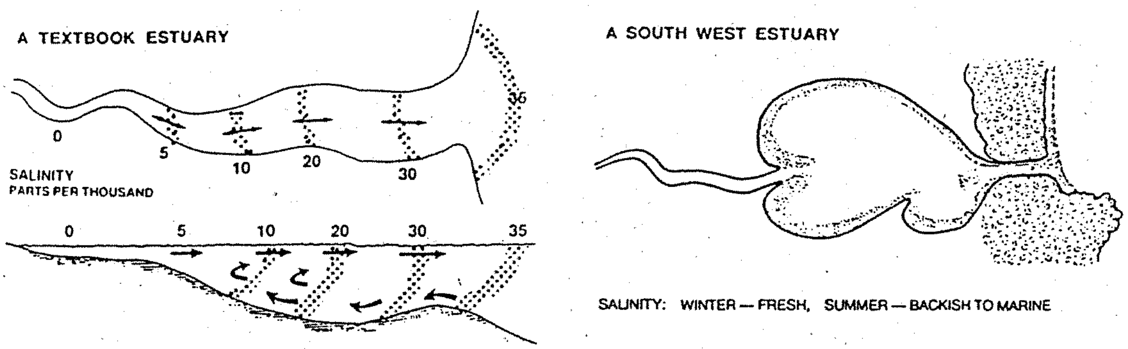


Figure 1. Geomorphology and hydrology of a 'textbook' estuary and an estuary of the south west.

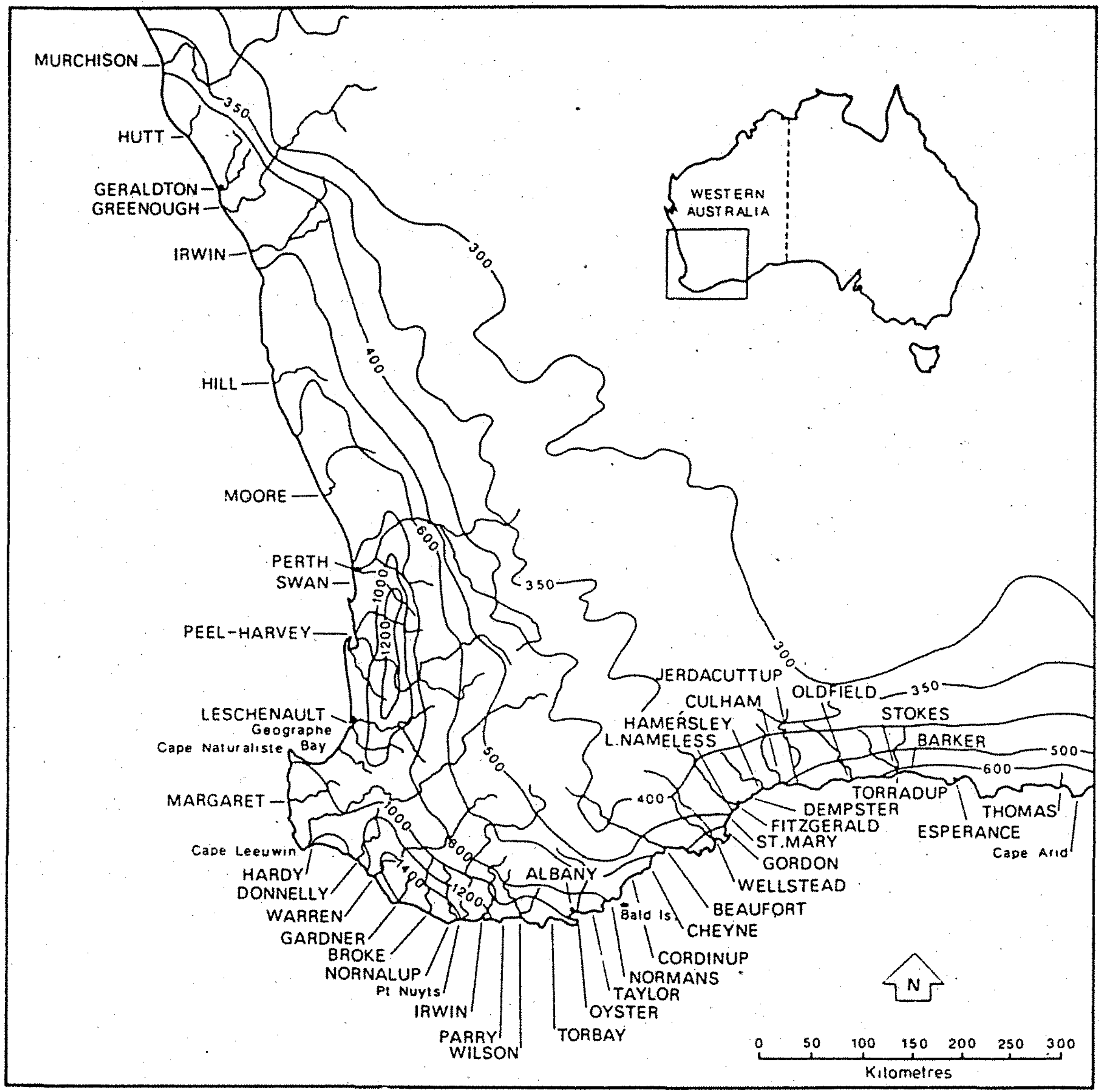
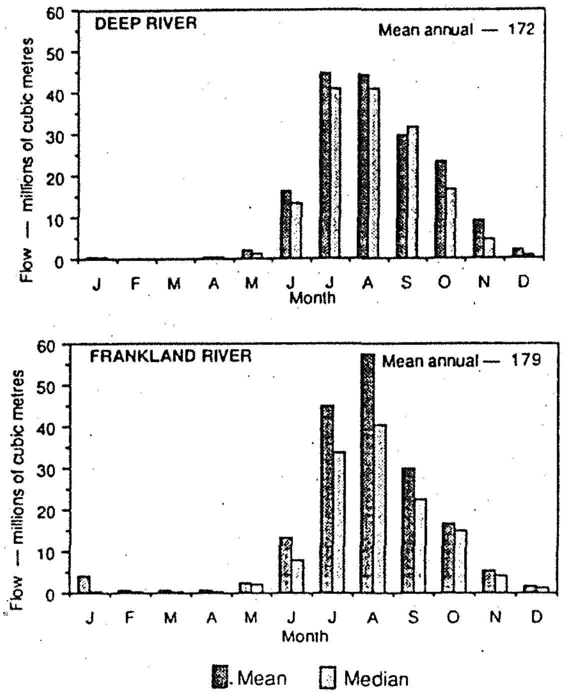


Figure 2. Estuaries of southwestern Australia. Isohyets — mm (Bureau of Meteorology).

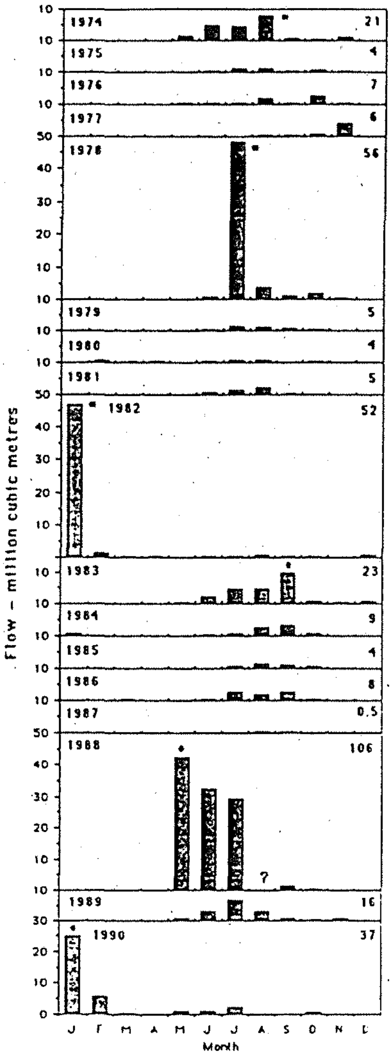


PATTERNS OF RIVER FLOW

Above: to Nornalup inlet

At right: to Beaufort Inlet

* Bar breaks



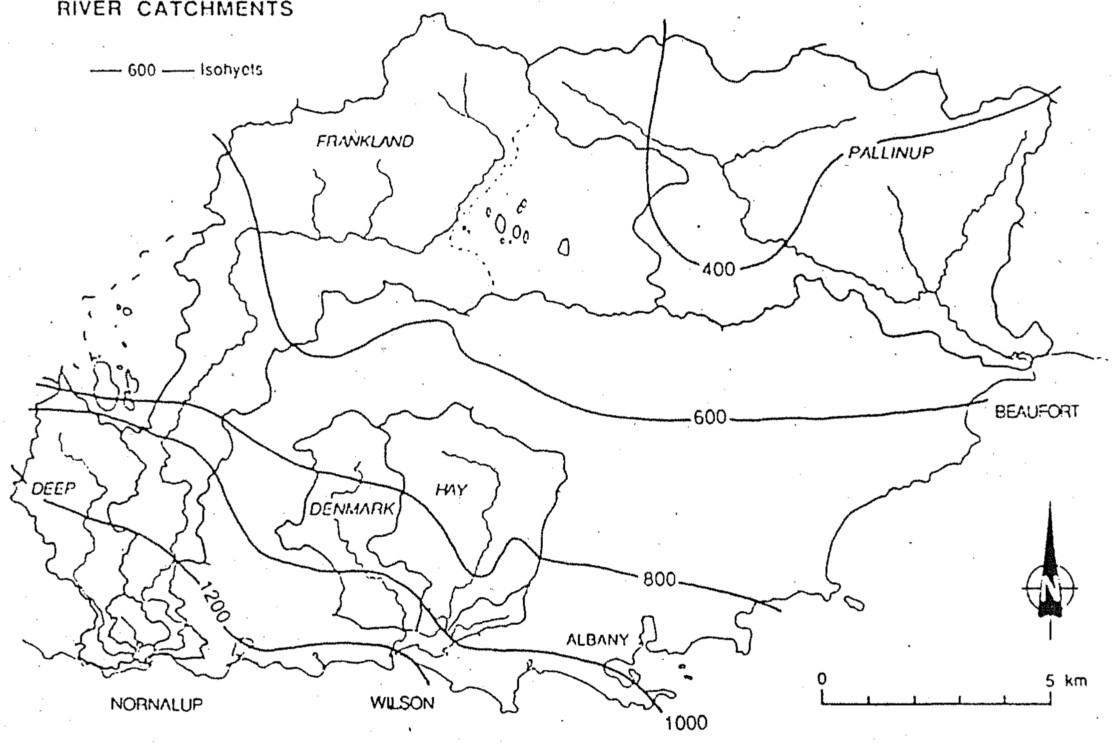


Figure 3. River flow to Nornalup Inlet from the catchments of the Deep and Frankland Rivers and to Beaufort Inlet from the Pallinup River.

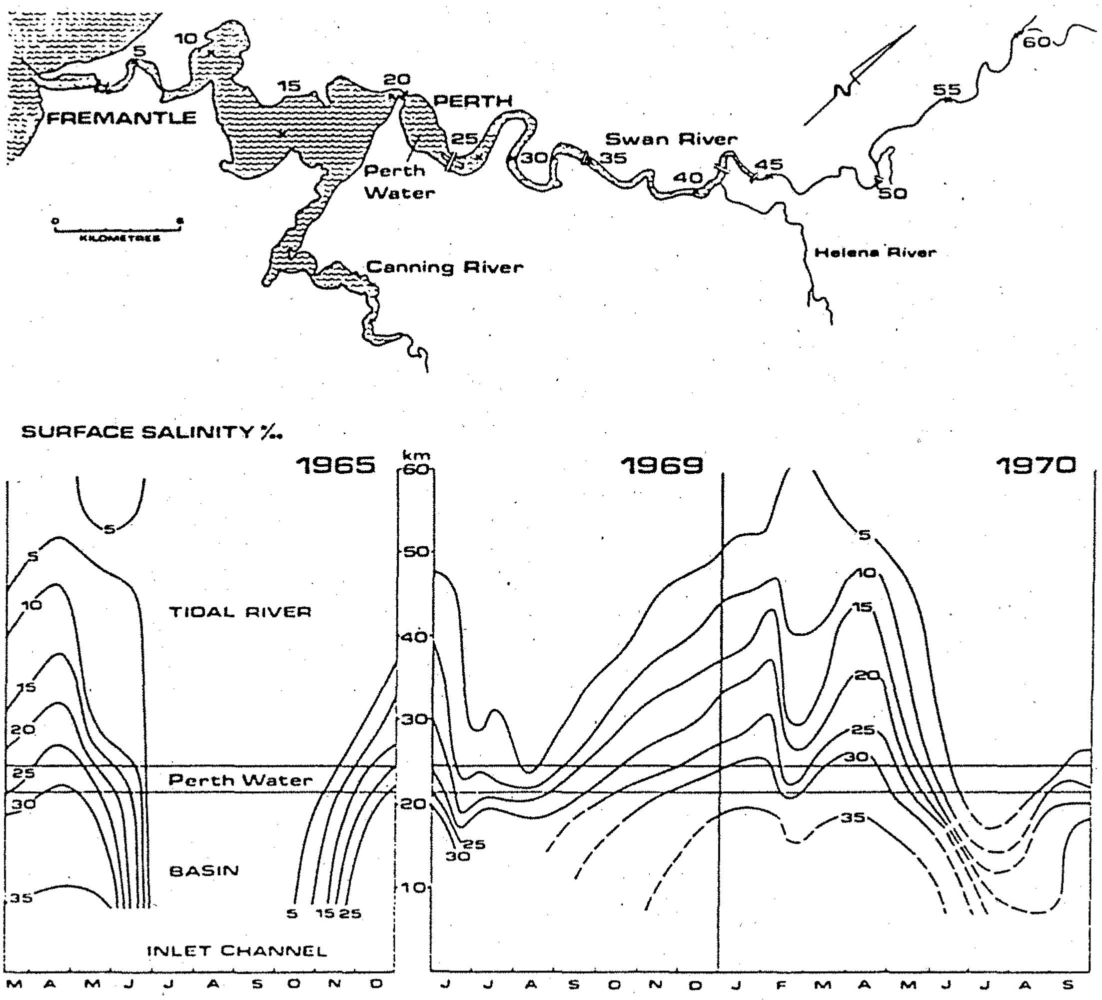


Figure 4. The Swan-Canning estuary. Salinity profiles.

2.0
The catchment

WATER QUALITY MONITORING IN THE SWAN-CANNING CATCHMENT

INTERIM RESULTS

by

D.M. Deeley, G.W. Parsons and R.B. Donohue

Swan River Trust 1992

SUMMARY

The Swan River has been experiencing seasonal blooms of phytoplankton over recent years especially in the reaches upstream of the Causeway. These blooms occur in response to the enrichment of the riverine system with nutrients such as phosphorous and nitrogen. Between 1987 and 1990 the Swan River Trust monitored water quality in 15 streams that flow into the Swan-Canning estuary. The aim of the monitoring program was to identify the magnitude and major sources of nutrients to the Swan-Canning estuary in the gauged catchment.

In all monitored catchments there were large seasonal fluctuations in rainfall and stream discharge. Nitrogen and phosphorus loads for the measured streams also varied widely from year to year. Ellen Brook and Claisebrook, typical coastal plain rural and urban catchments, showed especially strong seasonal trends in the measured parameters.

In the three year period 1987-1990 it was estimated that the gauged sub-catchments contributed an average of 500 tonnes of nitrogen and 60 tonnes of phosphorus per annum to the Swan-Canning estuary. The Avon River, Ellen Brook, Southern River and Bayswater Main Drain carried the largest loads, respectively. Flow-weighted data identified Ellen Brook, Bayswater main drain, Mills Street Main Drain and Southern River catchments as major sources of nutrients to the estuary. Claisebrook and South Belmont Main Drain were also shown to be important "hot-spots". The very high annual yields of nutrients from each hectare of the Susannah Brook catchment also classify it as primary source area of nutrients to the Swan estuary. The data suggest that Jane Brook is relatively free of nutrient input.

1 INTRODUCTION

Large blooms of phytoplankton and excessive accumulations of macro-algae are the more obvious biological indications of an over productive (eutrophic) aquatic system. These symptoms have been observed periodically in the Swan-Canning estuary for some time but phytoplankton blooms appear to have become significantly worse in recent years. Nitrogen and phosphorous are are essential plant nutrients and an over supply can stimulate the growth of aquatic vegetation. Enrichment of rivers and lakes with these nutrients has been identified as the primary cause of eutrophication (Cullen 1991). Phosphorous and nitrogen are present in sewage effluent, animal wastes and urban runoff, and are major components of agricultural fertilisers which may be washed into waterways from adjacent farmlands.

In late 1986 the Swan River Trust (then the Swan River Management Authority) responded to the problem in the Swan estuary by ceasing its quarterly estuarine water quality monitoring to free funds for a water quality monitoring program in the Swan-Canning catchment (Figure 1.1). The aims of the monitoring regime were to identify the major sources of nutrients to the estuary, to quantify the relative contributions from each of the sub-catchments, and if possible to relate these to the dominant land use.

If these aims were to be achieved the monitoring needed to be as comprehensive as possible in terms of the number of streams and types of catchments examined, and cover a sufficient period to assess annual variations in nutrient loading. Water quality was monitored weekly in a total of fifteen sub-catchments in the Swan-Canning river system (Figure 1.2) between 1987 and 1991. The sub-catchments varied in size from 120,000 square kilometres (km^2) to only 10 km^2. Soil types ranged from well drained sandy soils of the coastal plain to the heavier lateritic soils of the Darling Scarp. The monitored catchments included urban watersheds both residental and industrial, and rural catchments in the coastal plain and hills regions which, except for small areas of state forest near the Darling Scarp, have been largely cleared for agriculture.

This paper summarises the results of preliminary analysis of the data collected from the gauged sub-catchments (where possible some 1991 data is included). A detailed report of results from the five years of monitoring up to 1992 will be available when analysis of the data is complete after march 1993. Nutrient data are presented here in three ways. As:

i) total load (tonnes per year).

ii flow-weighted concentration (milligrams per litre per year).

iii) yield per unit area (kilograms per hectare per year).

Total annual nutrient loads are important as estimates of the quantities of nutrients involved and therefore of the scale of the management problem. But, considered in isolation, they may focus undue attention on the relatively large catchments drained by very large streams, and possibly mask those catchments that yield nutrients in quantities disproportionate to their size. Flow-weighted concentrations (FWC) allow meaningful comparison of water quality to be made between streams and catchments independant of relative size. Similarly, nutrient yields per unit area of catchment allow nutrient loads from large and small catchments to be compared. Examination of both FWC's and areal yield estimates can readily identify "hot-spots" or catchments contributing very large amounts of nutrients. Appraisal of the nutrient enrichment problem in the Swan-Canning system must consider all three views of the data.

2 METHODS

Nutrient loads were computed using continuous streamflow measurements and weekly observed nutient concentrations.

2.1 Streamflow

Streamflow was measured at all sites using automatic digital logging equipment. Measurements of stage height taken at five minute intervals were converted to daily streamflow (m^3/day) via rating curves which were developed using standard metering techniques.

The automated stage measuring equipment reduced the frequency of station visits. Savings on station maintenance and data processing were partly offset however by the need for data modelling to fill gaps in the record caused by undetected equipment failure. Water yield estimates from comparable sites were used to fill these gaps in the daily flow record. For this initial report regression techiques were employed to model the stream discharge between catchments and to fill gappy data. Regression coefficients (r^2) were typically above 0.7 for this simple streamflow modelling.

2.2 Nutrient sampling and analyses

Water samples were collected weekly, with additional sampling after heavy rains, from the streams draining the 15 sub-catchments. All samples were cooled in ice and transported to the Chemistry Centre of Western Australia (CCWA) for analysis. Conventional methods were employed to measure the following parameters:

ammonium nitrogen	(NH_4-N),
nitrite plus nitrate nitrogen	(NO_3-N),
total nitrogen (persulphate)	(TN),
soluble reactive phosphorus (- 0.45μm)	(SRP),
total phosphorus (persulphate)	(TP),
conductivity.	(Cond).

2.3 Nutrient load calculations

Analytical results from the weekly nutrient sampling were expanded to daily concentrations by simple linear interpolation between observed concentrations. Daily nutrient load was computed as the product of daily discharge and nutrient concentration. Total annual load of each parameter was calculated by summing the daily loads over the year. Total annual load was divided by total annual discharge volume to produce annual flow-weighted concentrations of nutrients. For each catchment, water and nutrient yield per unit area (hectares) were calculated by dividing total annual stream discharge, and total annual nutrient load, by catchment area.

2.4 Constraints

The linear interpolation between measurements relies on the assumption that intermittant measurements of chemical concentrations reflect conditions between sampling. This assertion is debatable but research has shown that the interpolation technique can produce accurate results over an annual time-frame (Rekolainen *et al* 1991). The Swan River Trust recognises the need to modify sampling strategies to take account of large fluctuations in nutrient concentrations associated with high flow events (Cullen 1991). Future sampling will rely more on stream stage height samplers.

Calibration of regression models, used here to fill gaps in the streamflow record, showed that resulting load estimates are reliable, mainly because the time periods in which data was missing are relatively short. Nevertheless final analysis of catchment nutrient loading will employ a more sophisticated approach to modelling disharge in the ungauged catchments. This will involve the development of linnear transfer function models for sub-catchment hydrograph generation (Moodie 1979).

Because of logistical difficulties, streamflow and nutrient loads have never been measured in a considerable area of metropolitan Perth . This deficiency is being redressed by the Swan River Trust which is, in consultation with local government and other public agencies, estimating both groundwater inputs and inputs from the ungauged sections of the Swan-Canning catchment. A report covering nutrient loads from all sources up to the end of 1992 will be released by the middle of 1993.

3 RESULTS

Results for the period 1987 to 1990 will be discussed in two formats. In Section 3.1 rainfall, streamflow and nutrient loads between catchments and years are compared. For the sake of brevity discussion is limited to three typical catchments, those of the Avon River, Claisebrook main drain and Ellen Brook. The Avon was chosen as an example of a large rural catchment that spans an area including the Darling Scarp and eastern wheat-belt. The catchment of Claisebrook main drain is a typical metropolitan catchment and Ellen Brook a rural catchment located mostly on the coastal plain.

In Section 3.2 the data from all 15 monitored sub-catchments are described in summary. The data presented are averages from the monitoring period 1987-1990.

3.1 The Avon, Claisebrook and Ellen Brook Catchments

3.1.1 Streamflow

The Avon River catchment, with an area of some 119,000 km^2 is the largest of the monitored sub-catchments. In every year of the study the Avon River discharged the largest volumn of water into the Swan estuary. Streamflow of the Avon River was characterised by its seasonality and variability between years. Over the term of the project it carried between 210 and 350 million cubic metres (m^3) of water while averaging some 256 million m^3 per year (Table 3.1). The relationship between rainfall measured east of Mundaring and stream discharge is relatively poor (Figure 3.1).

The Claisebrook main drain, one of the smallest of the monitored catchments, discharged a relatively minor amount of water, between 5 and 5.5 million m^3 annually (Table 3.2). The low level of variability in annual streamflow, and the significant base flow component to streamflow is typical of an urban/industrial water catchment with high groundwater levels (Figure 3.2). The strong relationship between rainfall measured near the Claisebrook catchment and stream discharge is apparent in the graphs.

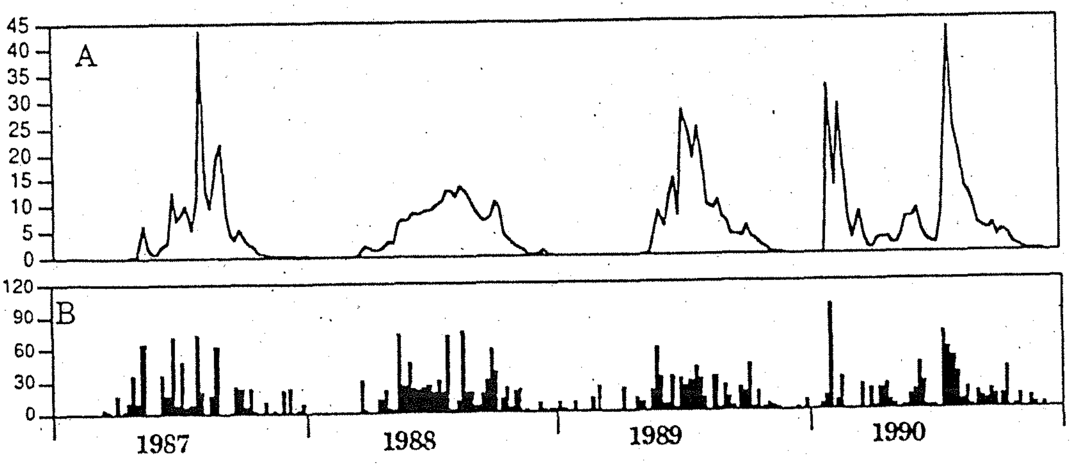


FIGURE 3.1: Graph A shows weekly streamflow (millions of cubic meters) in the Avon River 1987-1990. Graph B is a plot of weekly rainfall (mm) that fell in the catchment over same period.

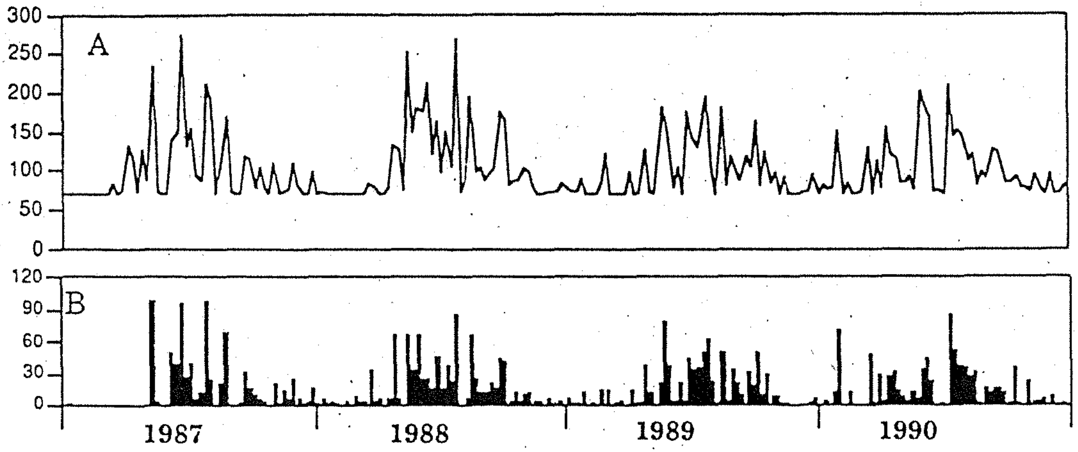


FIGURE 3.2: Graph A shows weekly streamflow (thousands of cubic meters) in Claisebrook 1987-1990. Graph B is a plot of weekly rainfall (mm) that fell in the catchment over same period.

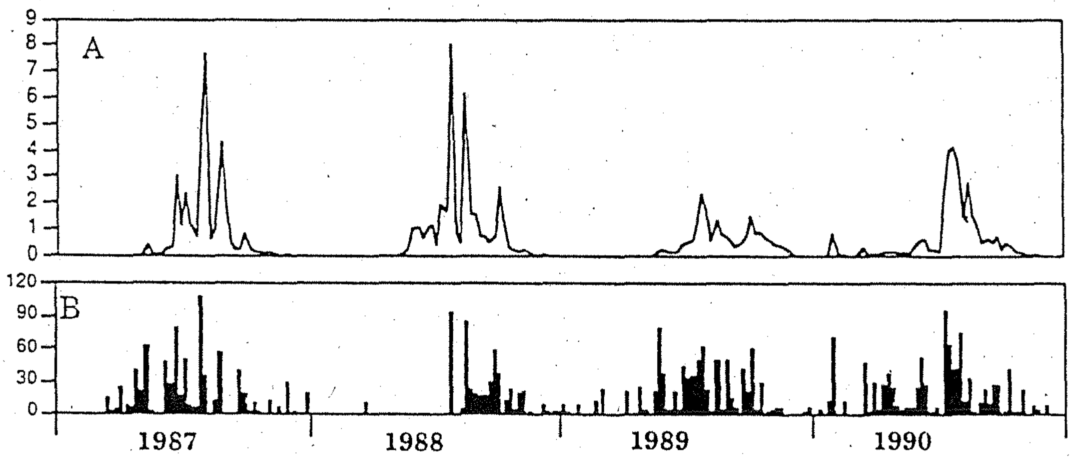


FIGURE 3.3: Graph A shows weekly streamflow (millions of cubic meters) in Ellen Brook 1987-1990. Graph B is a plot of weekly rainfall (mm) that fell in the catchment over same period.

In contrast to annual discharge from the Claisebrook catchment, streamflow in the Ellen Brook was highly variable, as it was in the Avon. The 700 km^2 of the Ellen Brook catchment contributed between 18 and 56 million m^3 of surface runoff annually (Table 3.3) and averaged about 30 million m^3 per year from 1987 to 1990. Like the Claisebrook, but for different reasons, the Ellen Brook data suggest a weaker relationship between rainfall in the catchment and streamflow (Figure 3.3). In this type of catchment the timing and pattern of rainfall relative to antecedent catchment wetness more strongly influenced streamflow than does the quantity of rain *per se*.

3.1.2 Nutrients

This section will discuss total loads of nutrients, the flow-weighted concentration and the areal yield of nutrients from each of the three example catchments

The Avon catchment

In every year the Avon River carried the greatest load of nutrients of any of the gauged streams. Annual nutrient loads were closely related to stream discharge and similarly variable between years (Table 3.1). Total nitrogen loads varied between about 375 and 170 tonnes/year and averaged some 290 tonnes per year over the five years of sampling. Phosphorus loads in the Avon were also characterised by their variation between years ranging between 9 tonnes in 1991 and 22 tonnes in 1989, averaging some 17 tonnes from 1987 to 1991. There was a poor correlation between the annual load of nitrogen and that of phosphorous over the study period (R=-0.59).

The nitrogen to phosphorus (N/P) ratio was generally very high. It ranged between 40:1 and 7:1, averaging about 23:1 over the four years of data examined here. Changes in the ratio of nitrogen to phosphorous in streamflow reflect complex dynamic processes between soils, contributing runoff and nutrients. Some of these processes include soil microbe influence on solubility and the rate of leaching from the soil, soil structure and ability to bind phosphorous as well as variations in the rate of denitrification and loss of nitrogen gas (N_2) to the atmosphere.

The proportion of inorganic forms of nitrogen was small (24%) in the Avon catchment. Similarly the soluble biologiocally available forms of phosphorus (SRP) were only about 13% of the total load. These results suggest that much of the phosphorus and nitrogen coming from the Avon catchment is as either particulate organic material or chemically bound to fine mineral particles. The WAWA have measured sediment loads in the Avon and found them to be considerable, indicating the need for stream lining in the Avon catchment to reduce silt loads entering the Swan estuary.

TABLE 3.1 Annual rainfall, discharge and nutrient loads for the Avon River 1987-1991. Flow-weighted concentration (FWC) and yields per hectare figures are annual averages.

Year	Rainfall (mm)	Discharge (10^6 m^3)	NH_3-N (tonnes)	NO_3-N (tonnes)	TN (tonnes)	SRP (tonnes)	TP (tonnes)
1987	662	211	16	33	167	2.5	24
1988	810	234	10	51	255	1.4	10
1989	596	233	18	78	318	1.6	22
1990	733	347	11	43	330	3.5	13
1991	570	261	47	141	375	2.6	9
Mean	700	256	14	51	267	2.2	17
FWC (mg/l)			0.05	0.2	1.04	0.009	0.07
Yield (kg/ha)			0.001	0.004	0.023	0.0002	0.0014

Mean proportion inorganic nitrogen	24%
Mean proportion inorganic phosphorous	13%
Mean N/P ratio	15.5
Mean NH_3/NO_3 ratio	0.26

Some points to note from the table are: 1) High variability in annual discharge and load; 2) High N/P ratio evidence of high retention of phosphorous in scarp soils; 3) Low proportion of inorganic nitrogen and normal proportion of ammonium-N to nitrate-N; 4) Low average flow-weighted concentration of total phosphorous.

The waters of the Avon River contained low concentrations of nutrients in every year, relative to Claisebrook main drain, Ellen Brook and to the other monitored streams. The concentration of both nitrogen and phosphorous varied little. Nitrogen ranged between 0.7 mg/l and 1.4 mg/l over the five years of monitoring and averaged about 1 mg/l while total phosphorous varied between a concentration of 0.03 mg/l and 0.1 mg/l and averaged 0.06 mg/l. These results are not surprising considering the very low amounts of nutrients leaving each hectare in the catchment, which averaged less than 25 gm/ha/yr for nitrogen, with very little variation between years (sd=0.07), and only 1 gm/ha/yr of phosphorus, again with little variation (sd=0.006).

The Claisebrook catchment

Predictably, considering their relative areas, total loads of nitrogen and phosphorous exported from Claisebrook main drain were much lower than those from the Avon catchment (Table 3.2). There was some variability in annual nutrient loads between years for the Claisebrook catchment but much less than that from catchments such as the Avon. From 1987 to 1990 nitrogen loads ranged between 8 and 11 tonnes per year and averaged 10 tonnes/year. The highest phosphorus load of 1.2 tonnes was carried in 1987 compared to a low of 0.8 tonnes in 1990. Phosphorous loads averaged just under one tonne per year.

The average N/P ratios in surface runoff were typically much lower in this catchment than in the Avon varying between 7:1 and 15:1 with a annual average of 11:1. To some extent this reflects both the mobilisation of dissolved nitrogen forms from applied and discharged sources, and the generally poorer phosphorous retention capacity of the Claisebrook soils (or perhaps the area of paving) in comparison to the soils of the Avon catchment.

The proportion of inorganic forms of nitrogen were relatively large on average (50%), with a generally very low percentage of ammonium-nitrogen in each year. Similarly, the proportion of soluble forms of phosphorus to total (24% on average) tended to be higher than those for the Avon Catchment.

TABLE 3.2: Annual rainfall, discharge and nutrient loads in Claisebrook main drain 1987-1990. Flow-weighted concentration (FWC) and yields per hectare are annual averages

Year	Rainfall (mm)	Discharge (10^6 m^3)	NH_3-N (tonnes)	NO_3-N (tonnes)	TN (tonnes)	SRP (tonnes)	TP (tonnes)
1987	757	5.2	1.00	3.23	8.50	0.15	1.18
1988	907	5.5	0.96	6.01	10.77	0.15	0.71
1989	820	5.2	1.22	4.88	10.09	0.34	1.00
1990	809	5.3	0.66	3.56	10.40	0.24	0.81
1991	759						
Mean	823	5.3	0.96	4.42	9.94	0.22	0.92
FWC (mg/l)			0.18	0.84	1.88	0.04	0.18
Yield (kg/ha)			0.6	2.8	6.2	0.14	0.58

Mean proportion inorganic nitrogen	54%
Mean proportion inorganic phosphorous	24%
Mean N/P ratio	10.8
Mean NH_3/NO_3 ratio	0.22

Points to note are: 1) Relatively low variability in stream discharge and nutrient loads; 2) High proportion of inorganic nitrogen and normal proportion of ammonium-N; 3) Low proportion of inorganic phosphorous and potential therefore for detention basins as management option; 4) Moderate flow-weighted concentration of total phosphorous.

In every year the flow-weighted concentration of nutrients in Claisebrook main drain was greater than that of the Avon River. While varying between 1.6 mg/l and 2 mg/l over the period of the project the flow-weighted concentration of nitrogen averaged about 1.9 mg/l per year. Phosphorous concentration also varied little between years in averaging 0.18 mg/l per year (sd=0.04). Flow-weighted mean concentrations for both nitrogen and phosphorous were twice those of the Avon River water between 1987 and 1990. As expected considering the flow-weighted figures, the average annual yields per hectare for total nitrogen (<6.2 kg/ha/yr), and total phosphorus (<0.6 kg/ha/yr), were considerably higher than those for the Avon catchment.

The Ellen Brook catchment

Annual loads of total phosphorous in Ellen Brook were comparable to those carried by the much larger Avon River (Table 3.3). Annual loads of nitrogen however were considerably below those of the Avon. Like the other measured catchments there was considerable variability in loads between years. The largest load of nitrogen was measured in 1991 (118 tonnes), the same year as that for the Avon, and the lowest load in 1989 (40 tonnes). The total phosphorus load ranged between 10 tonnes and 44 tonnes annually. Over the monitoring period total nitrogen and phosphorus loads averaged 70 tonnes and 25 tonnes respectively. The N/P ratio for runoff from this catchment was considerable below that of both the Avon and Claisebrook catchments as well as being less variable between years. It ranged between 4:1 and 2:1 and averaged about 3:1. These data point to a considerable enrichment of Ellen Brook with phosphorus. The average phosphorus load coming from the Ellen Brook catchment was over 40% higher than that coming from the entire 119,000 km^2 of the Avon catchment.

The proportion of inorganic forms of nitrogen to total was small, only 17% on average relative to total nitrogen. There with a very high percentage of ammonium-nitrogen which averaged over 5 tonnes annually. In contrast to the proportion of soluble nitrogen to total, the proportion of soluble phosphorus to total phosphorous were very high, averaging about 60% of the total load per year. The high ammonium-nitrogen and soluble phosphorus loads are indicative of significant faecal contamination in the Ellenbrook catchment.

TABLE 3.3: Annual rainfall, discharge and nutrient loads for Ellen Brook 1987-1991. Flow-weighted concentration (FWC) and yields per hectare are annual averages.

Year	Rainfall (mm)	Discharge (10^6 m^3)	NH_3-N (tonnes)	NO_3-N (tonnes)	TN (tonnes)	SRP (tonnes)	TP (tonnes)
1987	757	33	4.4	3.9	60	11.8	22
1988	907	35	8.5	3.5	67	19.8	25
1989	820	19	3.9	4.0	41	7.2	10
1990	809	29	3.0	6.5	60	11.6	26
1991	759	56	6.9	4.8	119		44
Mean	719	35	5	5	70	10	25
FWC (mg/l)			0.2	0.2	2.0	0.4	0.7
Yield (kg/ha)			0.08	0.07	0.9	0.2	0.3

FWC = Flow-weighted concentration

Mean proportion inorganic nitrogen	17%
Mean proportion inorganic phosphorous	61%
Mean N/P ratio	2.74
Mean NH_3/NO_3 ratio	1.11

Points to note are: 1) High variability of discharge and nutrient loads; 2) Low flow in 1989 relative to rainfall hence low nutrient load; 3) Low N/P suggesting enrichment with phosphorous; 4) Low proportion of inorganic nitrogen but high proportion of ammonoium-N suggesting possible feacal pollution; 5) Very high flow-weighted phosphorous concentration.

The mean concentration of nutrients in the waters draining this catchment, as well as the areal nutrient yield, confirm that Ellen Brook is a "hot-spot" and a significant source of nutrients to the Swan River. The average flow weighted concentration of both nitrogen and especially phosphorous were consistently very high during the monitoring period. Total nitrogen concentrations in Ellen Brook averaged 2 mg/l (sd=0.14) and 0.7 mg/l for total phosphorus (sd=0.14). By way of comparison with other eutrophic systems in Western Australia the levels of phosphorus in Ellen Brook are double those observed in the polluted Harvey River (Stage 2 ERMP).

Average annual nutrient yields from the catchment total nitrogen, and total phosphorus were less than those from the Claisebrook catchment. This suggests that there are large areas of the Ellen Brook catchment which contribute relatively small amounts of water and nutrients, and other areas that contribute very large quantities of nutrients to the stream. The phosphorus yield per hectare from the Ellen Brook catchment were 200 times the rate of the entire Avon catchment.

3.2 Average streamflow and nutrient loads

This section will discuss results for all fifteen catchments for which nutrient loads were monitored by the Swan River Trust. The data discussed are averages calculated over the period 1987-1990 (Tables 3.4 and 3.5).

3.2.1 Nutrient loads for 15 catchments

The 15 monitored sub-catchments contributed a total of about 60 tonnes of phosphorous and 500 tonnes of nitrogen per year to the Swan-Canning river system (Table 3.4). Almost 85 percent of the phosphorous and 78 percent of the nitrogen was supplied by just four streams, Ellen Brook and the Avon, Canning and Southern Rivers.

The Avon River and Ellen Brook between them were responsible for over 65 percent of the total annual average load of phosphorous. Ellen Brook contributed the largest load, an average total of about 20 tonnes annually, and the Avon River carried a similar load averaging some 17 tonnes of phosphorous per year over the four years 1987-1990. The Avon River, which drains the largest of the sub-catchments, carried by far the greatest load of nitrogen, some 270 tonnes on average per year of monitoring. Ellen Brook, the Canning River and Southern River were also important contributors of nitrogen.

TABLE 3.4 Average rainfall, stream discharge and nutrient loads for the 15 sub-catchments of the Swan-Canning river system averaged for the period 1987-1990.

Sub-catchment	Area (km2)	Rainfall (mm)	Discharge (1000's m^3)	NH_3-N (tonnes)	NO_3-N (tonnes)	TN (tonnes)	SRP (tonnes)	TP (tonnes)
Avon River	119000	700	256311	13.6	51	267	2.2	17.2
Bayswater M D	26	823	10118	4.9	6	17	0.4	4.9
Canning River	147	823	17899	1.0	15	24	0.3	1.3
Southern River	149	823	20753	1.7	14	35	3.5	6.0
Claisebrook M D	16	823	5288	1.0	4	10	0.2	0.9
South Belmont M D	10	823	2709	0.7	1	4	0.3	0.6
Mills Street M D	12	823	4474	2.2	3	10	0.5	1.2
Ellen Brook	664	748	29085	5.0	4	57	12.6	20.6
Helena River	161	823	8539	0.8	4	10	0.2	0.7
Jane Brook	135	778	16408	0.6	6	13	0.2	0.6
Blackadder Creek	13	959	2265	0.8	3	3	0.1	0.1
Bennett Brook	99	823	8981	0.6	5	14	0.3	1.2
Bannister Creek	23	823	7488	1.1	3	12	0.5	0.9
Susannah Brook	19	845	2387	0.2	2	4	0.1	0.3
Yule Brook	53	876	11343	0.8	6	15	0.4	1.2
TOTAL	120526		404048	35	129	494	22	58

3.2.2 Flow weighted means for 15 catchments

Two streams in particular contained very high concentrations of nitrogen and phosphorous, Ellen Brook and Bayswater main drain. High concentrations of phosphorous were found in Southern River and Mills Street main drain with the later also containing the highest concentration of nitrogen of the all the monitored streams. In comparison Claisebrook main drain and South Belmont Main Drain contained relatively moderate levels of phosphorous but amongst the highest flow-weighted concentrations of nitrogen. The Avon, Canning and Helena Rivers, the Bennett, Susannah and Yule Brooks, and Blackadder and Bannister Creeks all contained low concentrations of phosphorous. However, many of these streams show evidence of some contamination with nitrogen. The flow-weighted data suggest that only Jane Brook is not enriched with nutrients. It had very low average concenrations of both nitrogen (0.8 mg/litre) and phosphorous (0.04 mg/litre).

Broadly speaking, average phosphorus concentrations were below 0.1 mg/l for catchments east of the scarp, from 0.1 to 0.3 mg/l for urban catchments, and above 0.4 mg/l for heavily polluted streams. Relationships between catchment landuse and soil characteristics are being analysed further.

TABLE 3.5 Flow-weighted mean concentrations for streams draining into the Swan-Canning estuary. Figures are averaged for the period 1987-1990.

Sub-catchment	NH_3-N (mg/litre)	NO_3-N (mg/litre)	TN (mg/litre)	SRP (mg/litre)	TP (mg/litre)
Avon River	0.05	0.20	1.04	0.01	0.07
Bayswater M D	0.48	0.60	1.69	0.04	0.49
Canning River	0.05	0.86	1.35	0.02	0.08
Southern River	0.08	0.68	1.69	0.17	0.29
Claisebrook M D	0.18	0.84	1.88	0.04	0.17
South Belmont M D	0.26	0.42	1.44	0.11	0.21
Mills Street M D	0.49	0.56	2.19	0.12	0.26
Ellen Brook	0.17	0.15	1.97	0.43	0.71
Helena River	0.10	0.49	1.17	0.02	0.08
Jane Brook	0.04	0.37	0.79	0.01	0.04
Blackadder Creek	0.36	1.25	1.16	0.03	0.06
Bennett Brook	0.06	0.55	1.59	0.04	0.14
Bannister Creek	0.15	0.45	1.54	0.07	0.13
Susannah Brook	0.10	0.68	1.55	0.03	0.12
Yule Brook	0.07	0.53	1.30	0.03	0.11

FIGURE 3.6 Average water and nutrient per hectare from each of the sub-catchments. Data is averaged over the period 1987-1990.

Sub-catchment	Discharge m^3/Ha	NH_3-N (kg/ha)	NO_3-N (kg/ha)	TN (kg/ha)	SRP (kg/ha)	TP (kg/ha)
Avon River	22	0.001	0.004	0.022	<0.001	0.001
Bayswater M D	3859	1.85	2.32	6.51	0.16	1.88
Canning River	1099	0.06	0.95	1.49	0.02	0.08
Southern River	1394	0.11	0.95	2.36	0.24	0.40
Claisebrook M D	3296	0.60	2.76	6.20	0.14	0.58
South Belmont M D	2779	0.71	1.17	3.99	0.29	0.57
Mills Street M D	3883	1.89	2.19	8.50	0.46	1.00
Ellen Brook	438	0.07	0.07	0.86	0.19	0.31
Helena River	532	0.05	0.26	0.62	0.01	0.04
Jane Brook	1212	0.05	0.45	0.95	0.01	0.04
Blackadder Creek	1800	0.65	2.25	2.09	0.06	0.11
Bennett Brook	912	0.06	0.50	1.45	0.04	0.13
Bannister Creek	3404	0.50	1.53	5.25	0.24	0.43
Susannah Brook	23866	2.48	16.33	36.96	0.71	2.93
Yule Brook	2140	0.16	1.13	2.79	0.07	0.23

3.2.3 Catchment yield per unit area

The yields per hectare of nitrogen and phosphorous from the Susannah Brook catchment were very high over the monitoring period. The data suggest that every hectare in this small cartchment yielded an average of 40 kilograms of nitrogen and 3 kilograms of phosphorous per year. Clearly there is a major point source of nutrients in this catchment. Bayswater, Claisebrook, South Belmont and Mills Street main drains also yielded large quantities of nutrients per hectare per year. The Ellen Brook and Helena River yielded small quantities of nitrogen and phosphorous for every hectare of catchment. The Avon River catchment yielded very small average quantities of both phosphorous and nitrogen per hectare between 1987 and 1990.

On average, between 1987 and 1990, Blackadder Creek, Yule Brook and the Canning River catchments supplied moderate amounts of nitrogen per hectare relative to the other catchments. Ellen Brook yielded very small amounts of nirogen but relatively high quantities of phosphorous per hectare supporting the earlier observation that the Ellen Brook catchment appears to be contaminated by phosphorous rather than nitrogen

4 CONCLUSION

Rural catchments on the coastal plain surrounding Perth are a major source of dissolved nutrients especially phosphates and ammonium-nitrogen. These catchments contribute the majority of their streamflow and nutrient loads in the coldest months when low lying fertilized pastures are water logged. There are a number of possible point sources that could be contributing significant loads of faecal material to Ellen Brook, including piggeries and sewerage treatment facilities. Diffuse sources would include runoff from the broad acre sheep and cattle grazing carried out in the catchment.

5 ACKNOWLEDGMENTS

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Soils, land use, nutrient losses and algal blooms in the Swan-Canning estuary.

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Abstract

Principal factors affecting the trophic status of the Swan-Canning estuary are explored. Phosphorus is assumed to be the key factor, controlling primary production in most of the Swan-Canning estuary. Nitrogen and iron levels are the next most important factors. Tributary sources of P are identified in three main, soil-type determined, areas : the Avon catchment (duplex soils), the Darling Plateau (lateritic soils) and the Coastal Plain (sandy soils). Different types of land use in each of these areas lead to varying rates of accumulation of P in soils. Annual rates of accumulation can vary from 5-10 kg P/ha (low density residential, broad acre agriculture) to more than 500 kg P/ha (horticulture). This continuous accumulation of P in soils is transmitted to groundwater and surface water. Travel times to groundwater and surface water strongly depend on the adsorption capacities of soils for P and can vary from as short as a few years per metre soil (sandy soils) to as long as centuries or millennia.

Concentrations of phosphate in the Avon River and Susannah Brook at their entries to the Swan River are low. Concentrations of phosphate in Ellen Brook on the other hand are the highest of all major tributaries. Concentrations of iron are also high in Ellen Brook. High levels of nitrate are encountered locally in the lower reaches of the Swan River, coming from groundwater.

Research needs, relevant to future management of the Swan-Canning estuary, are identified.

1. Introduction

A healthy aquatic ecosystem supports a balanced chain of interdependent organisms. This chain starts with primary producers (bacteria, phytoplankton, macroalgae, seagrasses) and goes through grazers (zooplankton, crustaceans, insects, planktonic fish and birds) to piscivorous fish and birds (e.g. Hodgkin et al., 1980).

The availability of phosphate from sediments and the water column determines the level of primary produced biomass. As primary production increases, algae dominate over other organisms in the food chain. Algal cells contain between 0.5-1.5% of dry matter as phosphorus. If it is assumed that all P is used to produce algal biomass and that biomass has a water content of ≈ 80%, then 25 mg/l of wet algal biomass can be produced if the concentration of phosphate in the water column is 0.05 mg P/l. This translates into (wet algal cell biomass ≈ 10^{-10} g) 10^5 - 10^6 cells per ml water. Algal cell densities greater than 10^4 cells/ml are considered as significant blooms.

At a concentration of 0.05 mg P/l, a body of water has a 50% probability of becoming eutrophic (Vollenweider, 1985). Available phosphate from sediments is often an order of magnitude greater than the amount of phosphate present in the water column. Successions of different species of algae and bacteria mobilise phosphate from sediments and add it to the water column. The variation in accession to the water column of phosphate from sediments accounts in part for the observed variation in trophic status for given concentrations of phosphate in the water. Other factors affecting the trophic status of a water body are mainly physical : flow intensity, turbulence, stratification, temperature, turbidity, colour.

The ratio of available nitrogen to phosphate affects the succession of species of algae in a water body. Nitrogen fixing algae (blue green algae) are favoured at N/P ratios that are lower than ratios in algal cells (N/P <5). Blue green algae require relatively high levels of iron and molybdenum for their nitrogen fixing enzymes. Low levels of iron can cause primary production in a water body to be limited by nitrogen rather than phosphorus.

From a management perspective the principal factors affecting the trophic status of the Swan-Canning estuary need to be known. Only then can effective management strategies be developed with a reasonable chance of success.

2. Trophic status of the Swan-Canning estuary

2a. Principal factors

Phosphorus is likely to be the key element in determining the trophic status of the middle (Narrows-Kingsley Rd) and upper reaches of the Swan River as well as the major part of the Canning River.

Sources of phosphorus are sewage and fertilisers which enter surface water courses, feeding into the Swan-Canning estuary, from the following:

The Avon River (<- Mortlock River, Yulgan Brook, Brockman River)

Ellen Brook
Sussanah Brook
Jane Brook
Helena River
Canning River
Drains (Bayswater Main Drain, Claise Brook, Airport Drain)
Point sources short-circuiting into river (waste disposal sites, race courses, golf courses)

The phosphorus exported from these sources should be quantified as total phosphorus leached from the soils (throughflow) and as phosphorus from surface runoff (storm events). The contribution of particulate and dissolved phosphorus to these sources needs to be identified. Particulate phosphorus is not immediately available to algae, but rapidly increases available phosphate in river sediments.

Primary production could well be limited by nitrogen in the lower reaches of the Swan-Canning estuary as iron concentrations are often less than 0.01 mg/l. It is interesting to note that groundwater from springs in limestone outcrops in the lower reaches of the estuary was found to have $N\text{-}NO_3$ concentrations of the order of 5-10 mg/l (Table 2).

2b. Effects of land use

Total input of phosphorus in a catchment is determined by land use. Land use in the catchment of the Avon River system is mainly agricultural. Wheat is the main crop grown often in rotation with pasture and lupins. Annual inputs of P on wheat are 10-12 $kg.ha^{-1}$. Export in grains is about 2.5 kg $P.ha^{-1}$ resulting in net annual accumulation of 7.5-9.5 kg $P.ha^{-1}$ (Bowden, 1992).

Results of surveys of input rates of P and N in residential and agricultural areas of the Darling Plateau are shown in Figure 1. Annual input rates for P vary from less than 5 kg/ha in rural residential areas to 100 kg/ha in orchards (Figure 1) and 700 kg/ha in intensive horticulture (Sharma et al., 1991). In Figure 2 inputs of P and N from a residential area on the Coastal Plain in metropolitan Perth (housing density 10/ha) are compared with those from residential areas on the Darling Plateau. In Table 1 the relative contributions of P to total P input in residential areas from garden fertilisers, human waste (excluding detergents), household detergents and animal (pets) wastes are shown. The contribution of P from sewage (= human waste+detergents) relative to total input of P varies from ≈ 35-80 %. It decreases with increasing use of garden fertilisers and decreasing housing density.

2c. Effects of soil type

Amounts of phosphate leached from duplex soils in the Avon River, Mortlock River, Yulgan Brook and Brockman River catchments are small. Most soils are loams over clays and only a small proportion of soils in these catchments is predominantly sandy. Adsorption capacities for phosphate of most soils would be of the order of 100 kg $P.ha^{-1}$ per 10 cm soil. More data are necessary, however, to substantiate this figure. **Adsorption capacity is defined as the amount of ortho-phosphate (as P) added to the soil resulting in a solution concentration after 12 months of between 0.05 - 0.1 mg P/l.**

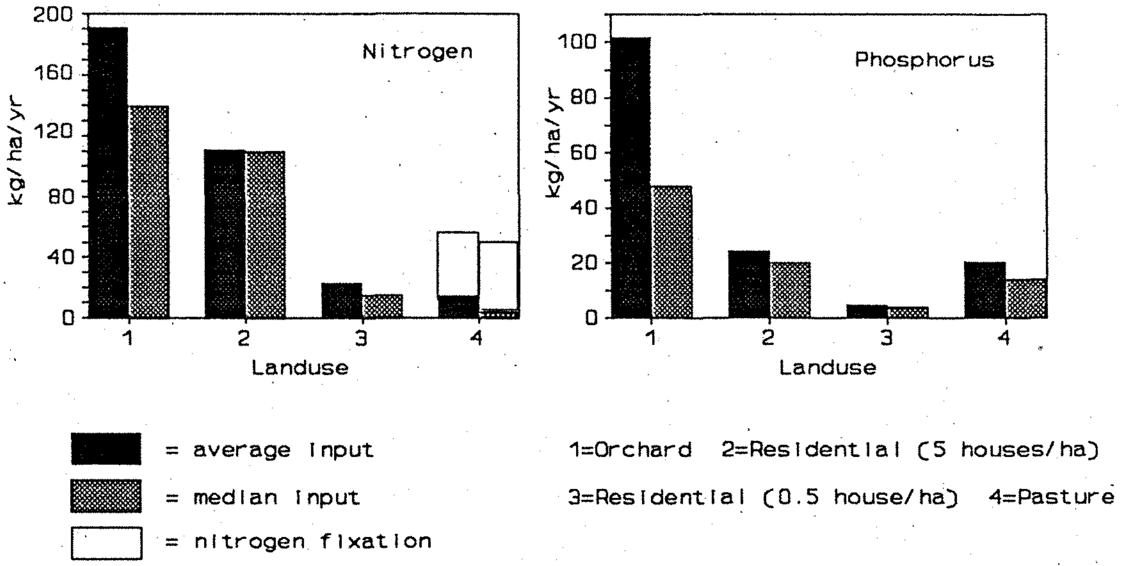

Figure 1 Average and median annual rates of input for N and P in relation to land use on the Darling Plateau.

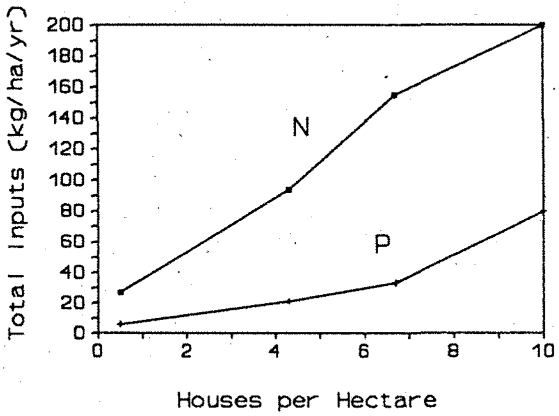

Figure 2 Total rates of input of N and P in unsewered residential areas in relation to housing density.

Table 1 Percentage contributions in residential areas of P from garden fertilisers, human waste (excluding detergents), household detergents and animal (pets) wastes

Area / houses per ha	Ballajura / 10	Gooseberry Hill / 6.7	Mundaring / 4.3	Susannah Brook / 0.5
Contribution to total P input from :	- % -			
garden fertilisers	50	13	7	53
human waste	25	41	41	17
household detergents	17	33	40	17
animal waste	8	13	12	13

Aspects that need further investigation in the Avon River catchment are contributions from particulate P in surface runoff and from local "hot spots" such as sandy soils and soils irrigated with sewage effluent.

Amounts of phosphate leached from the lateritic soils of the Darling Plateau are small. Concentrations in through-flow are mostly less than 0.01 mg P/l. Suspended particulate matter contributing to turbidity in runoff from surface horizons consists mainly of kaolinite. The associated suspended load of phosphorus is negligible (Turner et al., 1991). Occasionally after storm events, short bursts of phosphorus containing particulate matter from surface runoff are detected. Many soils have adsorption capacities for phosphate in excess of 500 kg $P.ha^{-1}$ per 10 cm depth. Additional storage capacity of phosphate through formation of the mineral hydroxyapatite is likely but, because of extremely slow rates of formation, has never been observed. *Present exports of P from the Darling Plateau to the Swan-Canning estuary are small.*

Amounts of phosphate leached from sandy soils to streams and drains in the Swan Coastal Plain are high in many areas. The contribution of particulate phosphorus from surface runoff is small. The surface horizons of the sandy soils are highly leached and have very little capacity to adsorb phosphate. *Adsorption capacities are often less than 5 kg $P.ha^{-1}$ per 10 cm depth. Despite this, concentrations of P found in groundwater are small and further work is necessary into characterisation of (subsurface) transport and discharge (i.e. to drains) of P.*

2d. Travel times of phosphate

From sections 2b and 2c it follows that for most types of land use there will be a steady net annual accumulation of phosphate in soils. This net accumulation translates in to a steady concentration of phosphate moving through the soil profile. This concentration is simply given by the ratio of annual accumulation of phosphate (section 2b) and the annual amount of water recharging groundwater. Travel times of phosphate through soils to groundwater and surface water are a function of recharge rate to groundwater, rate of accumulation of phosphate in soil and the soil adsorption or distribution coefficient for phosphate (Gerritse, 1990, 1992).

An appreciation of travel times and concentrations of phosphate accumulating in soils of the various catchments affecting the Swan-Canning estuary is crucial to future management. The potential increase of phosphate levels in the estuary and the time scale involved can then be estimated.

Travel times of phosphate in one metre of soils in the Avon River catchment would be of the order of centuries. Depending on type of land use (Figure 1) travel times of phosphate in one metre of soils in the Darling Plateau would range from a century to several millennia. Soils of the Swan Coastal Plain would show travel times for phosphate ranging from 1 year to ≈ 50 years per metre. All these figures are first estimates and need further substantiation.

2e. Monitored levels of chloride, phosphate, nitrate, iron and molybdate

Annual variations of concentrations of chloride, phosphate and iron in depth profiles of the water column are shown in Figure 3 for two sites in the Swan River for the period 1989-1991. One site is upstream near Guildford (Kingsley Rd) and the other site is downstream opposite Dalkeith (Lucky Bay). Corresponding levels of nitrate and nitrite are given in Figure 4. Data for ammonium and organic nitrogen are not available, though data for other sites (Henderson et al., 1983) show that ammonium-N dominates.

Concentrations of molybdate in the Swan River for a large number of sites are shown in Figure 5 as a function of the chloride concentration. On average the ratio of Mo/Cl is similar to the ratio of Mo/Cl in ocean water (≈ 10 µg Mo for every 20 g Cl). However, large fluctuations occur during algal blooms. In Figure 5 this is indicated with arrows for a bloom of a dinoflagellate in the Maylands area (April 1991). Concentrations of phosphate in the water column during this bloom were very high (0.5-1 mg P/l).

Concentrations of iron in the water column also fluctuate strongly in relation to algal blooms. About 90 % of iron in the water column was tied up with algal cells during the bloom of dinoflagellates at Maylands. It is difficult, however, to distinguish between the amounts of iron and molybdate adsorbed to the outside cell walls of algae and amounts actually taken up by algae.. *More work in this area is required as it relates directly to quantifying the limiting factors for algal growth in the Swan-Canning estuary.*

In Table 2 results are given of a limited monitoring of sources contributing nutrients to the Swan-Canning estuary. Noteworthy are the very high levels of both phosphate and iron coming from Ellen Brook and the high levels of nitrate in groundwater in the East Fremantle area. Most of the iron coming from Ellen Brook (>99%, determined after digestion) is complexed to dissolved organic matter. *The interaction of these iron complexes with phosphate and their fate in the Swan River requires further study as Ellen Brook is an important source of both phosphate and iron.*

Table 2 Chemical analysis data on some sources of nutrients along the Swan River.

location	period	Cl	P-PO_4	N-NO_3	Fe	Mo	B/Cl
		- mg/l -				µg/l	mg/g*10^{-3}
Upper Swan (Avon)	4/12/91-16/1/92	2000-4000	0.001-0.007	0.005	0.2-0.7	0.07-0.25	0.1
Ellen Brook	4/12/91-16/1/92	300-600	0.25-0.5	0.00-0.2	1.5-3	0.05-0.4	0.1-0.2
Helena River	11/9/89-14/6/90	150-450	0.005-0.02	0.02-0.2	0.06-0.4	-	0.3-0.5
Bayswater Main Drain	17/8/89-9/4/91	30-240	0.004-0.06	1	0.25	1.5	-
Claise Brook	9/4/91	20	0.04	0.3	0.15	2.0	-
Kennedy Memorial Fountain	30/4/91	160	0.004	2.1	0.007	0.01	0.1
Spring nr. Point Walter	27/11/90	1200	0.025	5	0.000	0.3	0.3
Groundwater nr. Bicton	1986	180	-	11.5	-	-	-

Borate from laundry detergents is more mobile in soils than phosphate (Gerritse et al., 1990). And the boron to chloride ratio (B/Cl) in Table 2 can be a useful indicator of the contribution of sewage to phosphate. The B/Cl ratio of ocean water is about $0.25.10^{-3}$ mg/g and dominates the ratio in the Swan-Canning estuary in most areas. Ratios in tributary sources above $0.1.10^{-3}$ indicate a possible contribution from sewage. *Further work is necessary into quantifying hydrochemical ratios (e.g. B/Cl, Cd/P, S/Cl, K/Cl) and other parameters (e.g.* $^{18}O/^{16}O$ *isotope ratio in* PO_4*) in terms of specific sources of phosphate.*

3. Conclusions

If it is assumed that phosphorus, nitrogen and iron are important elements in controlling eutrophication of the Swan-Canning estuary and thus algal growth, the following research needs can be identified:

1- Quantifying diffuse and point sources in terms of fluxes to major tributaries of particulate and dissolved P and total N.
2- Calculating the time scale of the potential increase in phosphate levels from transport of phosphate through the soil profile in different catchments to groundwater and surface water.
3- Quantifying the isotopic composition of PO_4 and hydrochemical ratios in terms of specific sources of phosphate.
4- Studying the fate of iron complexes and phosphate from Ellen Brook.
5- Quantifying the effects of iron and dissolved organic matter in limiting algal growth.
6- Investigating the importance of sediments in accumulating P and releasing P to the water column.
7- Extensive monitoring of chemical, physical and biological parameters in the water column.

Information from research areas 1-3 would make it possible to select areas where changes in land use and/or agricultural practices would lead to reduced fluxes of nutrients to the Swan-Canning estuary. It must be realised in this context that contributions of nutrients from diffuse sources are difficult to control and time scales involved in managing these sources can be much greater than a human life time.. Point sources on the other hand can be controlled more easily and quicker.

Information from the other research areas (4-7) would lead to a better understanding of conditions under which algal blooms develop. This is important as, given urban and agricultural activities in the catchments, some degree of eutrophication of the Swan-Canning estuary will always occur. Procedures to prevent or control algal blooms will have to be based on a conceptual model, built on information from research areas 4-7.

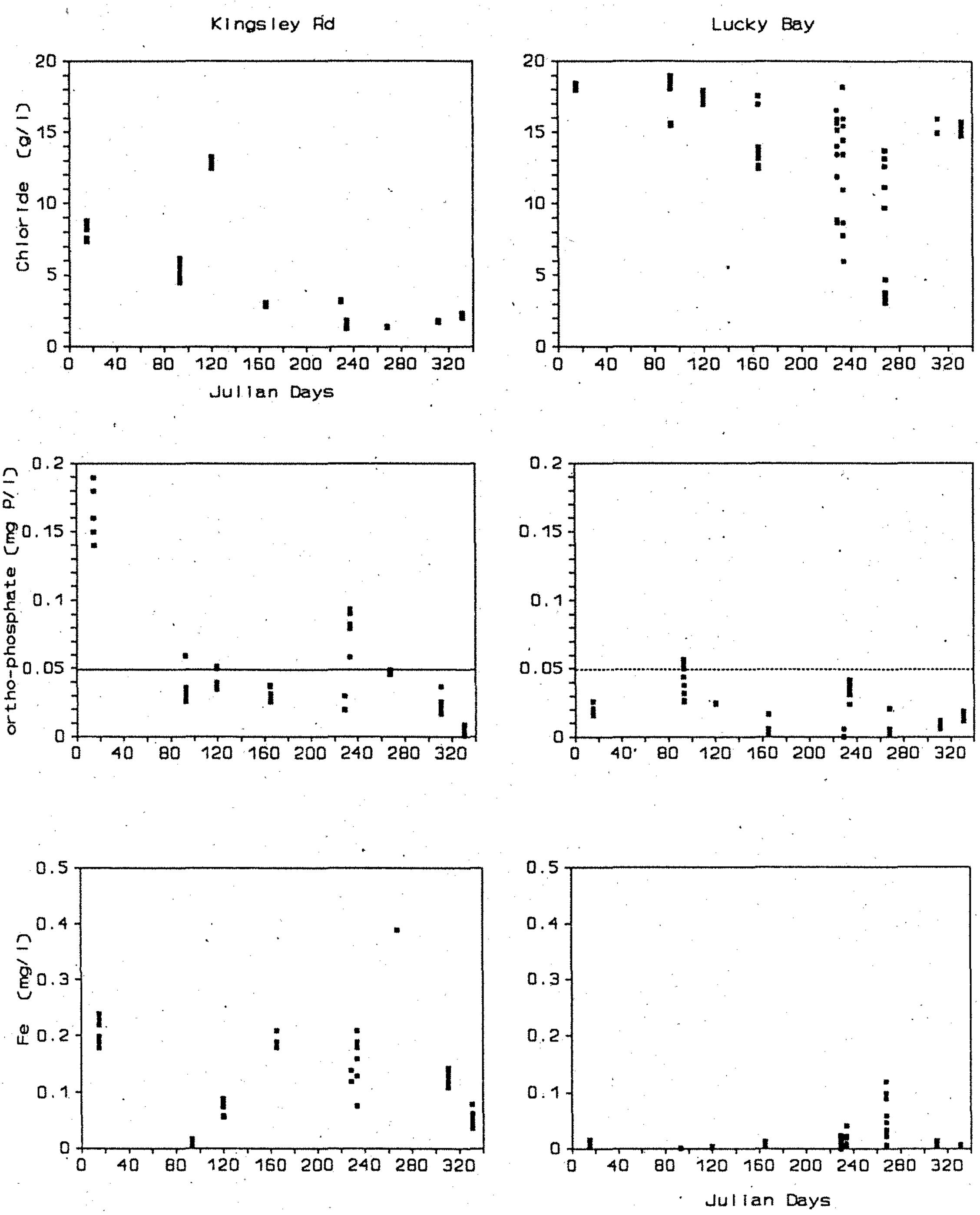

Figure 3 Annual changes (period 1989-1991) in the water column for chloride, phosphate and iron at two sites in the Swan River. Data (left side) are for a site off Kingsley Rd near Guildford and (right side) for Lucky Bay opposite Dalkeith.

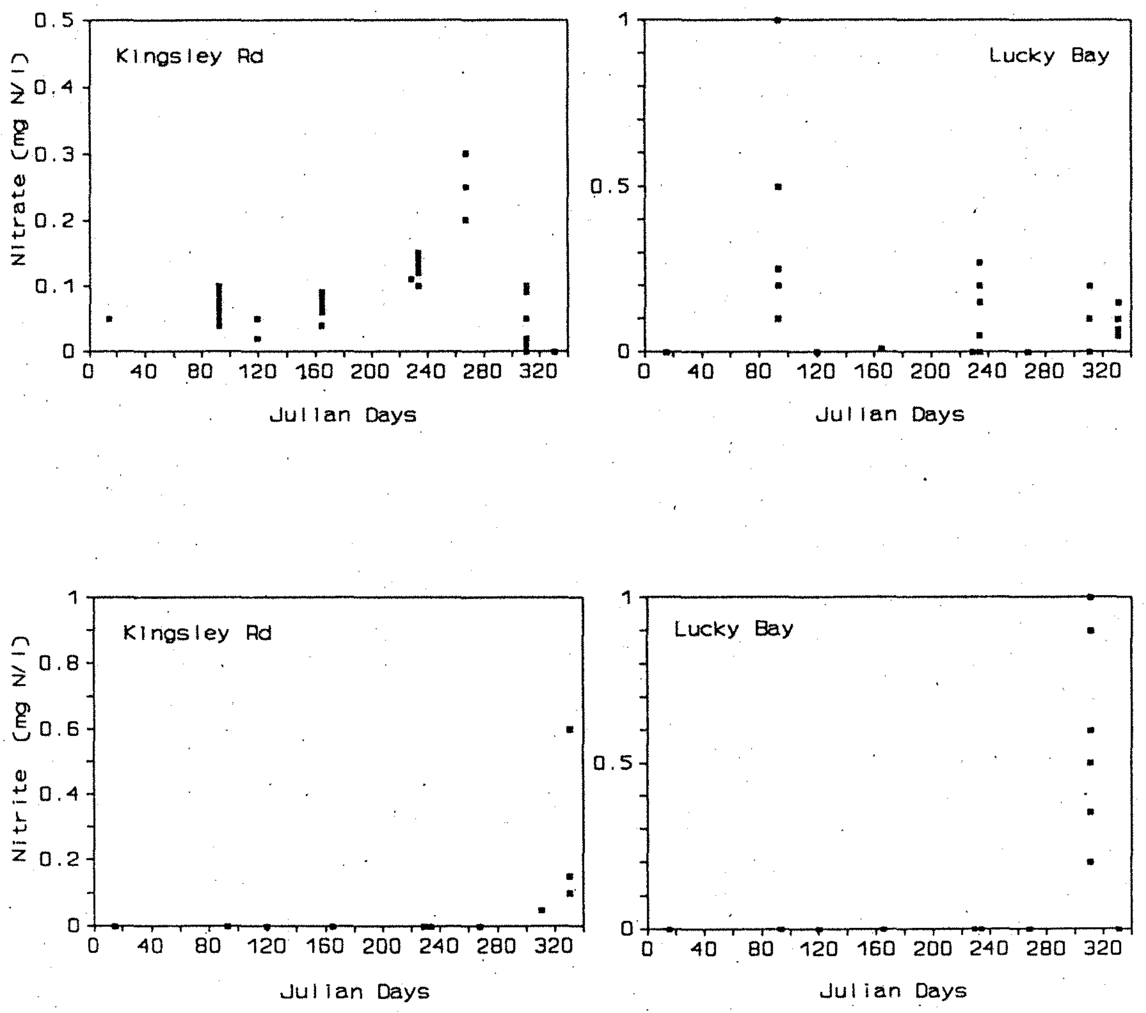

Figure 4 Time courses (period 1989-1991) for concentrations in the water column of nitrite and nitrate at two sites in the Swan River.

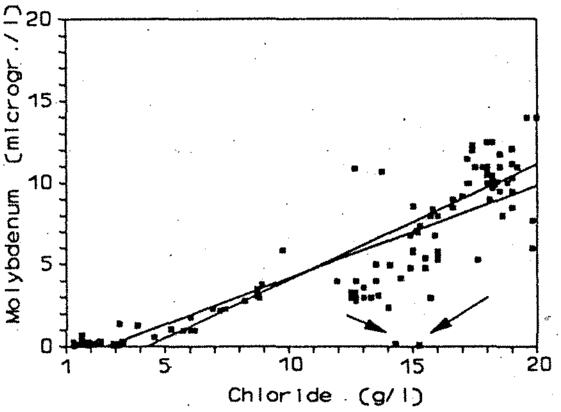

Figure 5 Molybdate concentrations in the water column at a number of sites in the Swan-Canning estuary as a function of chloride concentration. Arrows indicate measurements during a bloom of dinoflagellates in the Maylands area (April 1991).

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3.0

The estuary

HYDRODYNAMICS OF THE SWAN-CANNING ESTUARY

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1. Introduction

An understanding of the hydrodynamics of the Swan-Canning estuarine system plays an important role in calculating the assimilative capacity. Little previous detailed work has been carried out in this area, most modern investigations follow the work of Spencer (1956) who describes the results of an intensive sampling programme from 1951 to 1954. Jack (1977) analysed data from July 1974 to July 1975, with particular emphasis on de-oxygenation of bottom waters due to heavy winter salinity stratification. Silberstein (1979) also presented the onset of stratification during winter.

However, no present day investigations have been able to document the complete circulatory features of the estuary using modern profiling techniques, particularly with regard to the recovery cycle where the greater part of the lower estuary or basin is completely flushed by seawater due to tidal influence. The contents of this paper describes initial results from a sampling programme initiated on December 1991 and to be completed in December 1992. The initial period highlights the estuary recovery period from the influence of the winter rains.

Field data measurements were performed by profiling at 23 locations on the Swan and Canning rivers (figure 1). Data was collected using the Centre for Water Research's fine-scale profiler (F-probe) which samples depth, temperature, conductivity, pH and dissolved oxygen at 2 cm intervals. This paper concentrates on the physical dynamics of the estuary, hence only salinity and temperature data are presented.

2. Tidal cycle and weather patterns

The tides within the Swan River estuary are predominantly diurnal with an average maximum tidal range of 0.6 m. The tide may be considered as a progressive wave which propagates into the estuary, with an approximate 2.5 to 3 hour time lag between the ocean entrance and the Barrack Street Jetty, with the levels at Barrack Street approximately 85% of that at Fremantle. Short periods of semi-diurnal tides have also been observed, although their amplitudes are greatly reduced (Hodgkin and Di Lollo, 1958).

Although the maximum tidal range is 0.6 m, past recorded levels indicate much larger water level variations of up to 1 m which coincide with the passage of atmospheric pressure systems. However, during the initial sampling period, there were only a few occurrences of low pressure systems, typical of the high pressure dominating weather patterns during the summer period.

Rainfall records indicate a late finish to the rainy season in 1991, with November and December recording higher than average rainfall. Another major event, highly unusual for that period of the year, was experienced on February 9, when 120.6 mm of rainfall was recorded. Daily maximum and minimum temperatures closely resembled long term averages over the summer months.

3. Recovery cycle

C-T-D field measurements were made on four separate occasions during the study period.

(i) 91351 (December 17th, 1991)

A single transect was made along the Swan and Canning rivers as part of a familiarisation exercise and future site location programme. Allowing for the 2.5 hour tidal lag, Barrack Street tidal data shows that the transect was performed on a low to rising tide. Salinity contours (figure 2) highlight pronounced, but weak vertical stratification in the main basin and in the upper estuary. In the upper estuary there was a well defined longitudinal stratification between the 20 km and 40 km mark of nearly 20 pss, shear in the narrow river channel together with baroclinic adjustments must support this gradient.

The incoming tide moved water as a uniform front up to and over the sill at Fremantle; the entering saline water appeared to plunge vertically and fill the deep portion of the channel in the lee of the sill (figure 2). The same mechanism is illustrated by the temperature contours shown in figure 3; although temperature was a tracer, salinity completely dominated the density of the water. Such a plunging mechanism is similar to that postulated by Spencer (1956), but as we will see later, the mechanisms deviate more and more as the tidal cycle proceeds from that put forward by Spencer (1956).

The isohalines over the length of the upper reaches exhibited a relative uniform tilt of approximately 1 in 2000, which as we shall see below was the reflection of the baroclinic motion coupling with the outgoing tide. The isohalines in the Canning River (figure 4) showed similar slope.

(ii) 92016 (January 16th, 1992)

An attempt was made on the 16th of January to document the circulation in the estuary during a rising tidal cycle. Data from three transects were collected, the first at low tide, another at intermediate tide, and finally a third transect of reduced length at high tide.

The most noticeable difference to the previous picture of 91351 is the substantial breakup of the vertical stratification in the lower estuary (figure 5a). Following the movement of the contours upstream shows that the ocean water moved in as a vertical front as it propagated over the sill. The average propagation speed, as estimated from the displacement of the 34 pss isohaline was 0.08 m s^{-1}. This indicates that the rate of underflow just balanced the rate of inflow so that the internal Froude number was equal to or larger than one.

The movement of water in the upper reaches was strongly baroclinic; the sloping isohalines at low tide shown in figure 5a became almost vertical by the time the data shown in figure 5b was collected. Similar baroclinic adjustments were observed in the Canning Estuary (figure 6a and 6b), but with a diminished magnitude.

The isotherms (figure 7a, b and c) confirm the intrusion pattern over the sill, but they are contaminated in the upper reaches by the strong diurnal heating at the time.

(iii) 92028 and 92029 (January 28th and 29th, 1992)

In order to document the circulation characteristics of the estuary over a full tidal cycle, four transects were completed extending from one low tide to the next. The estuary had become more saline (figure 8a, b, c and d), but the overall structure was similar.

Once again the 36 pss isohaline was horizontal at low tide and the isohalines in the upper reaches were sloped at about 1 in 2000 (figure 8a). As the tide rose, the ocean water plunged over the sill (figure 8b) and joined the salty, deep estuarine water. At high tide, most of the deep basin had been filled with water at a salinity in excess of 36 pss and the 34 pss line had moved, on the surface, approximately 4 km upstream. The transect shown in figure 8d was taken the next morning, again at low tide, and showed a return to an almost identical structure as shown in figure 8a.

Comparison of the isohalines shown in figure 6a and b and 9a, b and c shows that longitudinal mixing had increased the overall salinity in the Canning Estuary by about 2 pss units, but again the structure, and so the dynamics remained similar to that observed a month before.

(iv) 92058 and 92059 (February 27th and 28th, 1992)

The sampling programme was again similar to the previous transects. The isohalines are shown in figure 10a, b, c and d and they clearly shown the influence of the strong runoff associated with the heavy rains on February 9.

The main basin showed a stronger stratification at low tide (figure 10a) reminiscent of the earlier profiles. The stratification in the upper reaches was also more severe, with isohalines as low as 1 in 5000 being documented. As the tide rose (figure 10b), a clear front formed at the 8 km mark and the isohalines in the upper reaches became almost vertical. This required a differential movement in the upper 20 km, between the top and the bottom of almost 10 km in six hours. The front at the surface just past the sill persisted into the high tide (figure 10c); it may have actually moved out a little. The 36 pss isohaline was nearly vertical, similar to what had been documented earlier. The isohaline positions on the subsequent low tide are shown in figure 10d. These are particularly interesting as they show very strong tilting in the upper reaches produced by the baroclinic outflow. Obviously figure 10d was closer to low tide than that shown in figure 10a. The near surface outflow shown in figure 10d was also recently documented in the Venice Lagoon by Imberger (1991).

Presently, the authors have installed an acoustic current meter to document the evolution of shear in the upper reaches of the Swan River.

4. The deep basin response

It was noted in 3.2 that the 36 pps isohaline remained almost vertical as the tide entered the deep basin over the shallow sill in Fremantle. This is quite different to the gravitational underflow postulated by Spencer (1956) and requires some further explanation. The baroclinic response of a stratified basin to a forcing (the tidal inflow) has received a great deal of attention recently. Many scientific investigators have dealt with this topic, either as field investigations (Wedderburn 1912, Mortimer 1952, 1953, and Heaps and Ramsbottom 1966), experimental studies (Keulegan and Brame 1960, Kranenburg 1985, Monismith 1986, Stevens and Imberger 1991, and Imberger *et. al.* 1991) and numerical experiments (Thompson and Imberger 1980 and Franke *et. al.* 1987).

The baroclinic response of a stratified basin results in a tilting of the stratified region (seiching). The time scale over which a two layer stratified basin undergoes a mode one interfacial tilt is given by Spigel and Imberger (1980)

$$T_1 = \frac{2L}{\sqrt{\frac{g' h_1 h_2}{h_1 + h_2}}}$$

where L is the basin length scale,

h_1 and h_2 are the depths of the upper and lower layers respectively

and g' is the density anomoly.

For a linearly stratified estuary

$$T_i = \frac{2L}{c_i},$$

and c is the linear wave speed given by McEwan and Baines (1974)

$$c_i = \frac{NH}{i\pi},$$

where N denotes the buoyancy frequency given by

$$N = \sqrt{\frac{-g}{\rho}\frac{\partial \rho}{\partial z}} ,$$

H is the mean depth of the basin,

and i is the vertical modal index.

Taking the basin length scale L as the distance of the wider, deeper parts of the estuary (figure 11) as 7 km and assuming a mean depth of 12 m, and using data from the density profiles at SW101 (figure 12), the seiching periods of the basin during each sampling period were estimated (table 1).

Julian Date	Stratification Type/ Intensity (Approximation from fig. 12)	Seiching Period T_1
91351	2 layer ($g'=0.048 m/s^2$)	10.26 hrs
92016	2 layer ($g'=0.022 m/s^2$)	16.65 hrs
92028	Linear ($N=0.044 s^{-1}$)	23.27 hrs
92058	2 layer ($g'=0.034 m/s^2$)	12.41 hrs

Table 1

The other time scale important in this problem is the time it takes for the inflowing ocean water to propagate over the sill and down the slope into the deep depression. Assuming the flow is governed by a simple inertia-buoyancy balance, then this time scale is

$$T_{int} = \sqrt{\frac{L}{g' \sin\theta}} ,$$

where L is the inflow length (approx. 5000 m) and θ is the angle of the valley (1 in 250). This time comes to about 1.4 hours for the 91351 data, which is relatively short indicating that there is a strong tendency to underflow, but as seen from the data in figures 5, 8 and 10, entrainment and bottom friction were sufficient to prevent complete underflow.

The above indicates that the time scale to underflow and the seiche period, are shorter or equal to the tidal period, exactly the conditions for large isohaline excursions.

5. Conclusion

The C-T-D data enabled a reasonably complete documentation of the tidal response of the Swan and Canning Estuaries during the summer period. The deep trough was found to fill by ocean water propagating over the sill at Fremantle, causing a major tilting of the basin isohalines. On the other hand, in the upper reaches of the Swan and in the Canning Estuary, the isohalines become vertical at high tide. The influence of the falling hole is to introduce a very appreciable shear in the water column which would support a continuous turbulent field. The flushing of the estuary is thus via a tidally forced baroclinic advection, coupled by vertical mixing supported by this shear.

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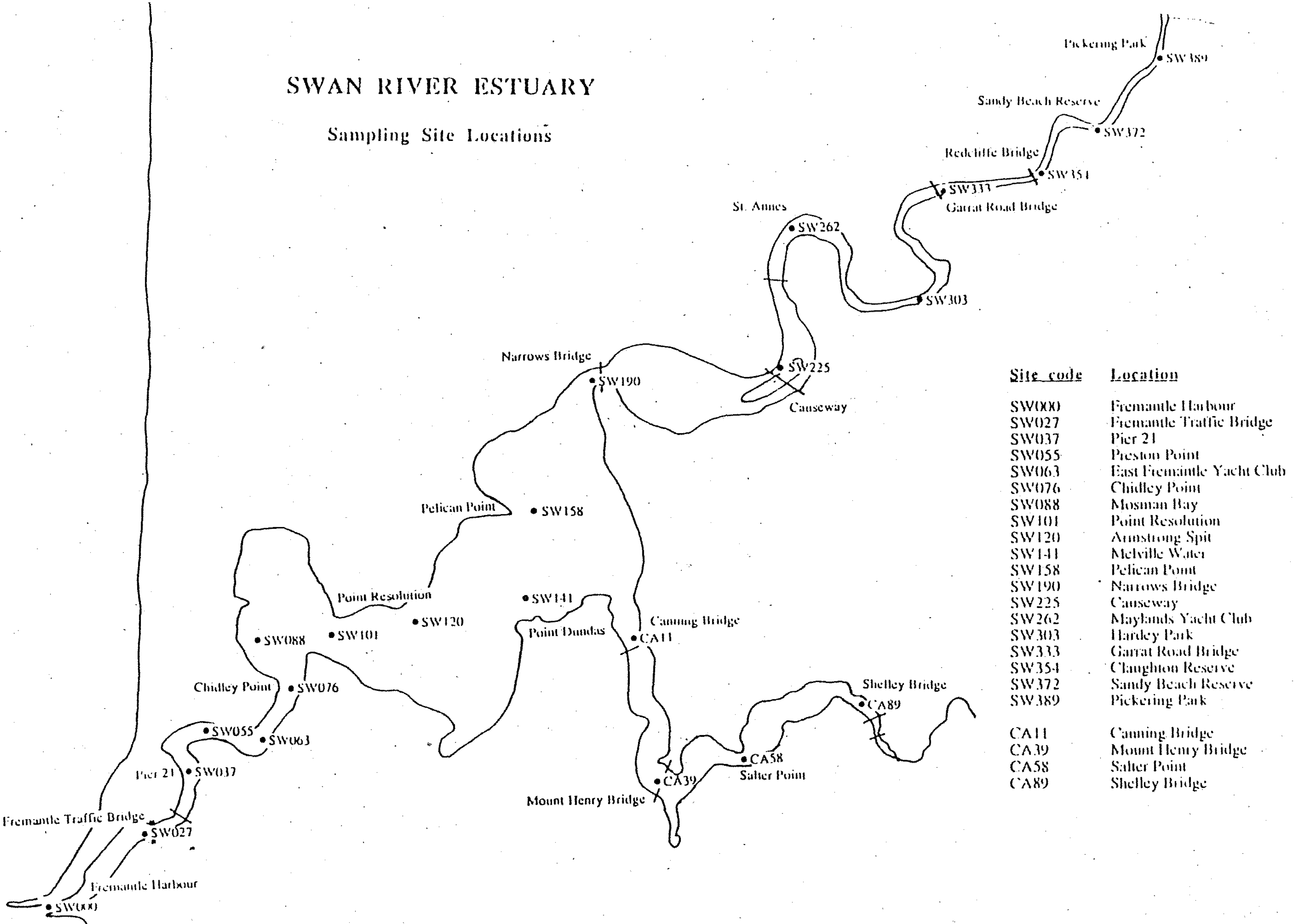


Site code	Location
SW000	Fremantle Harbour
SW027	Fremantle Traffic Bridge
SW037	Pier 21
SW055	Preston Point
SW063	East Fremantle Yacht Club
SW076	Chidley Point
SW088	Mosman Bay
SW101	Point Resolution
SW120	Armstrong Spit
SW141	Melville Water
SW158	Pelican Point
SW190	Narrows Bridge
SW225	Causeway
SW262	Maylands Yacht Club
SW303	Hardey Park
SW333	Garrat Road Bridge
SW354	Claughton Reserve
SW372	Sandy Beach Reserve
SW389	Pickering Park
CA11	Canning Bridge
CA39	Mount Henry Bridge
CA58	Salter Point
CA89	Shelley Bridge

Figure 1 Sampling site locations within the Swan and Canning River estuaries.

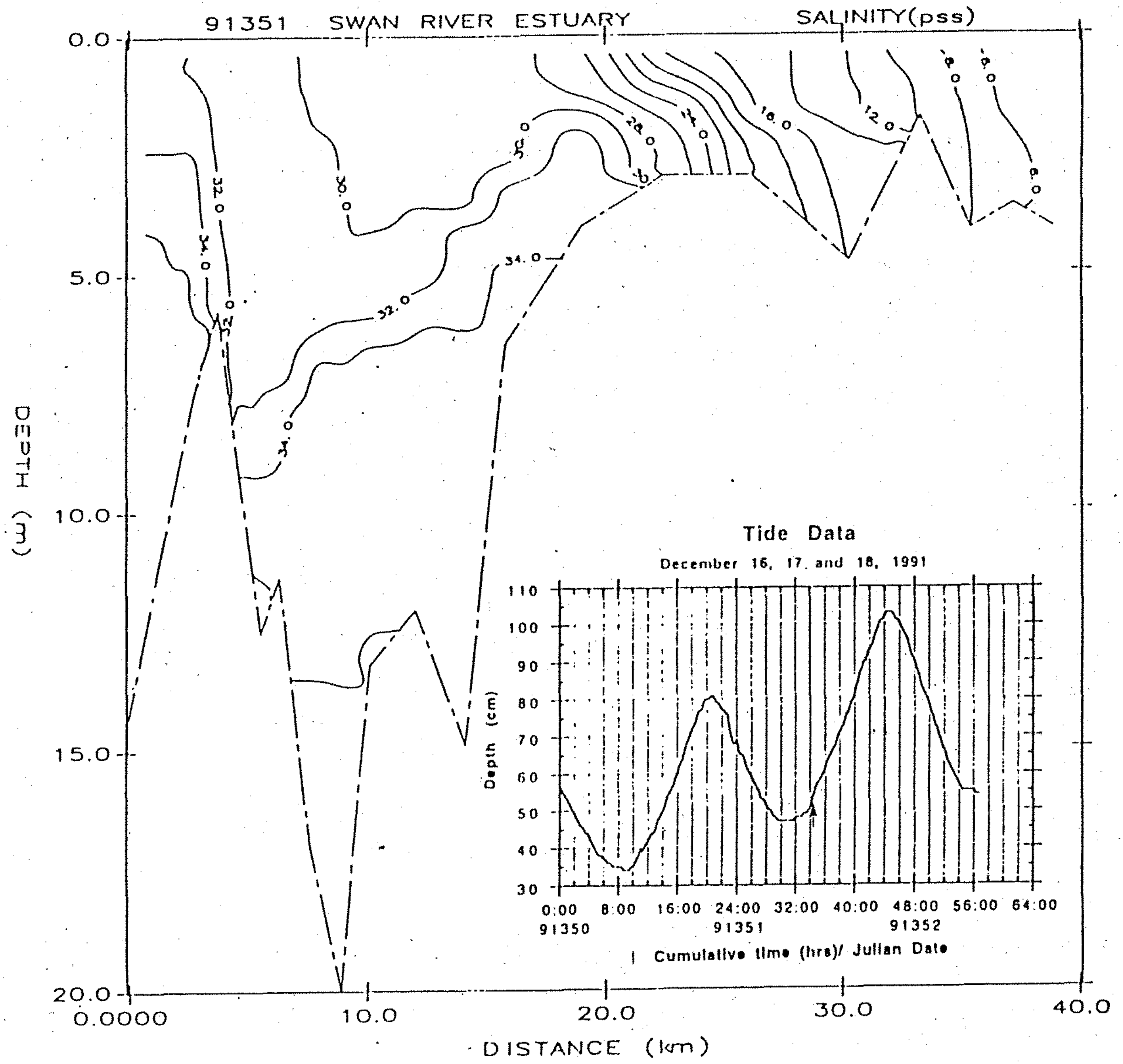


Figure 2 **Salinity Contours in the Swan River for 91351 gathered on a low rising tide.**

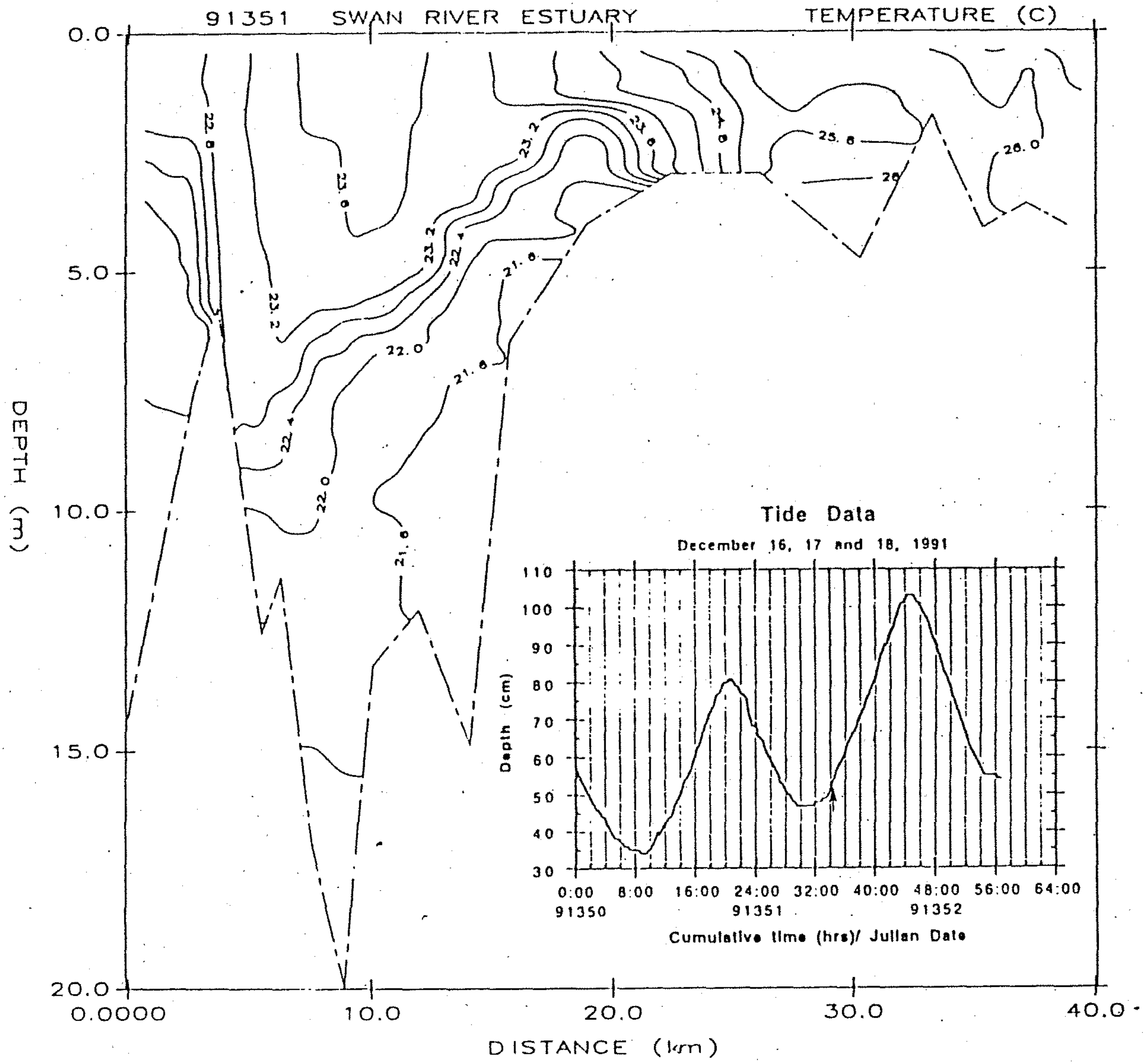


Figure 3 **Temperature contours in the Swan River for 91351 gathered on a low rising tide.**

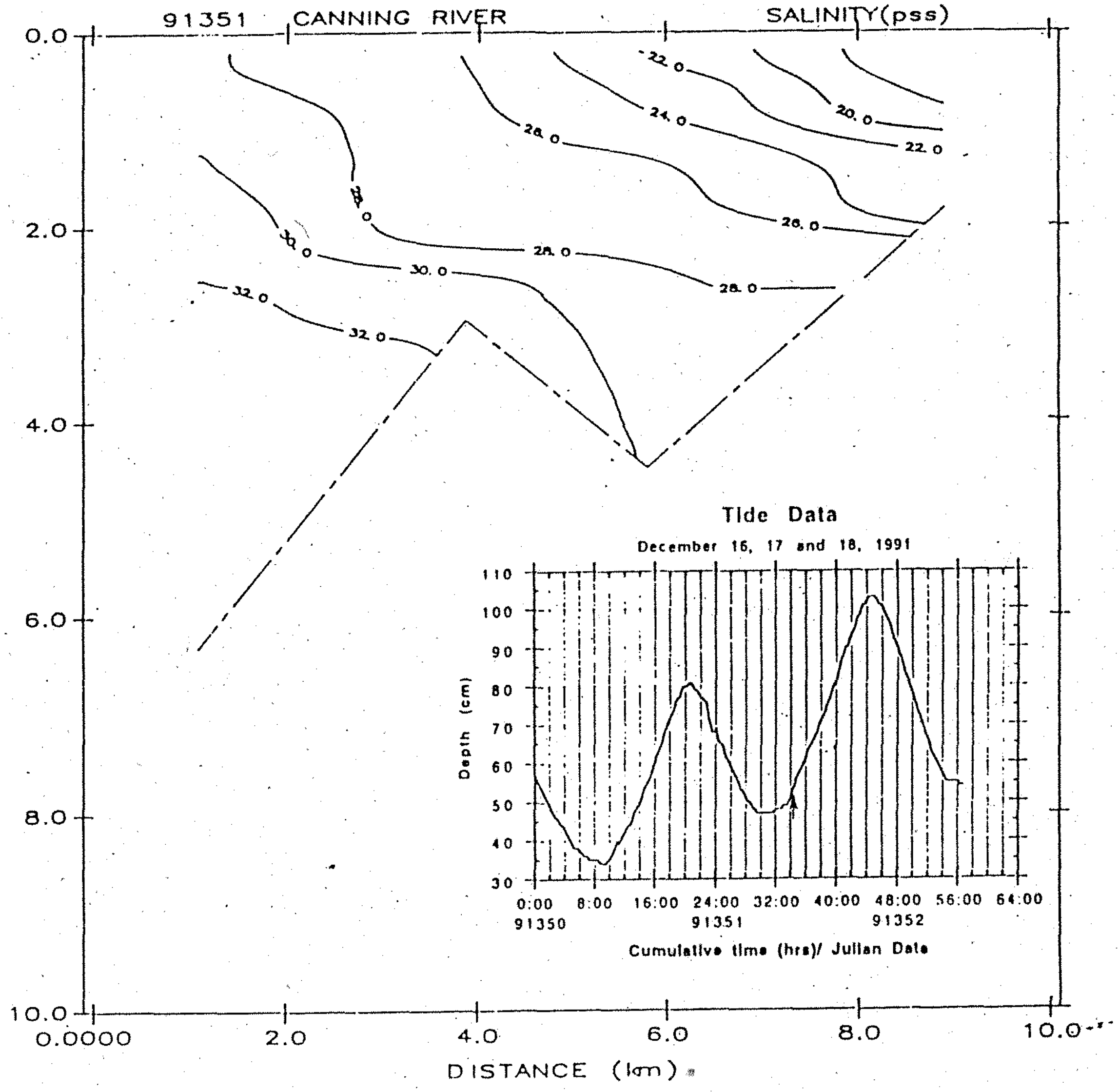


Figure 4 Salinity contours in the Canning River for 91351 gathered on a low rising tide.

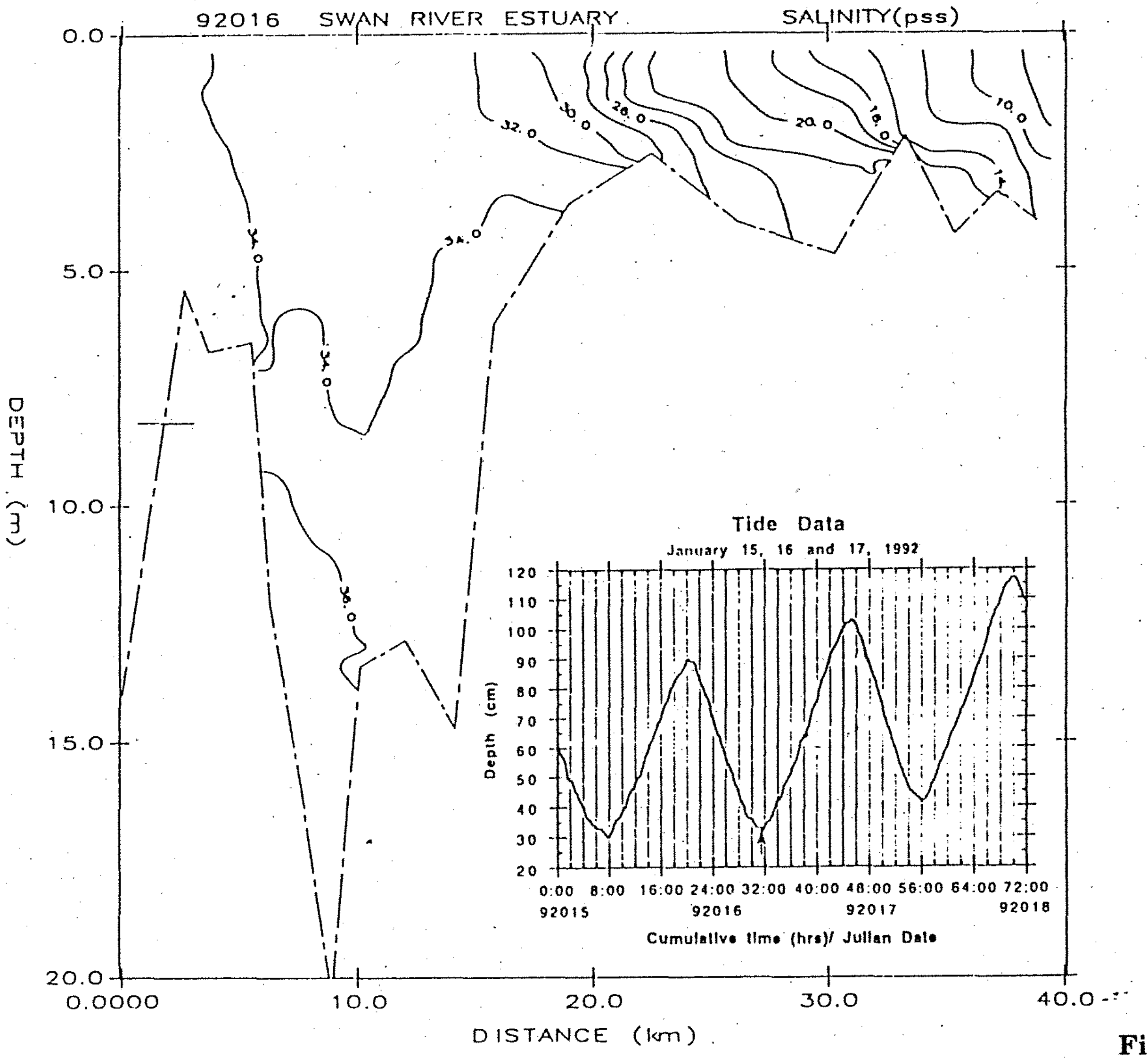


Figure 5 (a) Salinity contours in the Swan River for 92016 gathered on a low rising tide (transect 1).

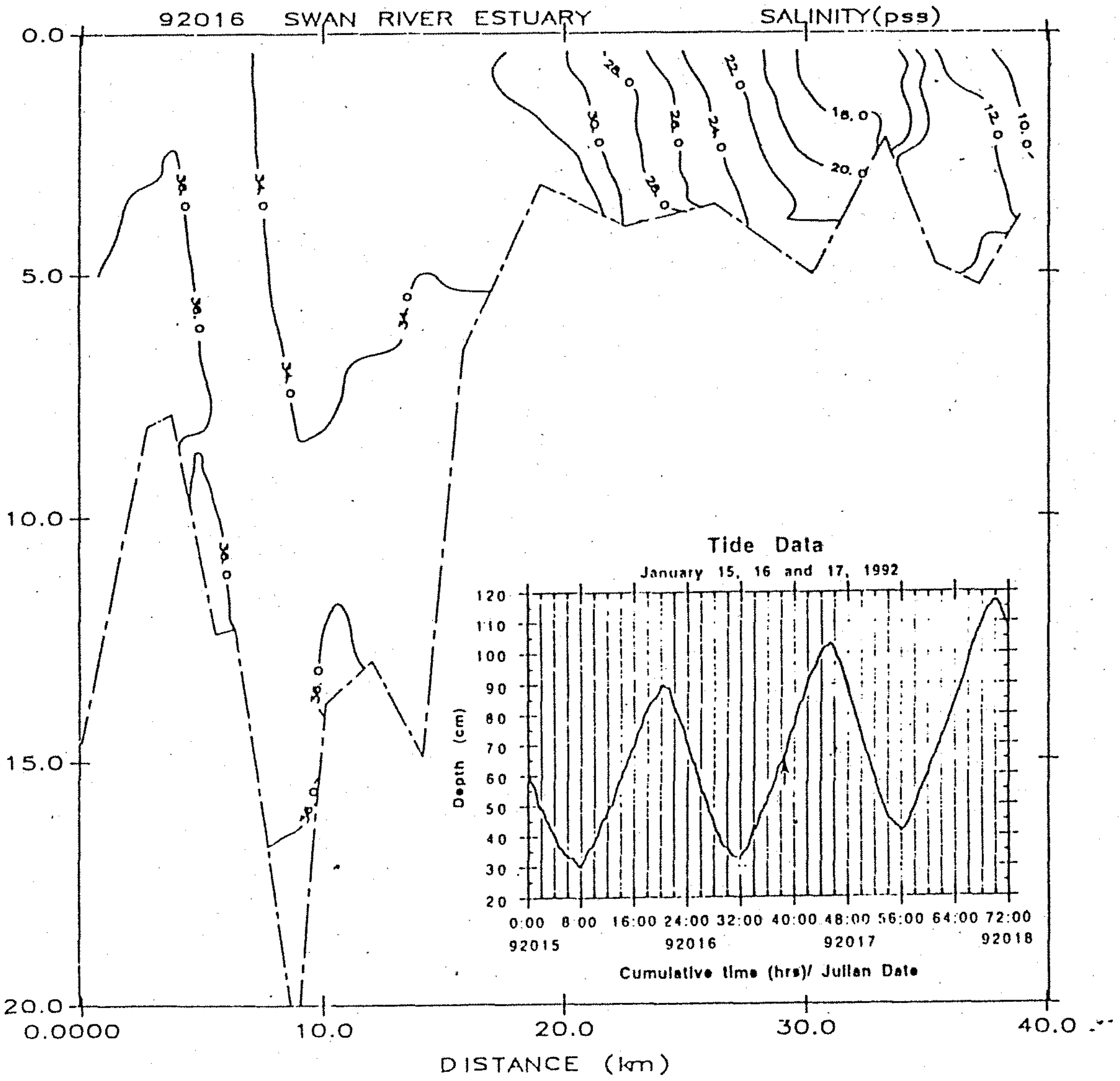


Figure 5 (b) Salinity contours in the Swan River for 92016 gathered on an intermediate rising tide (transect 2).

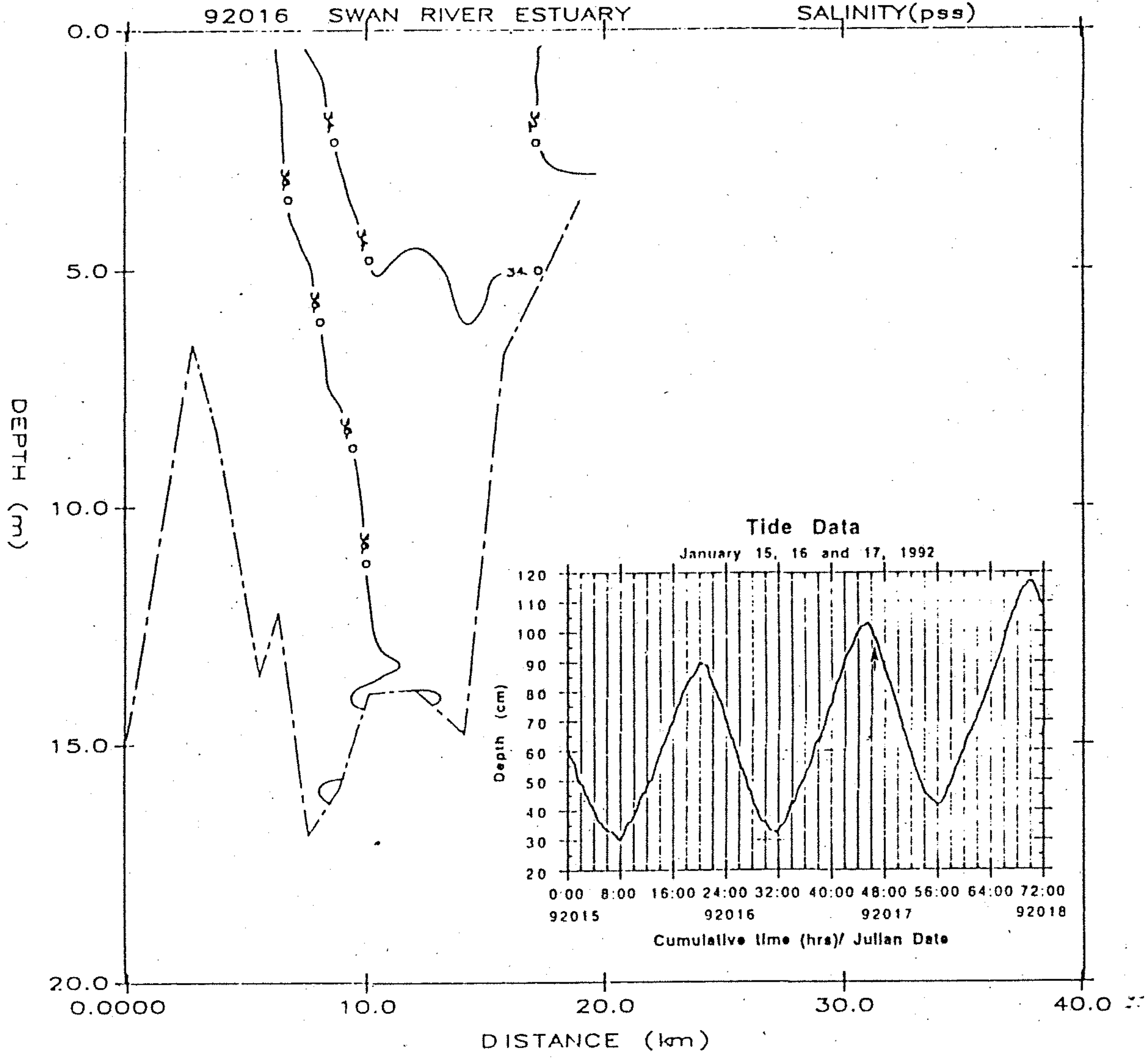


Figure 5 (c) **Salinity contours in the Swan River for 92016 gathered on a high falling tide (transect 3).**

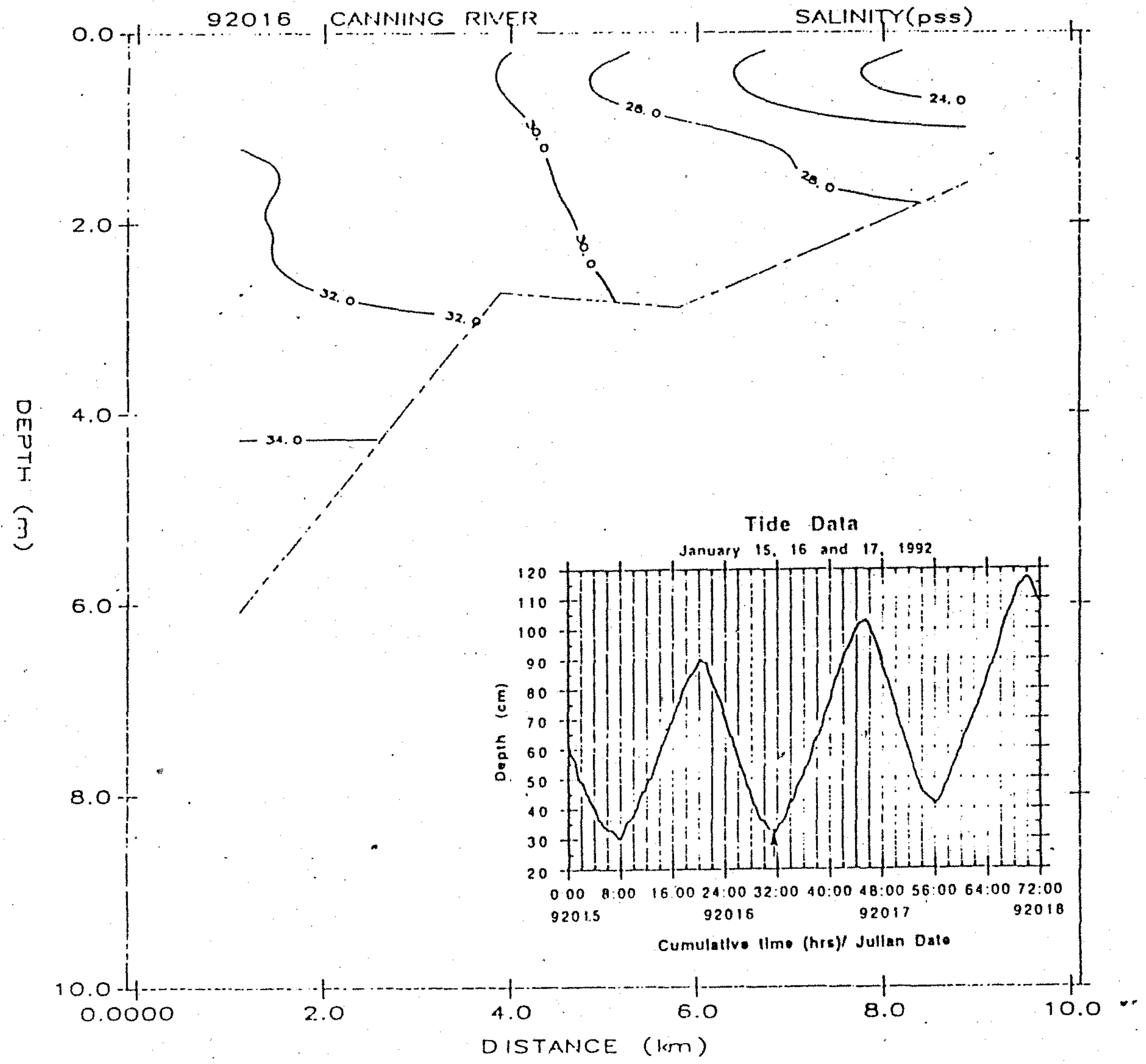


Figure 6 (a) Salinity contours in the Canning River for 92016 gathered on a low rising tide (transect 1).

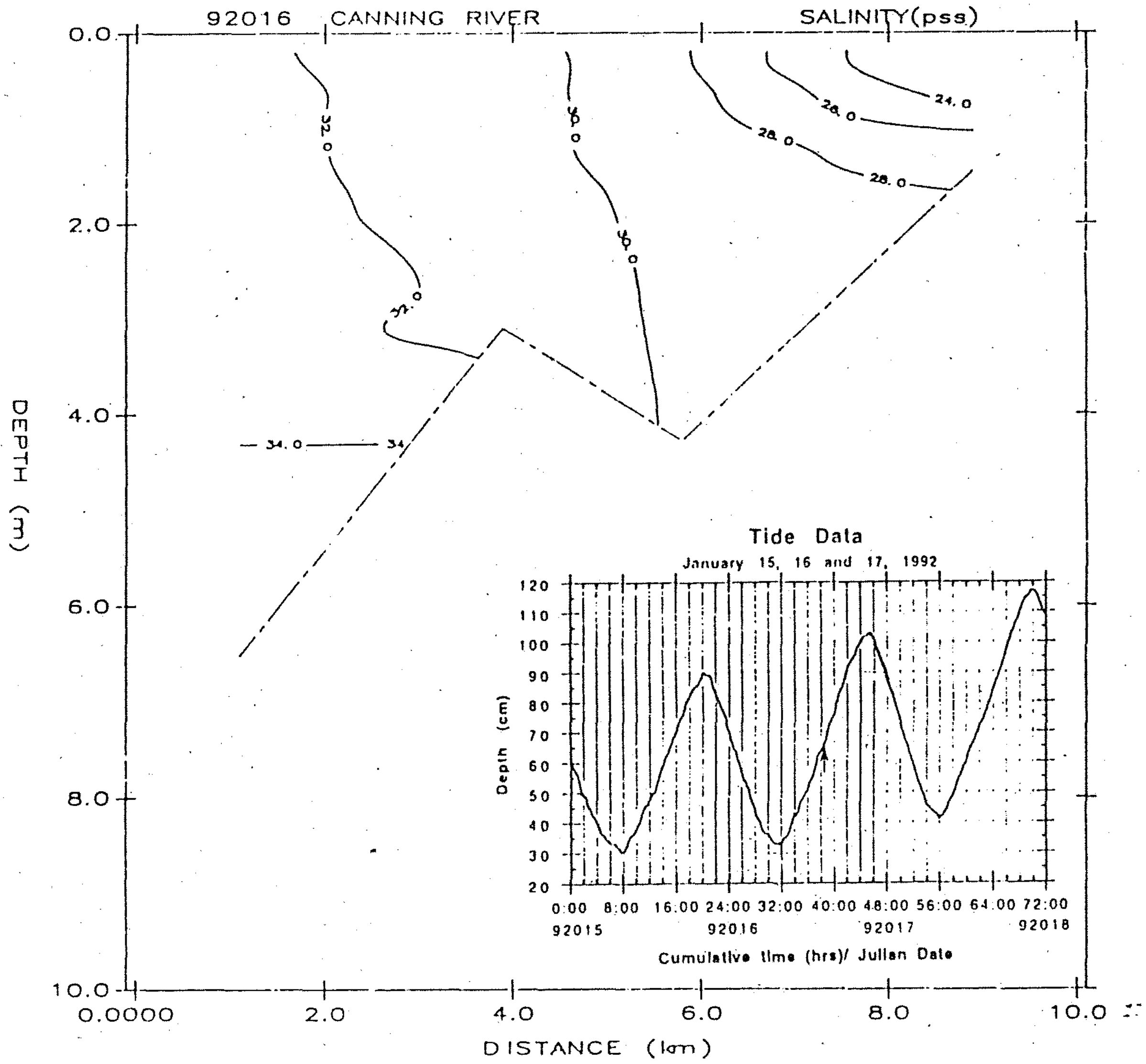


Figure 6 (b) Salinity contours in the Canning River for 92016 gathered on an intermediate rising tide (transect 2).

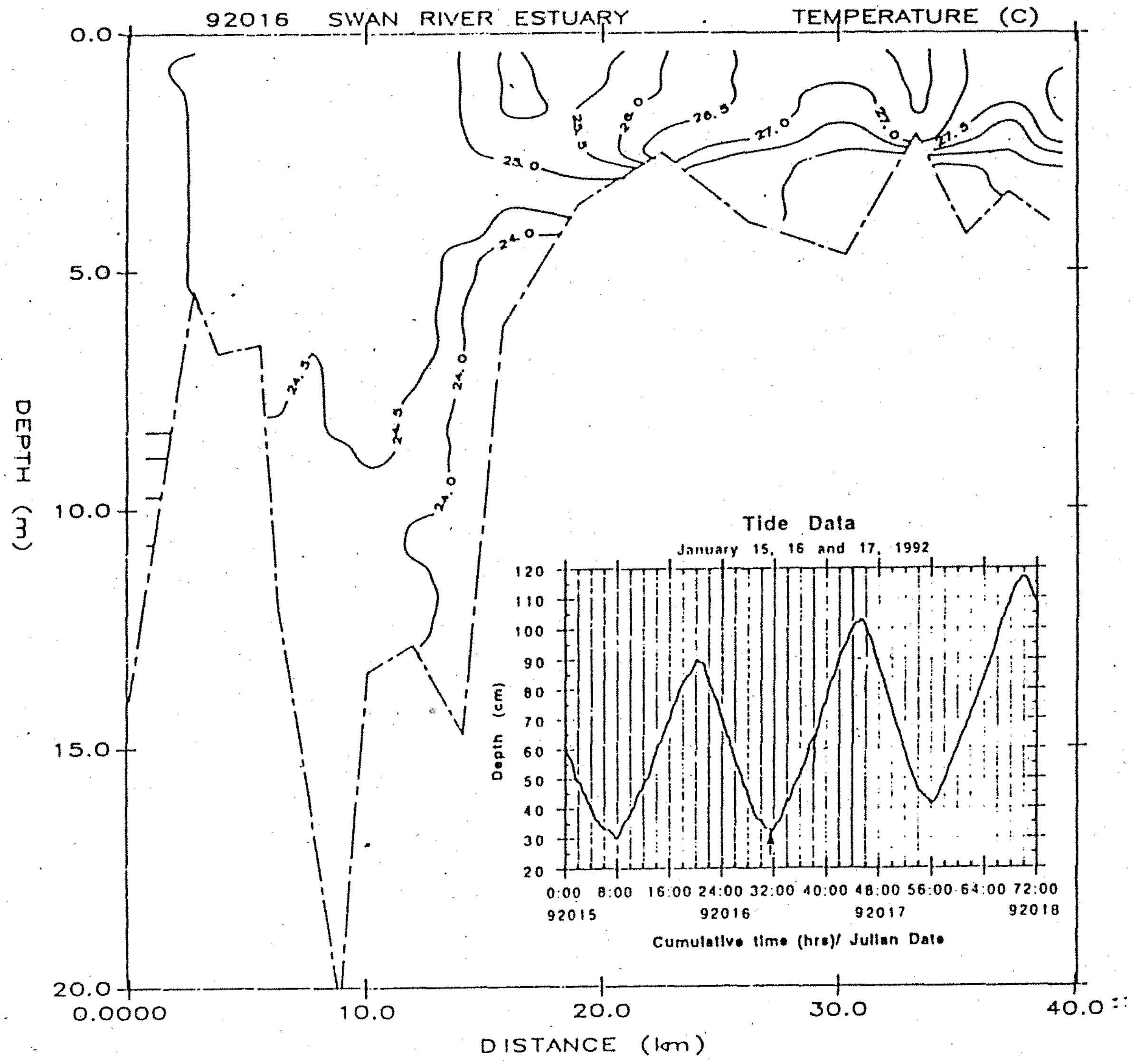


Figure 7 (a) **Temperature contours in the Swan River in 92016 gathered on a low rising tide (transect 1).**

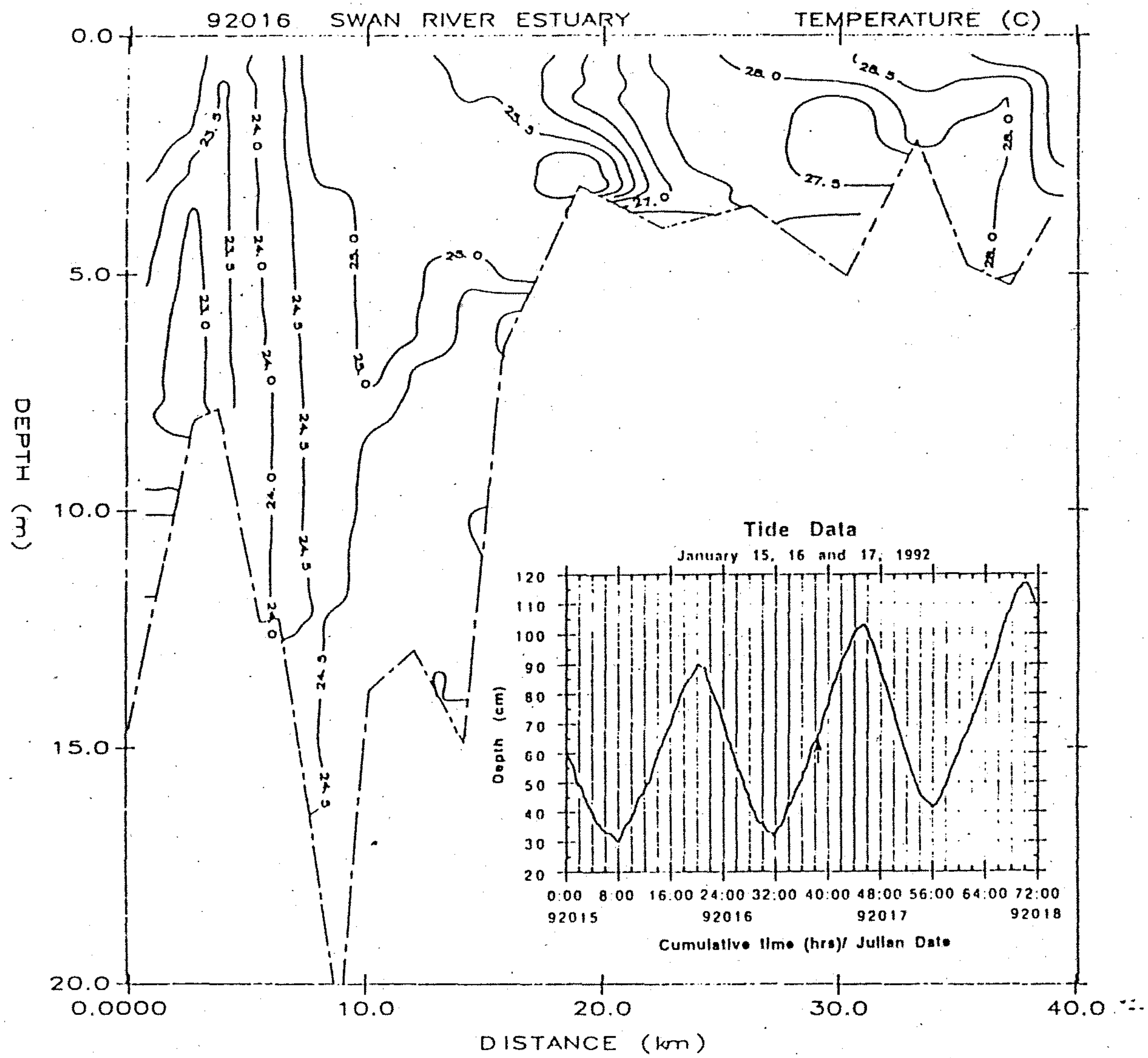


Figure 7 (b) **Temperature contours in the Swan River for 92016 gathered on a low rising tide (transect 1).**

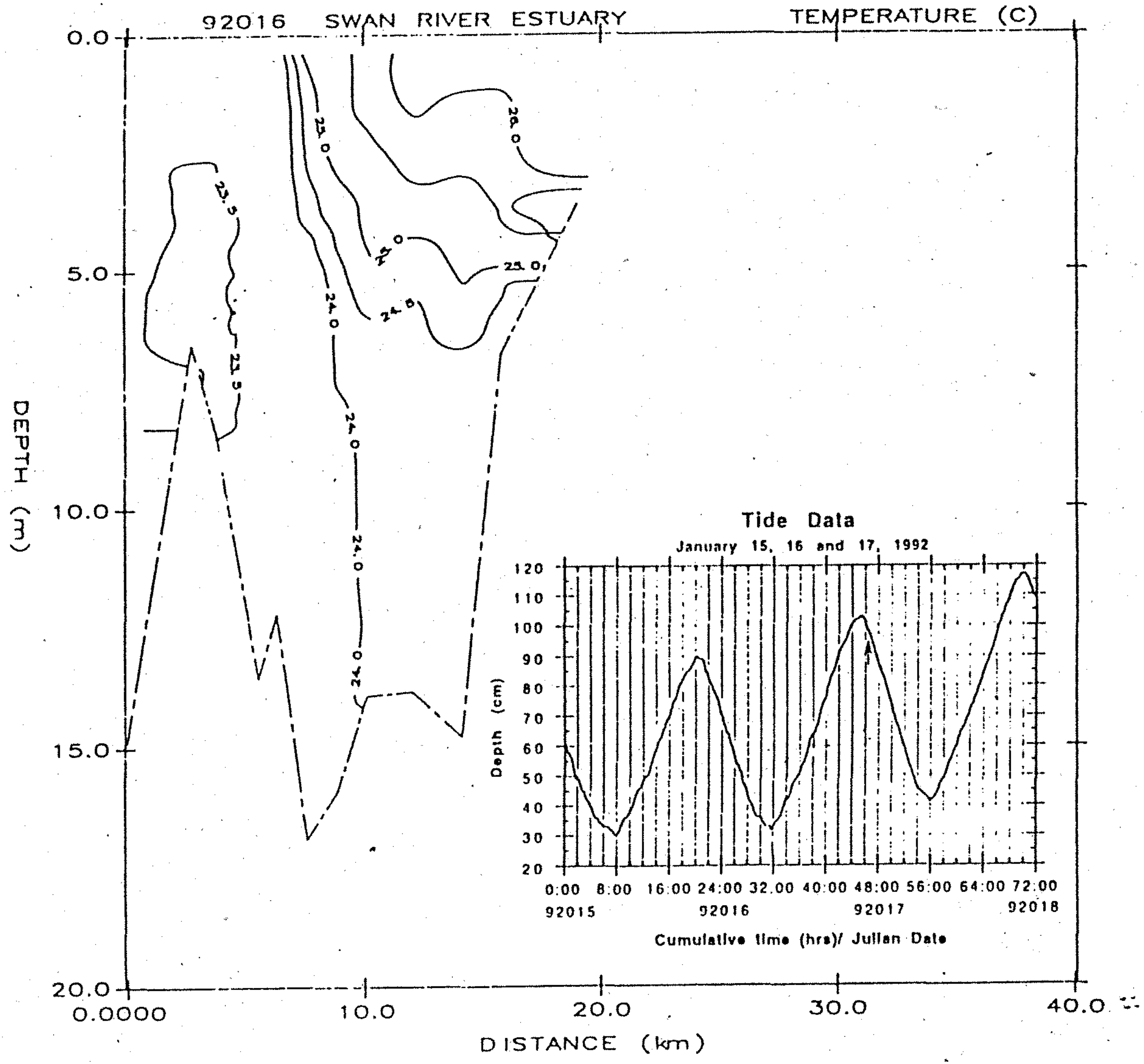


Figure 7 (c) **Temperature contours in the Swan River for 92016 gathered on a high falling tide (transect 3).**

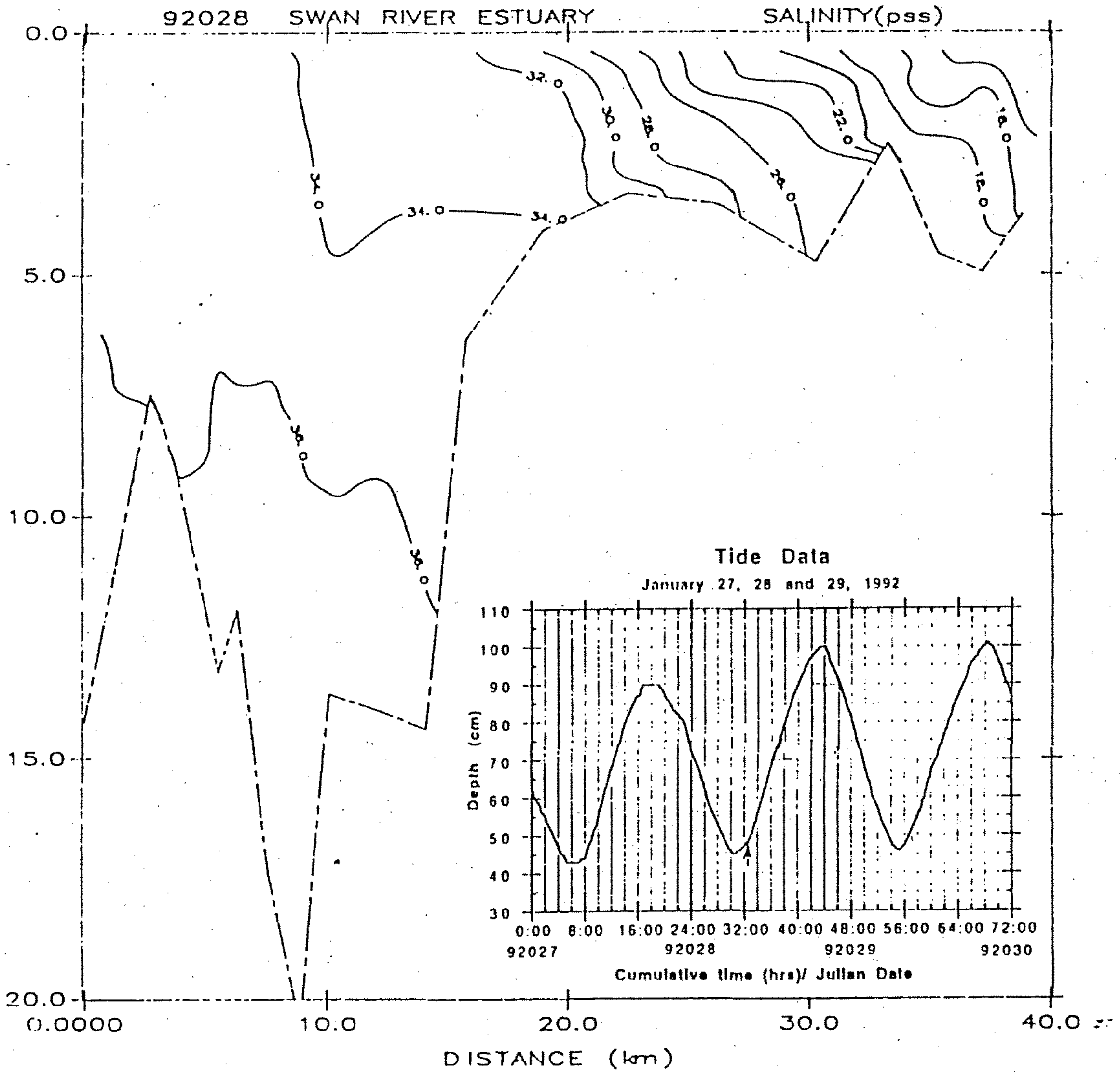


Figure 8 (a) **Salinity contours in the Swan River for 92028 gathered on a low rising tide (transect 1).**

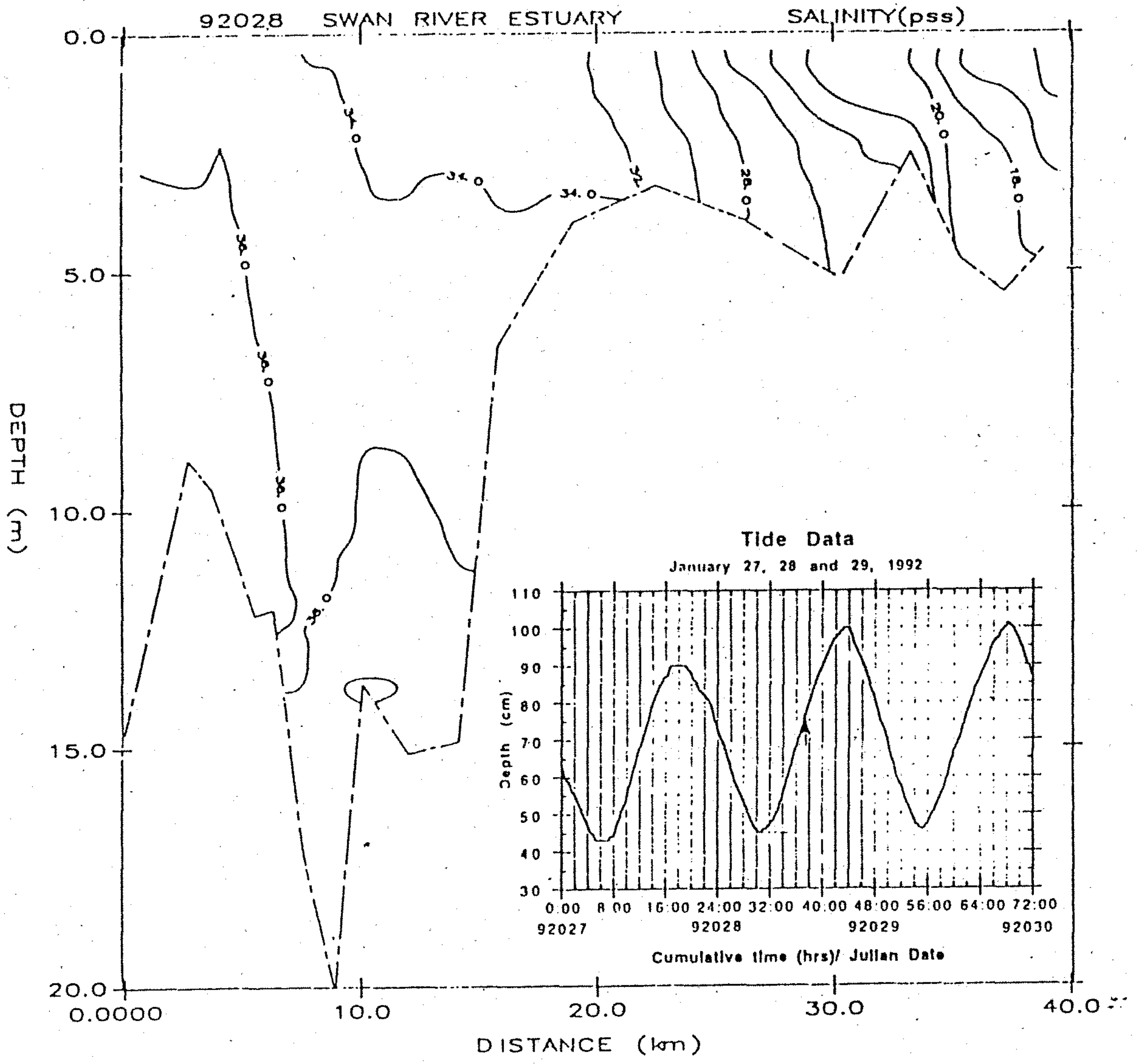


Figure 8 (b) Salinity contours in the Swan River for 92028 gathered on an intermediate rising tide (transect 2).

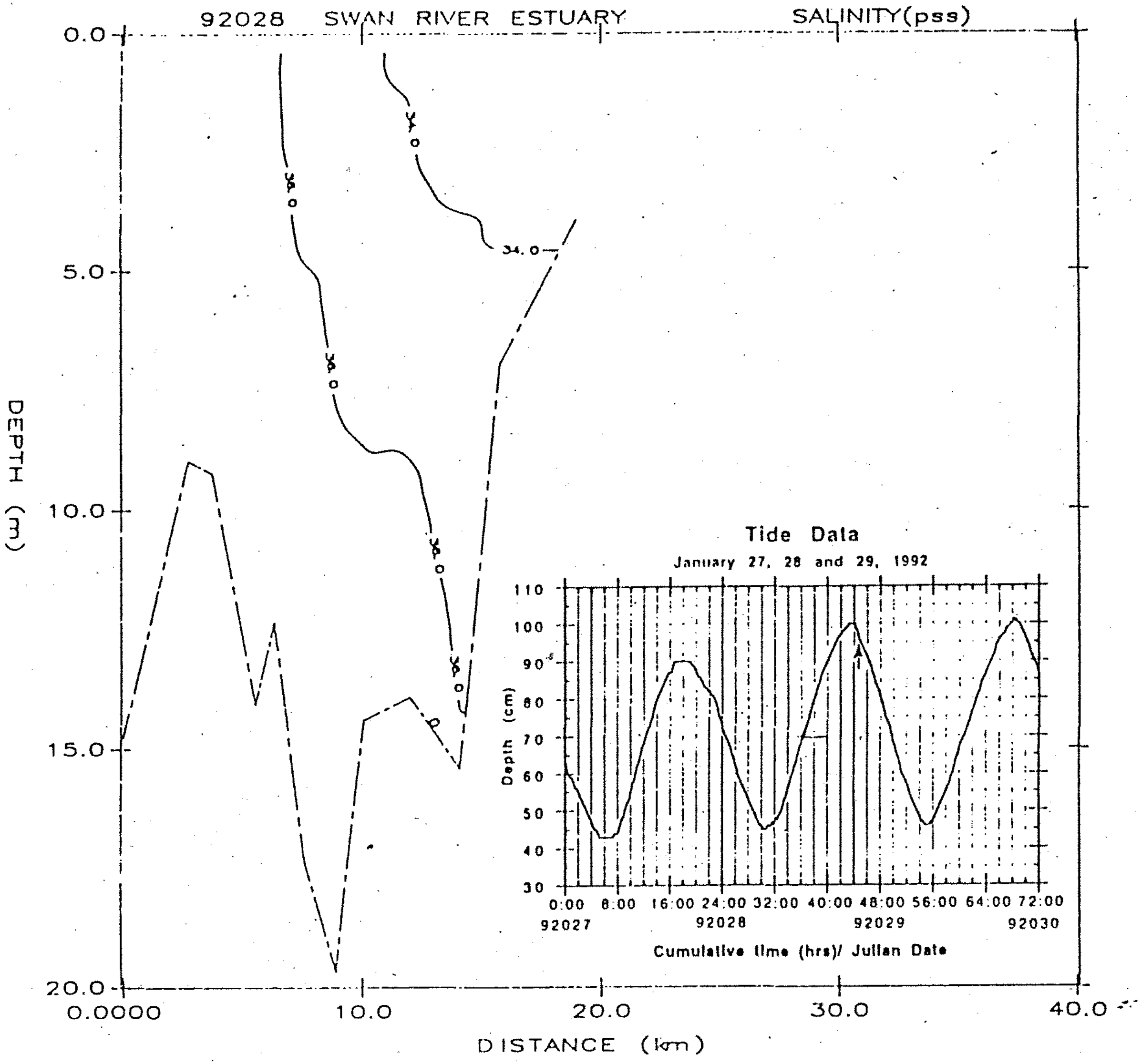


Figure 8 (c) **Salinity contours in the Swan River for 92028 gathered on a high falling tide (transect 3).**

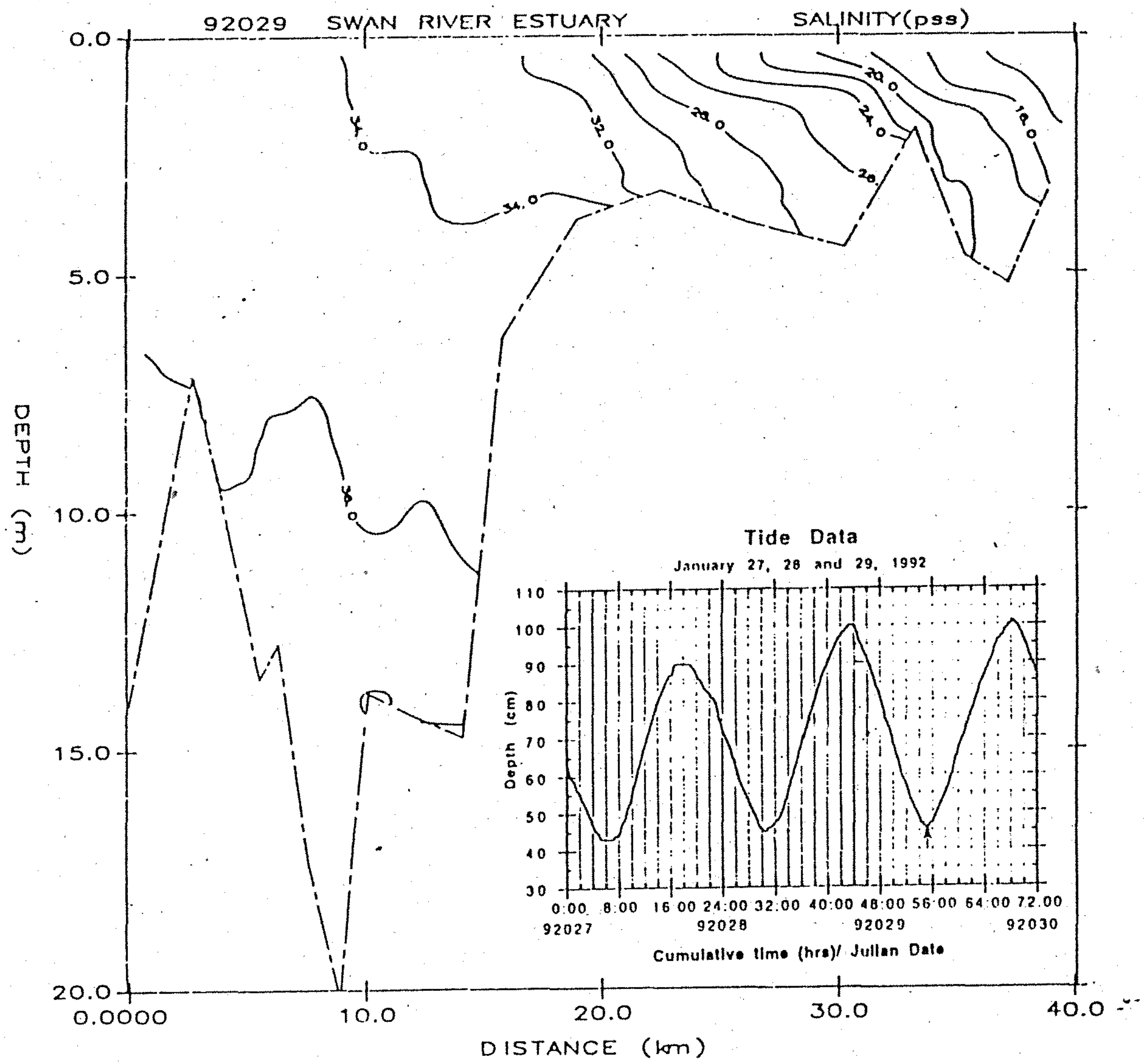


Figure 8 (d) **Salinity contours in the Swan River for 92029 gathered on a low rising tide (transect 4).**

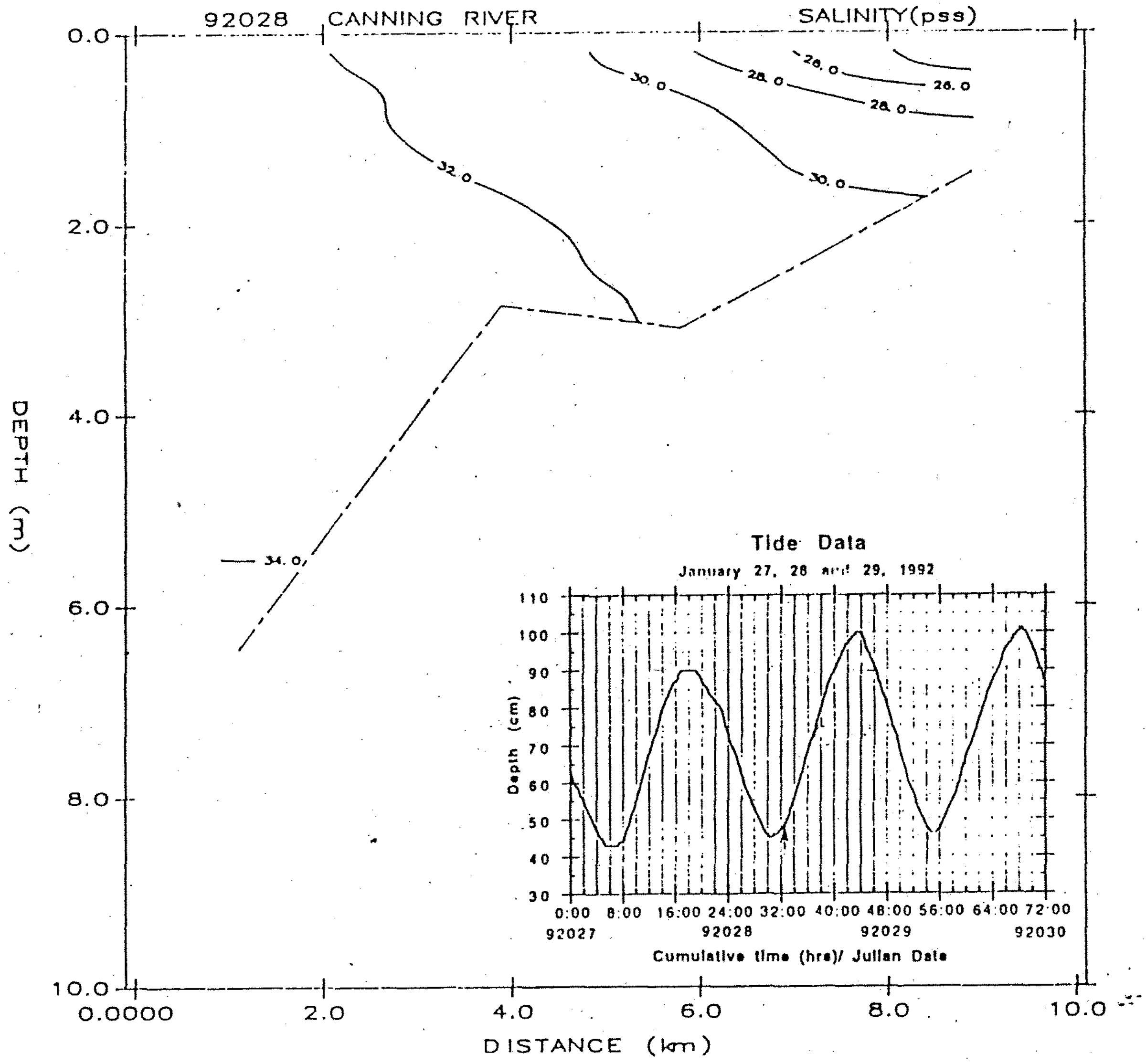


Figure 9 (a) Salinity contours in the Canning River for 92028 gathered on a low rising tide (transect 1).

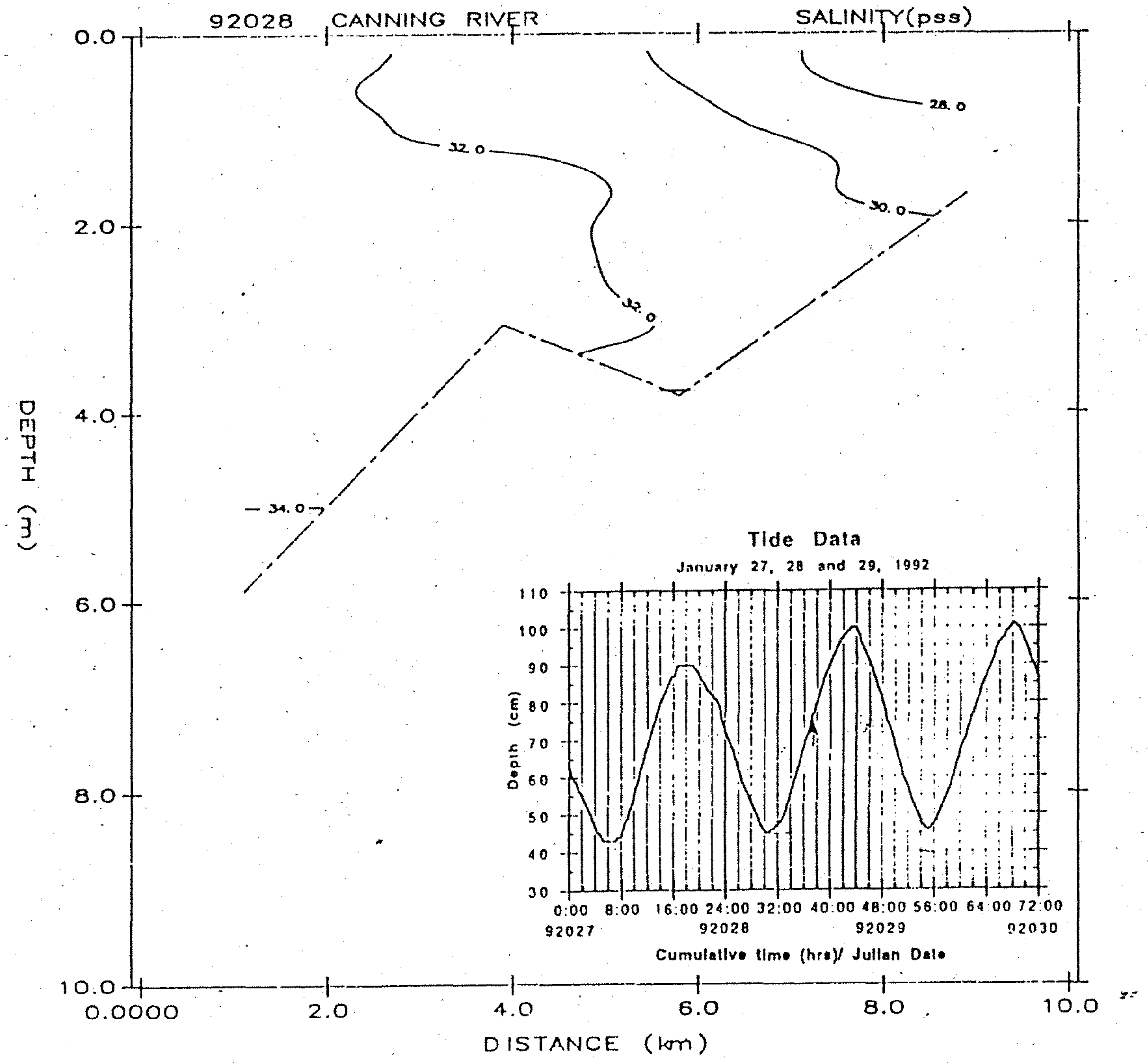


Figure 9 (b) Salinity contours in the Canning River for 92028 gathered on an intermediate rising tide (transect 2).

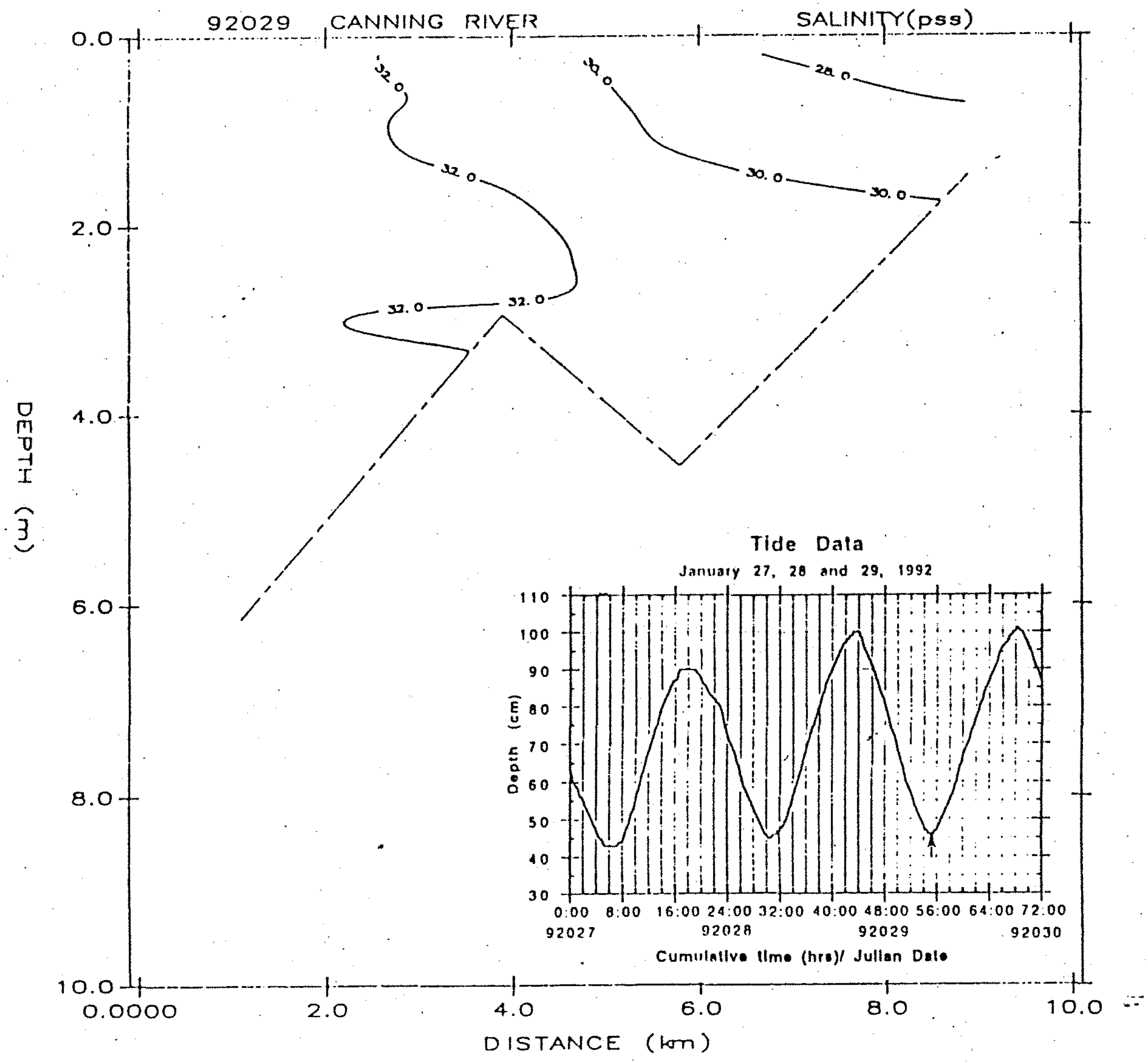


Figure 9 (c) **Salinity contours in the Canning River for 92029 gathered on a low rising tide (transect 4).**

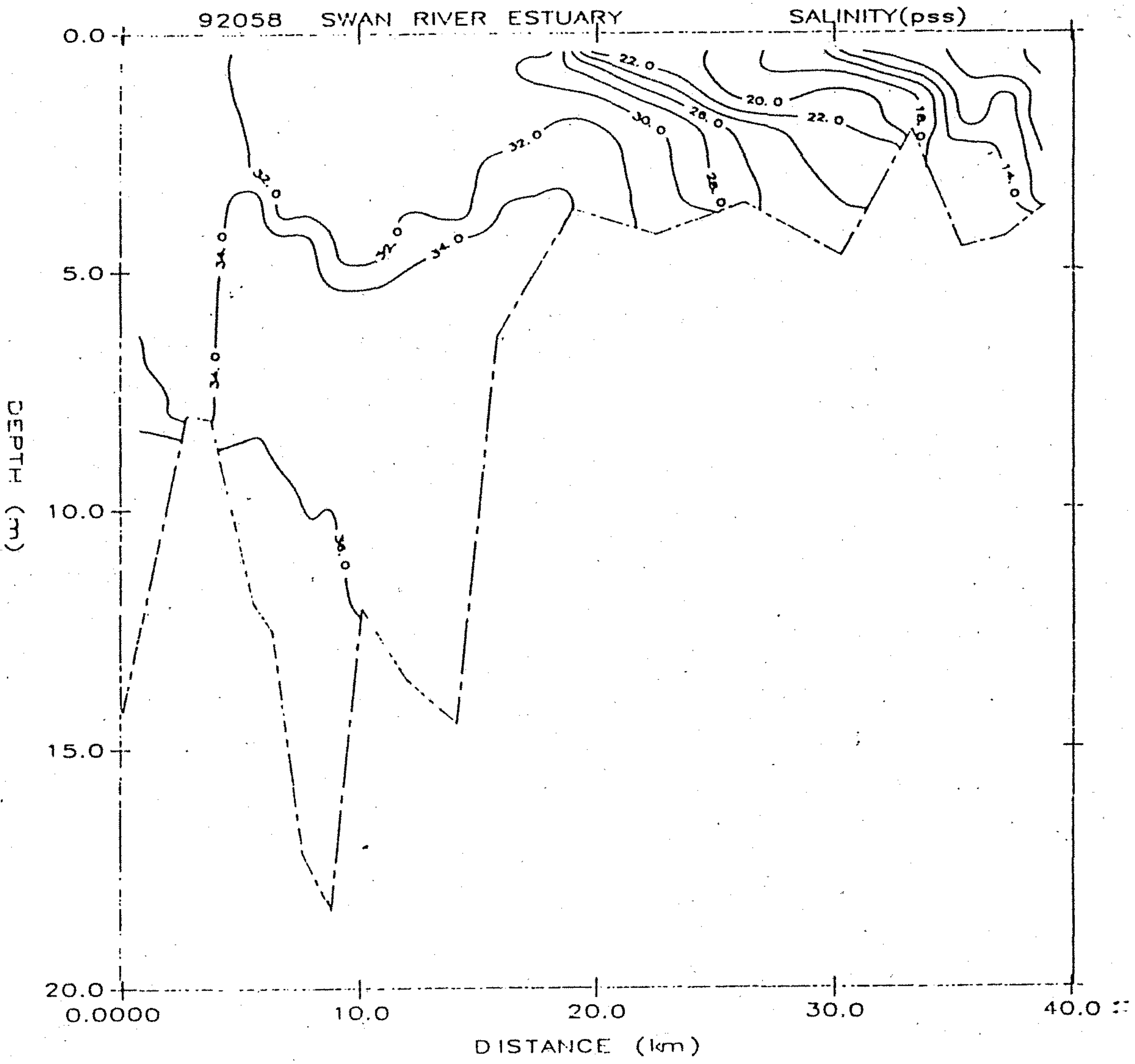


Figure 10 (a) **Salinity contours in the Swan River for 92058 gathered on a low rising tide (transect 1).**

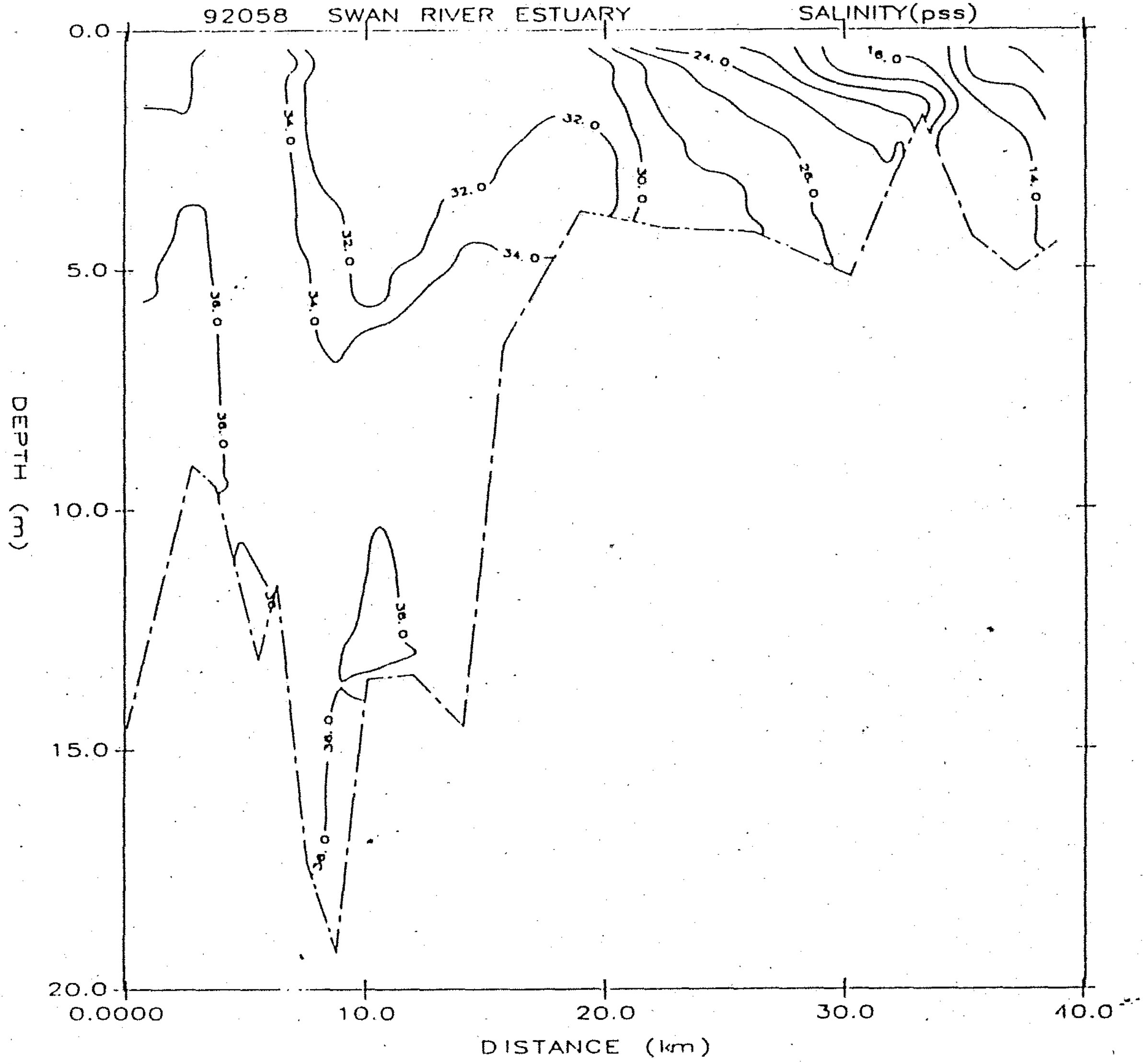


Figure 10 (b) **Salinity contours in the Swan River for 92058 gathered on an intermediate rising tide (transect 2).**

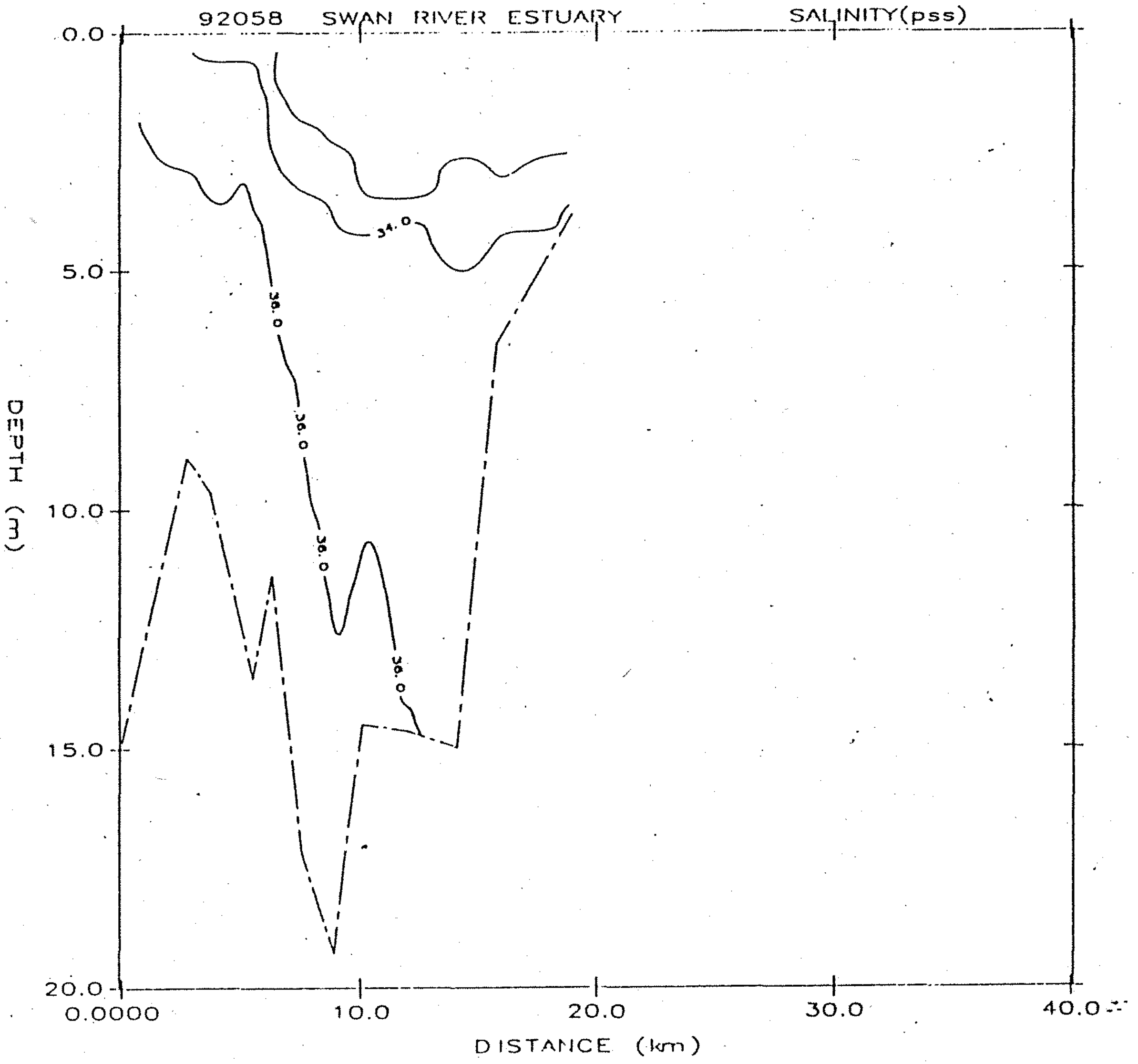


Figure 10 (c) Salinity contours in the Swan River for 92058 gathered on a high falling tide (transect 3).

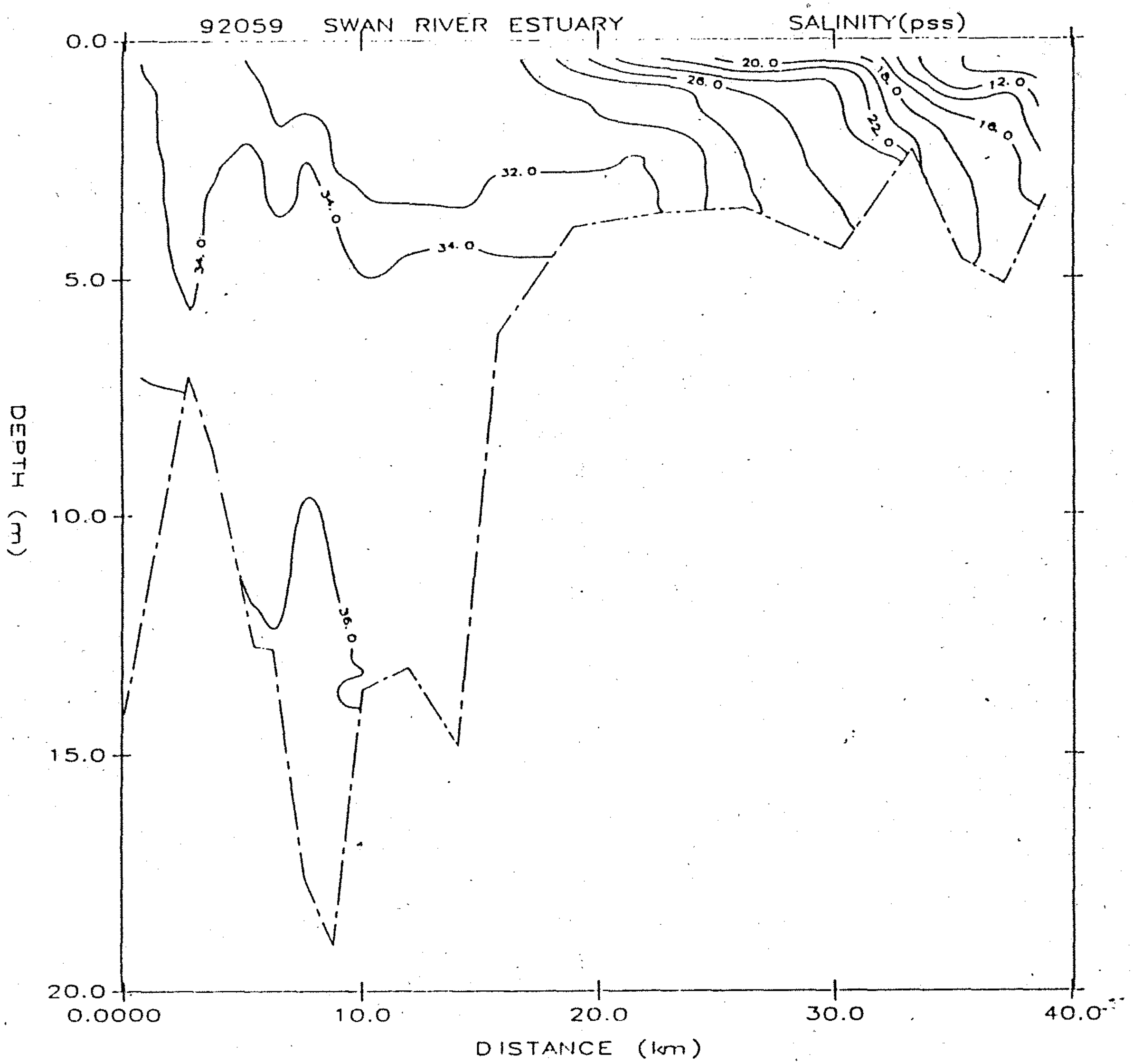


Figure 10 (d) **Salinity contours in the Swan River for 92058 gathered on a low rising tide (transect 4).**

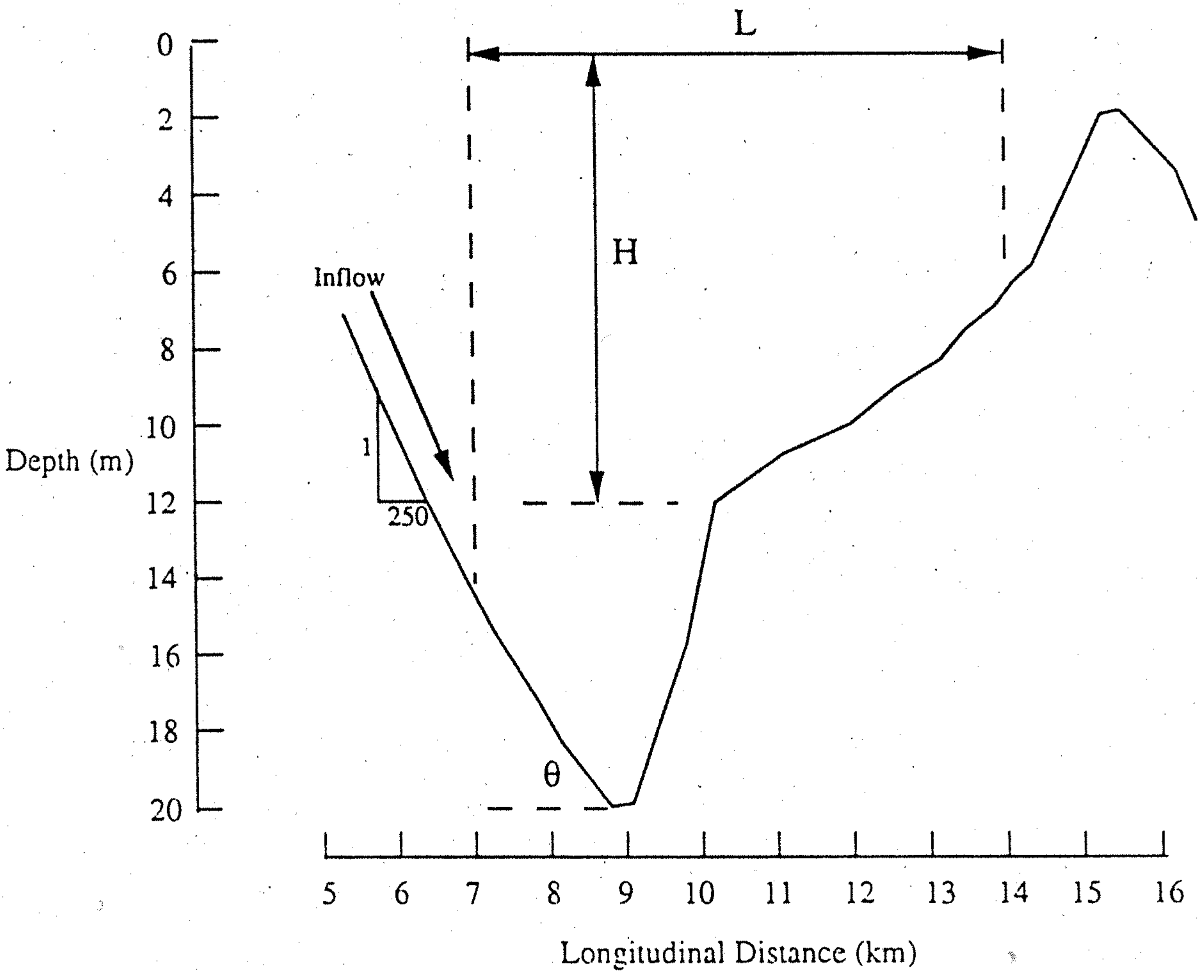


Figure 11 Morphometry of the Swan River basin.

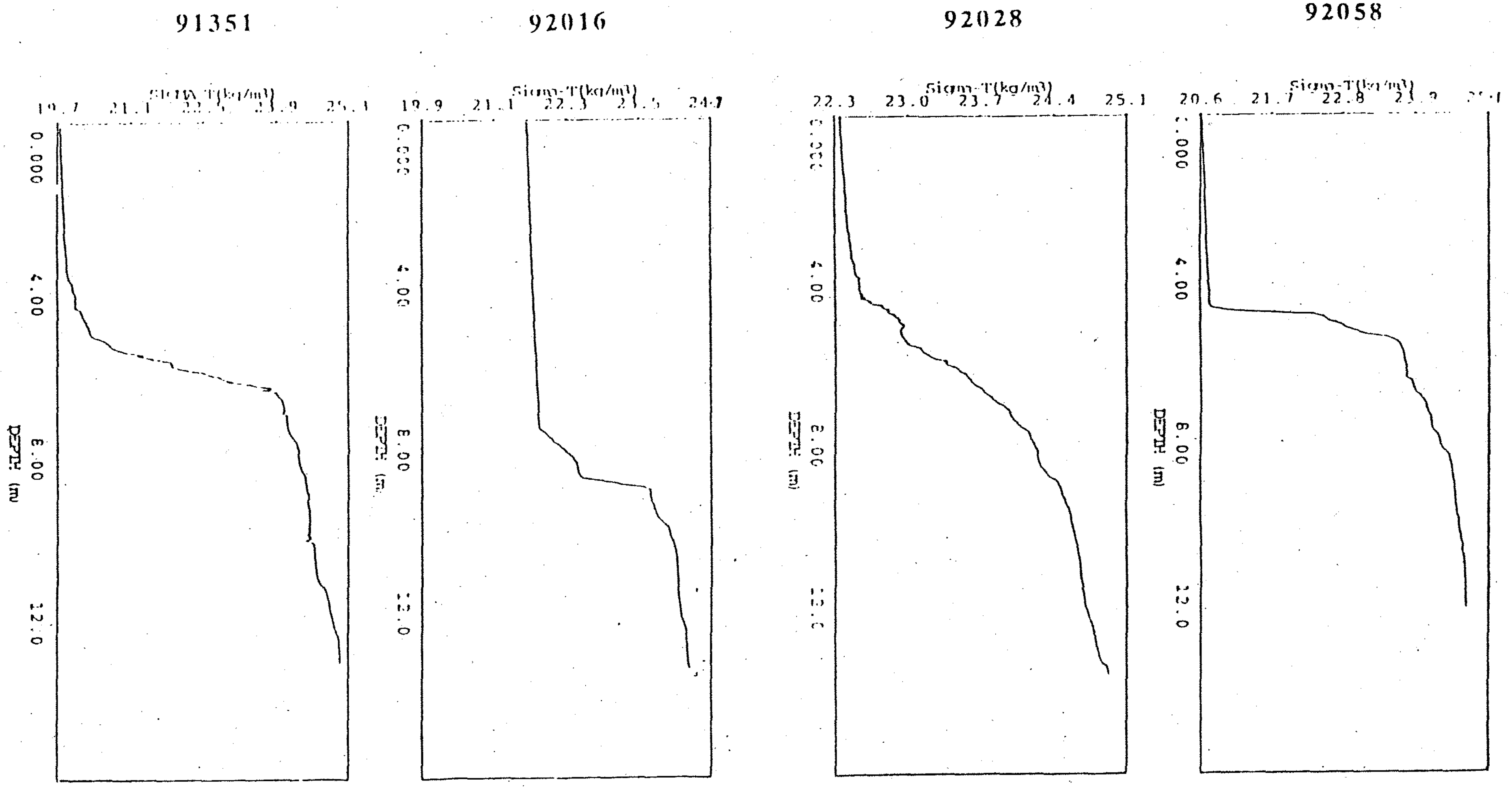


Figure 12 The development of density profiles at station SW101 over the sampling period.

The Role of Sediments in Phosphorus Cycling in the Swan River Estuary

(T.F. McAuliffe, R.J. Lukatelich and N.A. Hill)

1 Introduction

This paper deals with the role played by surface sediments in regulating the nutrient status of overlying waters. As phosphorus is usually considered to be the limiting nutrient in inland and estuarine waters, the discussion will concentrate on phosphorus and refer to nitrogen in only specific examples.

This paper will also briefly describe key methods for understanding the sediments of a water body and present a summary of findings that characterize the sediments of the Swan.

We will also evaluate the significance of sedimentary nutrient cycling in the Swan-Canning system with reference to the comparisons provided by Peel-Harvey and Leschenault systems. Finally we will attempt to draw attention to specific considerations that may provide insight into the future health of the Swan River Estuary.

Sample locations established for the collection of sediment data from the three estuarine systems are shown in Figure 1.

2 The Role of Sediments

The sediments of a water body may act as either a sink or a source of nutrients in the context of the overall system. Under the right conditions incoming nutrients may be gradually stripped from the water column to be bound in organic and inorganic forms within the sediment pool. In this way the sediments of a water body may contribute significantly to its assimilative capacity.

Conversely, given appropriate conditions, a portion of the nutrient store held by the sediments may be released to the overlying water column to support algae blooms and the eutrophication process.

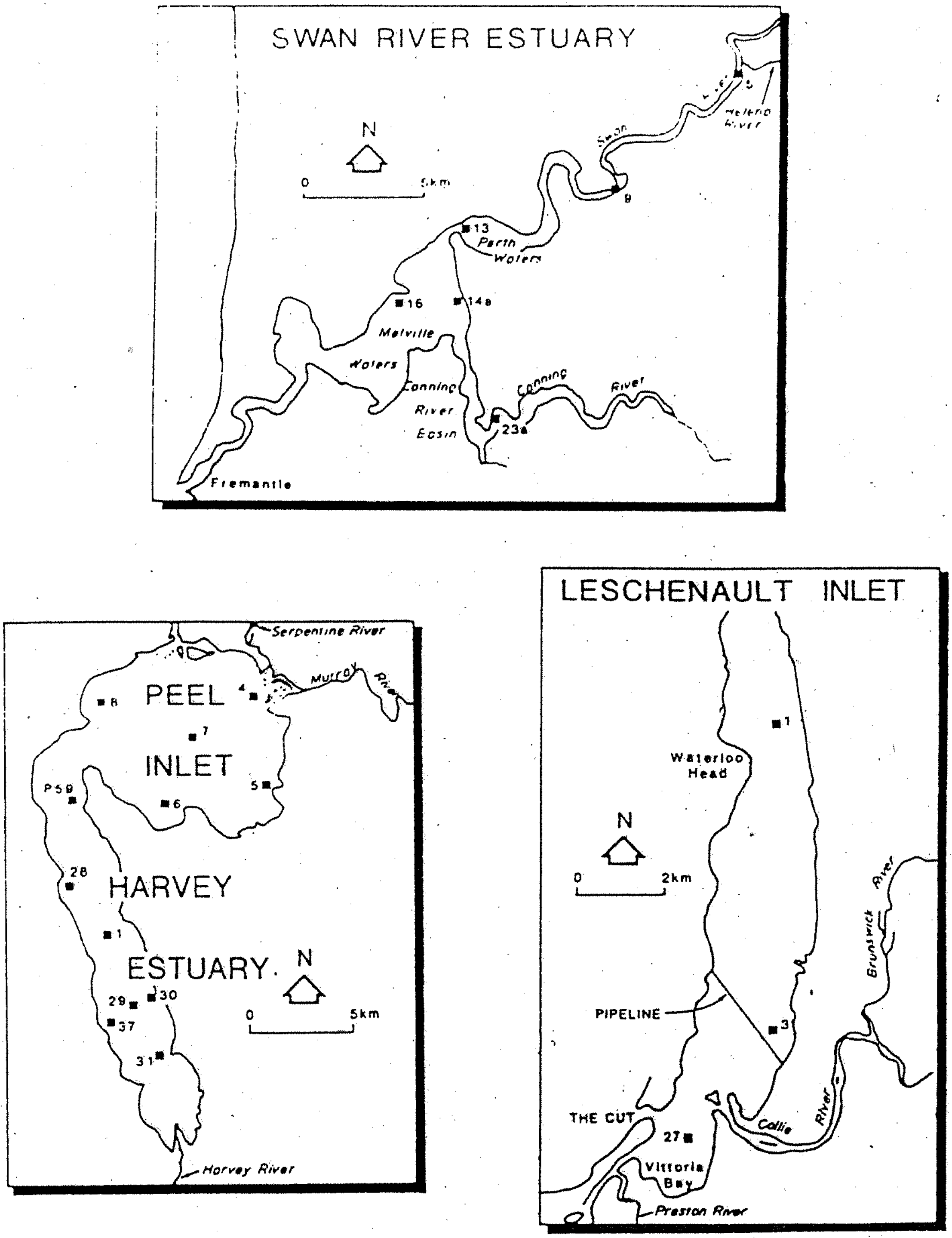


Figure 1 Sediment Sampling Locations in the Swan-Canning, Peel-Harvey and Leschenault Estuarine Systems.

It is typical in enriched water bodies that either process will dominate at a given time and with some spatial variability throughout the water body. We have observed that a switch from adsorbing to releasing conditions may occur over a matter of a few hours in sediments of Harvey Estuary.

To provide an idea of the sediment phosphorus store held in the Swan we can make some approximations (Table 1).

Table 1 Approximate Sedimentary Phosphorus Stores Held in South-western Estuaries

	Total P Conc (µg/g)	Area (km^2)	TP Store (t)	Release Rate ($mg/m^2/d$)
Swan-Canning	877	53	2,500	6.2
Harvey Estuary	431	60	1,300	18.1
Peel Inlet	206	77	790	5.1
Leschenault	331	27	450	---

As an approximation there is around 2,500 tonnes of phosphorus bound in the top 2cm of sediment. At an average release rate of 6.2 $mg/m^2/day$ it would take about 20 years to exhaust the sedimentary store with no additional input.

3. Sediment Study Techniques Used in SW Estuaries

3.1 Baseline Data Collection

Sediment Characterisation
- Grainsize (including silt & clay fractions)
- Water content
- Organic matter (LOI)

Nutrient Status
- Phosphorus fractionation
- Extractable nitrogen forms

Nutrient Release
- Intact core response
- Oxygen and carbon manipulation

3.2 Further Considerations

Evaluation
- Sediment metal concentration (ICP scan)
- More detailed P fractionation
- Interstitial nutrient concentration
- Constituent depth profiles

Experimentation
- Adsorption capacity determination
- Response to pH
- Resuspension considerations
- Sediment- algae relationship

4 A Comparison Between Swan & Other Estuaries

4.1 Sediment Characteristics

The following table compares key sediment characteristics of central basin sites in the Swan/Canning, Peel-Harvey and Leschenault Estuarine systems.

System	Md	%H_2O	TP	NaOH-P	HCl-P	Org-P
Swan (16)	6.8	76	696	391	228	155
Peel (7)	4.5	39	217	73	73	60
Harvey (1)	4.9	79	676	327	148	193
Leschenault(3)	5.9	69	313	110	81	97

The Swan site has fine sediments with a high phosphorus content, including a high P concentration held in the readily releasable (Na-OH extractable) fraction. It is this fraction of sedimentary phosphorus that is released in response to low oxygen conditions at the sediment-water interface. In brief this component represents the P bound by the surface charge of clays and in relatively weak bonds to elements such as iron.

In comparison to more eutrophied southern estuaries the Swan may have even greater potential for internal phosphorus loading than the Peel-Harvey or Leschenault systems.

The percentage distribution of the various phosphorus fractions is not dissimilar between the different systems and the high absolute phosphorus retention by the Swan and Harvey systems may represent evidence of anthropogenic P loading being retained by fine basin sediments.

If we examine the correlation between sediment water content and sediment P concentration we see that increased phosphorus concentration is associated with the finer, more fluid and recently deposited sediments.

While this relationship holds true for the basin sediments of both the Peel-Harvey and Swan/Canning systems, the absolute degree of P retention is most marked in the Swan River Basin (Figure 2a & 2b).

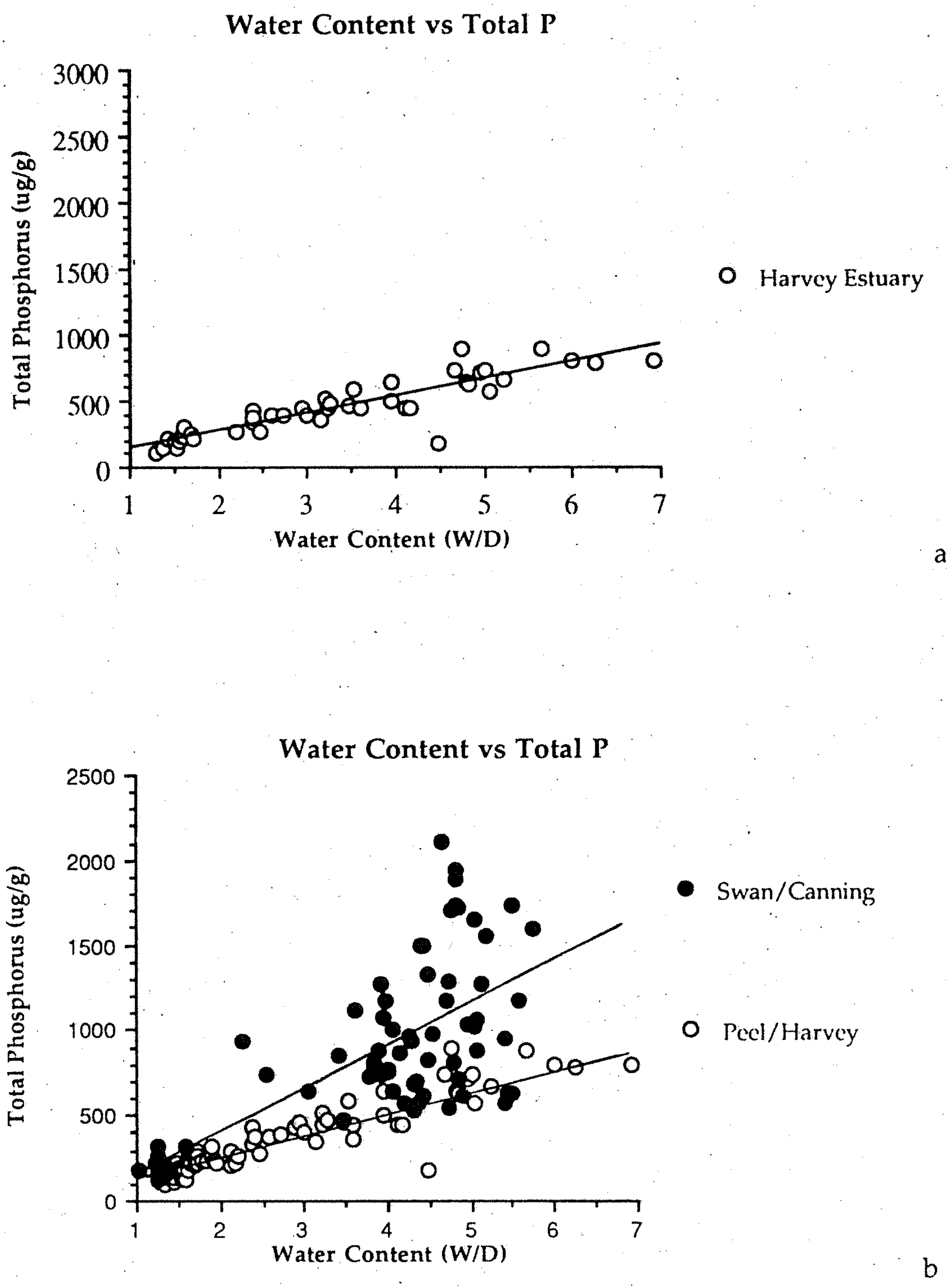


Figure 2 Correlation between water content and total phosphorus in sediments of; a, the Peel-Harvey System and b, the Peel-Harvey and Swan-Canning System.

We do not know how this relationship would be represented without the influence of external P loading from humankind's activities. We do know, however, that the Peel-Harvey system has historically received and retained a considerable phosphorus loading. The sedimentary record indicates that this effect may be even more pronounced in the Swan/Canning system.

Given that the Swan-Canning system receives and retains a high phosphorus loading, is this important to the system, is it significant from a water quality perspective. In attempting to answer this question we need to examine the phosphorus release characteristics of the Swan sediments.

4.2 Phosphorus Release

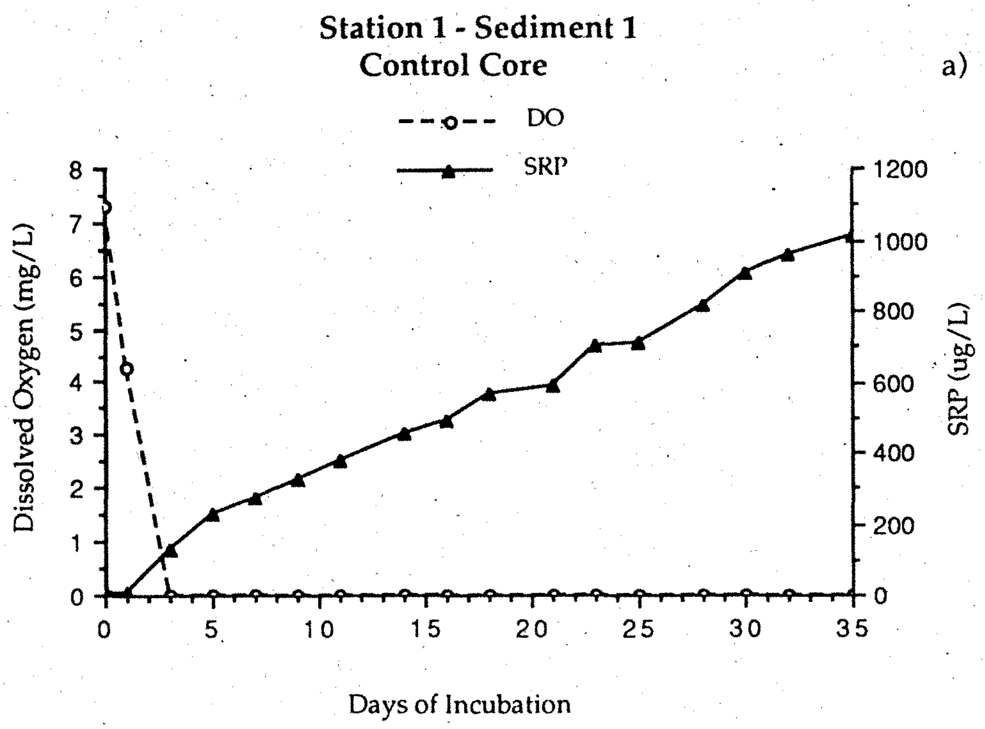
The following table represents average Total Phosphorus release rates measured as 10 day mean values in intact sediment-water cores, collected from either the Swan, Peel or Harvey estuaries at central basin locations.

Total Phosphorus Release Rates (10 day) During 1989

	Total Phosphorus (mg/m^2/day)		
	Swan Basin (16)	Peel (7)	Harvey (1)
Nov	0.9	6.7	- 0.2
Dec	1.6	26.5	20.4
Jan	0.1	16.8	18.9
Feb	1.9	31.8	17.6
Mar	0.9	0.6	64.4
Apr	3.7	2.0	42.9
May	0.5	3.2	2.0
Jun	2.2	3.5	- 0.2
July	-4.9	7.4	1.9
Aug	2.0	18.4	75.4
Sep	1.0	5.1	21.5
Oct	1.5	---	12.2
Mean	1.1	11.1	23.1

Even though the potential for nutrient release from Swan sediments is at least equal to the Peel-Harvey system, only relatively low release rates from the Swan central basin sediments are evident.

The high release rates measured at the sediment-water interface in the Peel-Harvey system are due largely to low dissolved oxygen concentrations in the overlying water. The dissolved oxygen concentration of overlying and interstitial water is a critical determinant of the rate of phosphorus release from sediments rich in Na-OH extractable P (such as our south-western estuaries). Microbial degradation of organic matter occurs continuously in the upper sediments of these estuaries effectively consuming oxygen from the dissolved oxygen pool in the bottom waters. Under stratified conditions very little oxygen can be supplied to bottom waters from the surface, thus the dissolved oxygen concentration at the sediment-water interface falls. If sufficient organic matter remains to be broken down after the dissolved oxygen has been consumed, other substances are reduced during anaerobic respiration. One such substance is iron which is reduced from a 3^+ to a 2^+ state. Much of the P bound in the Na-OH extractable fraction is bound in iron-phosphate-hydroxy complexes which become soluble when Fe^{3+} is reduced, releasing reduced iron and phosphate to interstitial and overlying water. This process is responsible for the large increase in P release observed in response to falling DO concentrations in the Peel-Harvey and other enriched estuaries (Figure 3).



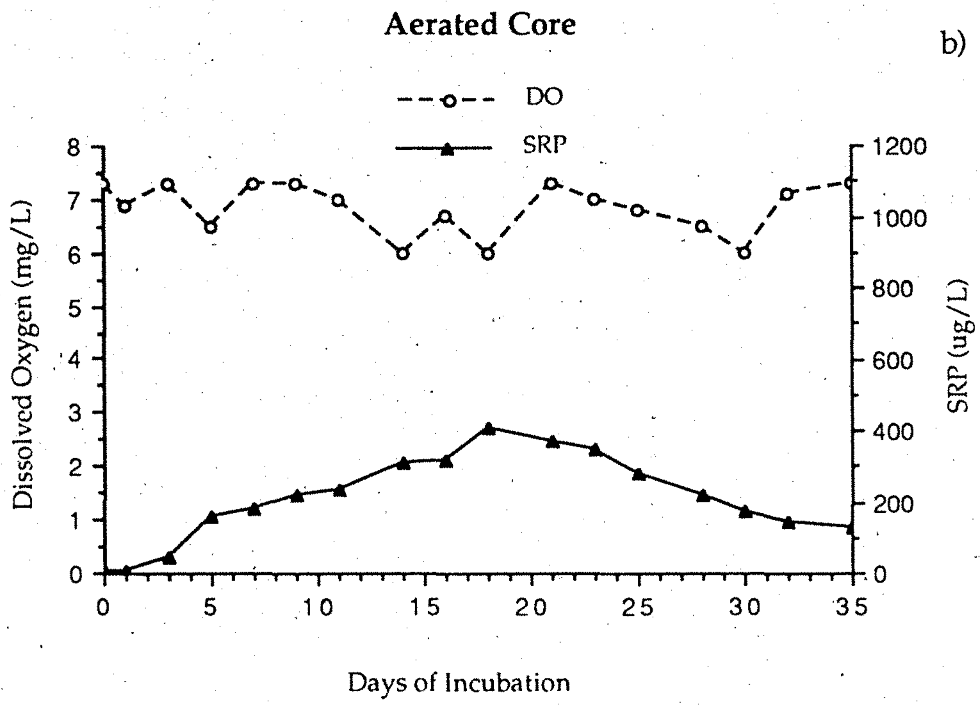


Figure 3 Changes in water column concentrations of DO and SRP in station 1 sediment #1 under a) control and b) aerated conditions

This same response to falling dissolved oxygen has also been observed in sediment-water cores from the Swan (Figure 4). When oxidisable carbon levels at the sediment surface are sufficient to deoxygenate the sediment-water interface, the Swan sediments will respond with notably increased phosphorus release rates. However these observations have to date been limited to locations upstream of the main basin and on isolated occassions only. As the data presented in the following paper will indicate such a response may have recently been observed during field monitoring, at upstream locations. It is also likely that this same process may lead to deoxygenation, increased nutrient release, localised phytoplankton blooms and fish deaths in upstream embayments.

To date the main basin of the swan Estuary appears relatively free of sediment nutrient release stimulating phytoplankton blooms.

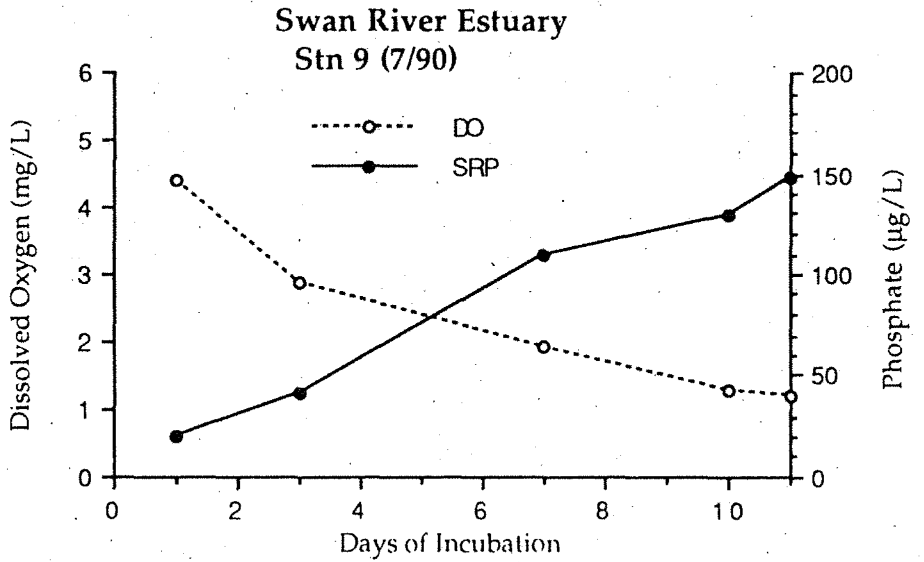


Figure 4 Dissolved oxygen and Phosphate concentration in an intact sediment-water core collected from the Swan River Estuary (location 9).

In the Peel-Harvey system the yearly cycle of phosphorus and phytonplankton follows the pattern shown below.

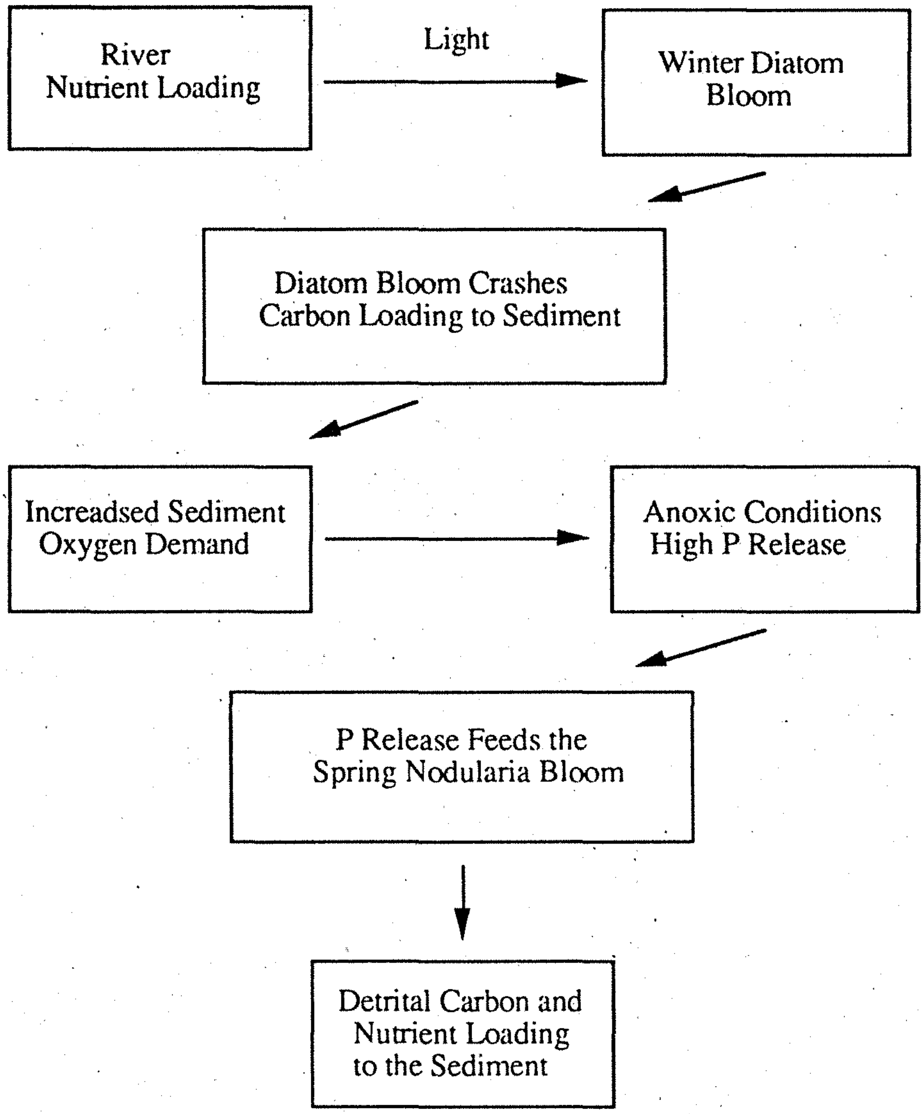


Figure 4 Sequence of Events Leading to *Nodularia* Blooms in Peel-Harvey.

Key considerations in this sequence of events are:

the uptake of incoming nutrients by diatoms,
die off of the diatoms and carbon loading to the sediment;
anoxic sediments releasing high P concentrations;
the ability of Nodularia to take advantage of the nutrient release.

In the Swan River Estuary the nutrient store is available in the sediments with a large component available for release in response to anoxic conditions, similarly the incoming nutrients with river flow are taken up by primary producers (largely phytoflagellates in the Swan), furthermore it is reasonable to expect that high sediment P release would stimulate a phytoplankton bloom. The critical factor that may be missing from this cycle in the Swan main basin is the detrital carbon loading to the sediments (the crash of the winter diatom bloom in Harvey Estuary). An alternative hypothesis may be that the detrital carbon loading to the Swan sediments is oxidised without exhausting dissolved oxygen at depth, through competition by other electron acceptors such as riverine nitrate loading.

Paul Lavery will discuss the phytoplankton dynamics of the Swan in more detail shortly and speculation regarding the absence of a diatom crash in the Swan is best left for him to discuss. For the purposes of sediment nutrient considerations in the Swan it is imperative to note that it is only the absence of sediment oxygen demand, driven by detrital carbon loading, that prevents the considerable sedimentary phosphorus store of the Swan assuming the internal loading significance evident in the Peel-Harvey system.

5. Research Priorities (further work)

General Aim

1. To determine what conditions will result in high nutrient release rates.
2. To provide management based evaluation of key sedimentary processes and aid in predictive decision making.

Experimental

Examination of factors controlling P release.
Evaluation of the potential for internal P loading.
Estimation of the sediments adsorptive capacity.
Evaluation of the long-term implications for continued nutrient and carbon loading to Swan sediments.

Methods

Primarily achieved by laboratory-based incubations with limited in situ work.

Sediment Monitoring Priorities

Sediment oxygen demand; initially establish any seasonal trends then infrequent at numerous sites
In situ P release; infrequent (seasonal) at key representative sites.

Acknowledgements

The work leading to this paper was funded primarily by the Waterways Commission of Western Australia, we are indebted to staff of this body and The Centre for Water Research (UWA and Murdoch) for their assisstence and support.

Swan Canning River Estuary - Primary Production

P. Lavery , W. Hosja and G Bastyan

Many aspects of primary production in the Swan River Estuary are common to other estuaries; the major groups of primary producers are phytoplankton, macroalgae and seagrasses and their biomass and distribution are affected by several factors including substrate, light and nutrient availability, temperature and salinity. These factors are all linked directly or indirectly to the hydrologic cycle and it is the inter-annual differences in these events that generate notable changes in estuarine productivity.

There are also significant differences between the Swan River Estuary and other S-W Australian estuaries that have been studied, such as the Peel -Harvey System. One such difference is the degree of influence that the summer intrusion of marine waters have on the primary producer assemblages. The influence of this becomes apparent when examining the dynamics of the primary producers as is demonstrated below.

Phytoplankton

The phytoplankton of the estuary are dominated by diatoms and flagellated, unicellular algae (phytoflagellates), the biomass and composition of which varies seasonally and spatially in response to hydrologic events affecting salinity and nutrient concentrations. Two distinct biotic zones occur within the estuary, the upper/middle reaches and the lower reaches, a zonation which applies equally to macroalgae and seagrasses. The geographical division between the lower and upper estuary vary but are determined by the degree of saline intrusion into the estuary. The generalised spatial and temporal changes in phytoplankton are summarised in Table 1.

	Winter	**Spring**	**Summer**	**Autumn**
Lower	*Skelatonema/Chaetoceros*		*Prorocentrum*	marine diatoms and dinoflagellates
Upper	*Chlamydomonas*	*Eutreptia*	*Cryptomonas*	

TABLE 1 Generalised seasonal phytoplankton species composition for the different reaches of the Swan River Estuary.

In general terms, the lower estuary is dominated by diatoms in winter and spring, the major species being *Skeletonema costatum*, but over 360 other species have been recorded. Under freshwater influences the upper estuary is dominated by brackish water species, principally diatoms, such as *Melosira, Cyclotella* and *Nitzchia*, but also other of species such *as Chlamydomonas*. Phytoflagellates such as the dinoflagellate *Prorocentrum* dominate during spring. Chlorophyll 'a' concentrations of over 220 ug/l have been recorded during spring blooms, but values are typically less than 100 ug/l.

With the intrusion of saline water into the estuary during summer and autumn lower reach species such as *Skelotonema* flourish in the increasingly saline conditions of the middle reaches. Meanwhile, in the upper reaches, the winter bloom degenerates as the winter nutrient flush ceases, and is replaced by species such as *Eutreptia* and *Cryptomonas*. As marine intrusion intensifies, the system moves towards a highly diverse, low biomass community characteristically dominated by marine diatom species. The winter rains however initiate freshwater discharge and a return to dominance of brackishwater species.

The principal driving force behind phytoplankton succession is the seasonal change in salinity while biomass seems to respond to seasonal loading of nitrate and phosphate to the system. This is similar to the Peel-Harvey system where there is a shift from Cyanobacterial blooms in spring to diatom blooms in winter and late summer. However, under 'normal' conditions, there is an important difference between the systems; there are few large scale collapses of blooms in the Swan system, which may be due to the salinity limitation on composition. As salinity increases during summer, a gradual rather than sudden decline in the biomass of freshwater species occurs. Simultaneously there is an increase in the biomass of marine diatom species. Consequently, there is no drastic loading of carbon to the sediments which could support nutrient remineralisation and initiate an bloom cycle, as in the Peel-Harvey Estuary.

All of the above suggests that production in the Swan River Estuary may be largely dependant on external nutrient loading. This, highlights a concern previously raised that any change to the hydrology of the system that reduce marine intrusion and flushing will in all likelihood result in more visible signs of eutrophication. However, under unusual circumstance, quite dramatic differences arise that indicate the potential for the Swan Estuary to switch to an 'internal loading system'.

Unusual rains occurred at Christmas 1991 followed by a dense bloom of the dinoflagellate *Prorocentrum minimum* in the upper reaches. This bloom eventually collapsed, presumably due a depletion of water column nutrients, following which there was a widespread decline in dissolved oxygen concentrations and fish kills (Fig 2 a). The time series of dissolved oxygen levels in the system shows that shortly after the fish deaths, saline intrusion and flushing resulted in a return to higher oxygen levels (Fig 2b) except in some deep areas of the middle reaches. At the same time an increase in phytoplankton biomass was noted (Fig 3), presumably supported by the remaining water column nutrients as well as nutrients released from the sediments during the period of anoxia.

On the 8th February record rainfall was recorded, resulting in immediate stormwater runoff into the river from urban areas (Sites 7 -11) and delayed run-off to the upper reaches from rural areas. In the 'urban' region the water column became stratified as incoming freshwater displaced saline water at the top of the water column (Fig 3a), but flowed over denser, deoxygenated water in the deeper areas (Fig 2c). This was followed by a period of deoxygenation at the bottom of the water column throughout the middle reaches of the system (Fig. 2c,d), possibly through BOD in the sediments, which coincided with high nutrient levels at the bottom of the water column (Table 2) and a dense dinoflagellate bloom at the surface (Fig. 3). This state persisted in the middle reaches, around Rivervale, until the freshwater runoff diminished and saline intrusion reduced the level of stratification (Fig 2e). In the upper and lower reaches of the system oxygen stratification quickly broke down and oxygen concentrations increased, as is shown in the structure at the Causeway and Guildford (Fig. 4), although more recently stratification and deoxygenation has recurred as the salt wedge intruded further upstream. It is not unreasonable to suggest that the high nutrient concentrations were derived from sediment remineralisation under anoxic conditions and that this acted as an internal nutrient source for a phytoplankton bloom cycle, as in Harvey Estuary. The most recent data shows that as the saline wedge intruded upstream into areas with algal blooms (eg Guildford), stratification and deoxygenation occurred again in the bottom waters.

These events not only resulted in unseasonal blooms, but they also reset the normal seasonal cycle of phytoplankton composition. This is evident in Figure 3, where at Site 5 the normal summer-autumn increase in diatom biomass halted following the February rain event, with a subsequent domination by dinoflagellates which is typical of winter/spring. It is only later, when normal salinity and oxygen structures returned , that the summer domination by diatoms began to be re-established.

TABLE 3 WATER QUALITY AT SITE 9 (RIVERVALE) ON 20 FEBRUARY 1992.

	Diss. O_2	NO_3-N	NH_4-N	PO_4-P	Chl 'a'	Tot N	Tot P
Surface	8.5	<0.02	0.03	0.03	0.043	1.2	0.08
Bottom	0.5	<0.02	0.73	0.60		1.3	0.67

Macroalgae

The macroalgal species in the estuary are similar to those in other south-western Australian estuaries. The most comprehensive survey of macroalgae was undertaken by Allender in the late 1960's and identified two principal benthic community forms in the estuary: Sand and mud communities, and Rock Formation communities. Within each group are supra-littoral, littoral and sub-littoral assemblages. The mud and sand communities are restricted largely to the sub-littoral zone, and the most common species found was *Gracilaria*, the plants usually being detached and possibly dying. Upstream of Perth Water the system was devoid of benthic macroalgae with the exception of occasional banks of *Gracilaria* washed into deeper channels although *Potomogeton* was noted in the most upstream sites.

A far greater diversity of species was recorded for the Rock Formation. These included *Enteromorpha, Ulvaria* and *Bangia* in the supra-littoral, *Cladophora, Polysiphonia* and *Gracilaria* in the littoral and *Vaucheria, Gracilaria,Ulva* and *Colpomenia* in the sub-littoral, with *Enteromorpha, Cladophora* and *Melosira* dominant in the winter.

The total number of species at any site was correlated positivly with salinity. Consequently, fewer species were recorded with increasing distance from the estuary mouth. Four distinct assemblages with were observed by Allender which correspond to regions of the system (Table 4).

TABLE 4 MACROALGAL ASSEMBLAGES IN THE SWAN RIVER (based on Allender, 1970)

REGION	**Mean Salinity**	**COMMENTS**
Lower to Point Preston.	25 ppt	Included 9 exclusively marine macroalgae that occurred only in the region up These were in late summer and early winter, (the period of peak salinity)
Mid-transition species diversity *Hormosira*	23 ppt	Point Preston to Melville Water; characterised by a gradual reduction in and included some species not recorded closer to the mouth, such as
Mid cut off diversity. The	22 ppt	Melville Water to Matilda Bay, the area of most dramatic decrease in species upper limit of 14 benthic species.
Upper transition upper reaches	< 22 ppt	Gradual decrease in diversity with increasing distance upstream. At extreme freshwater species *Rhizoclonium* and *Potomogeton* occurred.

Overall, species diversity in the estuary was greatest in autumn (43 species) and least in spring (28 species) and while half of the species occurred throughout the year most grow least in winter/spring, particularly green and red macroalgae. This winter decline of biomass is consistent with observations in Peel Inlet, where the biomass of both dominant species declines over winter in response to lower salinity, temperature and light conditions.

Allender collected no biomass data but noted that some species, such as *Cladophora, Enteromorpha Ulva , Polysiphonia,* and *Gracilaria* 'bloomed' in late spring. Calm weather conditions also allowed short-term biomass accumulation but these were rapidly removed under 'dynamic' conditions.

A more recent survey has been undertaken of the Fremantle to Melville Water and some preliminary results are available. Unfortunately, these results do not yet include the rocky species which Allender found on rigid substrates and man-made structures. However, within the mud areas from the mouth of the estuary to Melville Water no differences in species composition were noted. The dominant specie was the red macroalgae *Laurencia* spp. with subdominant red and green algae such as *Hypnea, Enteromorpha, Laurencia, and Chondria.* The community appeared to represent a typical marine intrusion community, which would be expected at this time, although unlike Allenders' observations, it was not dominated by *Gracilaria*, except in the Canning River Estuary. Benthic accumulations of *Caulerpa* were also noted, but are not mentioned by Allender.

The recent survey does not allow a full comparison of changes that may have occurred between the 1960,s and today but it does suggest that macroalgal banks are continuing to accumulate on the shallow flats and that during summer the species composition of the lower estuary is dominated by marine species. The survey also recorded *Caulerpa* and healthy *Halophila* under 100% macroalgal cover. This would suggest that while algal accumulations do occur over summer, they do not result in the death of underlying species. Presumably this is because of the tidal and wind-driven mixing process that do not permit large scale accumulations such as those recorded in the Peel and Leschenault Inlets.

From the recent survey and studies in the Peel Inlet it is possible to target light, salinity and nutrient availability as the most likely factors controlling growth . Biomass data and tissue nitrogen data for macroalgae in Peel Inlet show marked seasonal trends. Growth and biomass are lowest in winter(Figs 5 & 6). Differences in growth rates of plants suspended at different heights in the water column shows a marked reduction in biomass in the deeper samples, indicative of light limitation (Figure 5). The recent survey also noted that in the Swan Estuary, macroalgal biomass generally occurs above 2–3 m depth, again indicating light limitation at depth.

Nutrient limitation of macroalgal growth in Peel Inlet has been demonstrated for some, but not all, species. In the case of *Chaetomorpha,* dense, relatively stable banks of algae generate anoxic conditions over the sediment such that sediment nutrient release occurs, elevating nutrient concentrations around the algae and supporting growth (Table 5). This reduces the species' dependence on water column nutrients and there is no annual cycle of nutrient limitation. *Ulva* on the other hand is incapable of forming dense banks that facilitate sediment nutrient release and is reliant on the water column for nutrients. Owing to low biomass during winter, the period of peak nutrient concentrations, *Ulva* is unable to store sufficient nutrients for the summer growth period and is regularly nitrogen limited in summer (Fig. 6).

TABLE 5 WATER QUALITY JUST ABOVE ALGAL BANKS AND IN THE ALGAL BANK JUST ABOVE THE SEDIMENT.

	PO_4	NH_3 (mg/L)	Diss. O_2
Above algal bank	6	27	0
Within bank/above sediment	52	664	6.7

While nutrient availability can limit macroalgal biomass the effect seems generally to be on an inter-annual, rather than annual, scale. This is evident in the association of major shifts in macroalgal composition in Peel inlet which are linked to shifts in the inter-annual hydrologic and nutrient cycling events. This has not been verified for the Swan River Estuary and in the absence of large, persistent banks of algae capable of generating sediment nutrient regeneration there may be a greater potential for limitation of algae since they will be permanently dependant on the water column for nutrients.

In conclusion, it is probably reasonable to say that, at this stage, the lower Swan River Estuary is a healthy system in respect of macrophyte biomass and diversity. With the possible exception of the Canning River, there does not seem to have been an noticeable increase in the biomass or distribution of macroalgae. Reports of decaying weed on the shores litter the history of the Estuary and so it is unreasonable to expect to eradicate similar occurrences in the future.

Seagrasses

Seagrasses are an important component of the estuarine flora and have been studied in detail by Karen Hillman. The dominant seagrass is *Halophila ovalis,* with only a small amount of *Zostera* having been recorded near the estuarine mouth (Fig 1b). *Zostera* is similarly restricted in other estuaries and appears to be very susceptible to changes not only in salinity but also in light penetration. Experience in the Peel-Harvey System has shown that *Zostera* does not grow only in the entrance channel and only below -1.3m AHD, presumably due to poor light penetration below that depth.

Unlike some other meso-eutrophic estuaries in WA, the seagrass in the Swan River Estuary is a large, and very important, component of the primary productivity. Maximum growth rates of up to 40g dwt m-2 are recorded in summer, about twice the spring and autumn rates, while effectively no growth occurs in winter. At peak biomass the species covers up to 600 ha, or 20% of the lower estuary, accounting for about 350t dry weight.

The vast majority of seagrass in the Swan River is found below the Narrows Bridge and at depths of less than 2m. Its occurrence in the Canning River is variable between years. This distribution appears to be affected principally by salinity and light limitation. The plant grows best in the range 14 - 39 ppt salt, but can tolerate salinities as low as 9 ppt for up to 6 weeks in the estuary. Long exposure to freshwater kills the plant, accounting for the ephemeral distribution of the plant in the Canning River Estuary, where occasional prolonged period of low salinity occur. Under normal conditions, winter depression of salinity is not considered sufficient to result in a severe decline in biomass. In the Swan River, the Narrows Bridge marks a point of significant change in the average annual salinity which appear to coincide with the tolerance limit of *Halophila*.

Light is probably the most important single factor affecting the growth of *Halophila*. The photic depth in the lower estuary is approximately 2-3m for most of the year and about 1 m in the upper estuary. This average photic depth approximately corresponds to the depth limit of *Halophila*. Hillman suggests that even if all other factors were suitable for growth, light limitation would prevent the growth of the species in the upper estuary. The lack of growth of *Halophila* in winter can be attributed to the decreased light penetration which results from increased sediment load in the water column, and tannin stained freshwater run-off. In summer months, occasional periods of low growth result from phytoplankton blooms and sediment resuspension events which increase light attenuation.

While no detailed data is currently available, preliminary data from the recent Waterways Commission survey indicates little change in the distribution of *Halophila* in 1992 compared with Hillman's 1985 reports. While a small decline in the Canning River biomass may have occurred, new records of biomass have been noted in areas previous devoid of the species.Again, this indicates that in the lower reaches the estuary no deterioration in the status of the benthic plant community has occurred and that the distribution of Halophila will vary, as is expected from this 'pioneer/ species of seagrass.

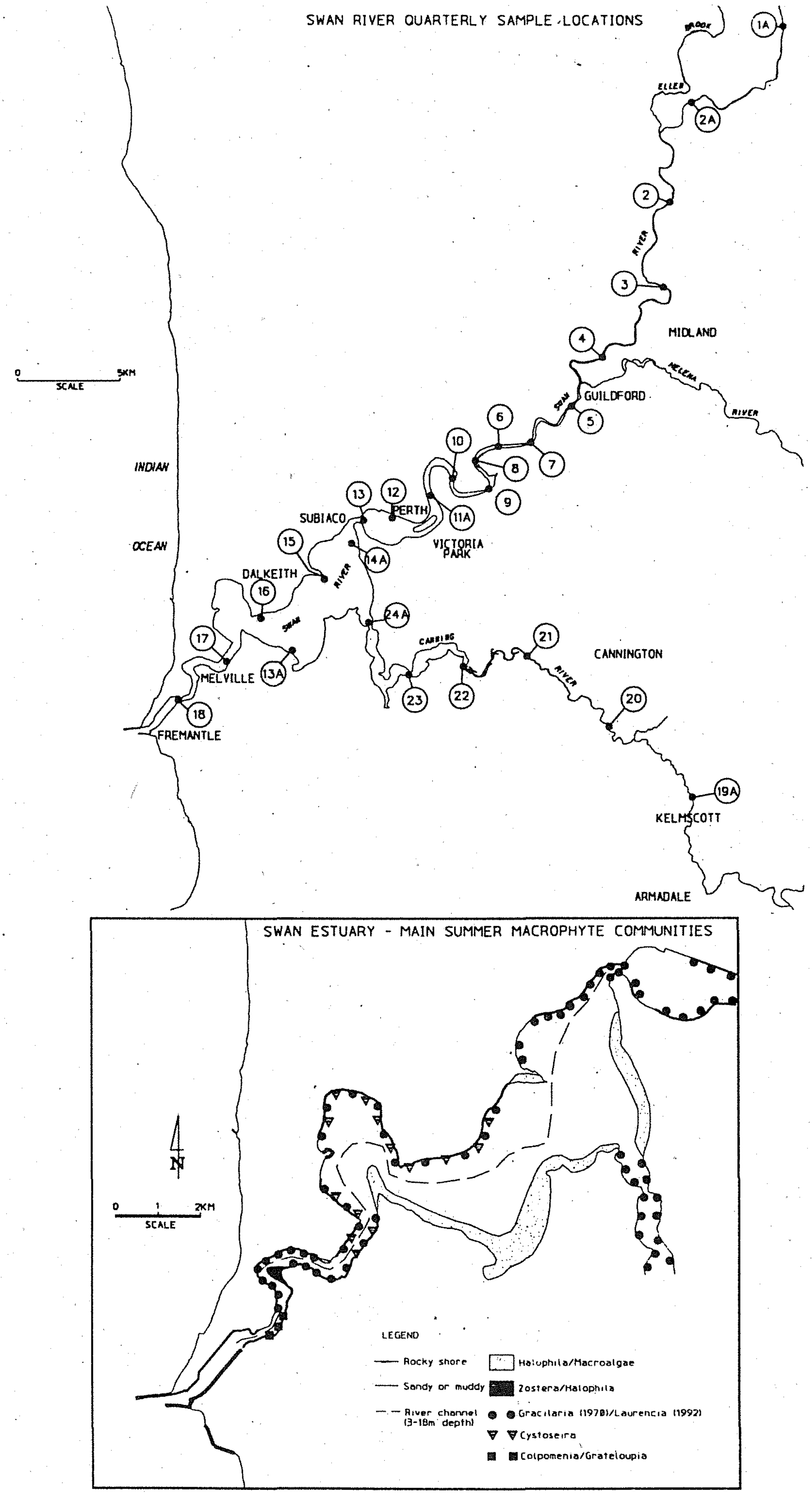
Conclusions

The data suggests that the Swan River Estuary has two distinct zones of primary productivity, the upper and lower reaches. While blooms regularly occur in the upper estuary this is not a new or unusual occurrence. Algal problems have been reported in the estuary since European settlement. Non-the-less, there are reasons for concern. The foremost is that while productivity in the system is generally dependant on external nutrient loading, recent indications are that in unusual conditions, internal nutrient regeneration can support blooms. With continued nutrient loading from the rural catchments, this has the potential to result in self-sustaining phytoplankton bloom cycles, as noted in other estuaries. This highlights the need to maintain the current hydrodynamic cycle and prevent excessive carbon and other nutrient loading to the system.

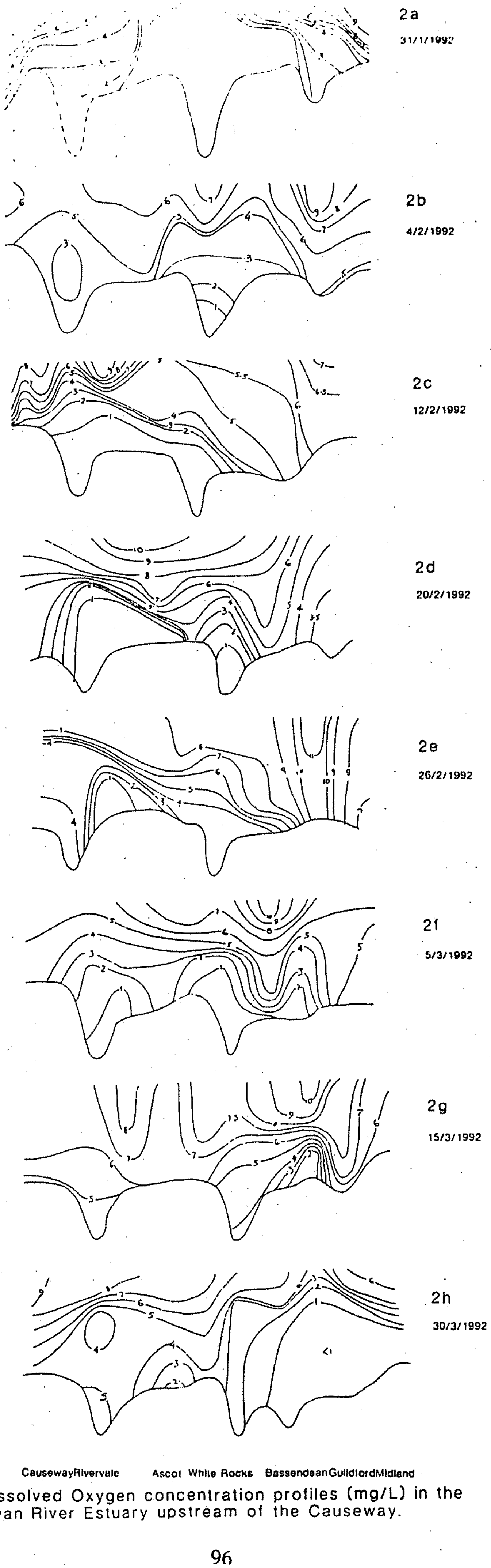
The lower reaches of the system contain an apparently healthy benthic macrophyte community. Seagrass biomass and distribution is often used as an indicator of ecosystem health. In the Swan River estuary, *Halophila* biomass and distribution appears to have altered little in the past 7 years. Again, this is probably due largely to the flushing of the system which prevents algal accumulation, and the seasonal salinity cycle which prevents the sustained growth of any one species for more than one or two seasons.

All of the factors affecting productivity are linked to the annual hydrologic cycle, in particular the volume and timing of freshwater input. This affects light and nutrient availability, salinity, temperature, and the density stratification of the water column. We are limited in our ability to control many of the consequences of freshwater input, in particular the volume and timing and its effect on salinity and density stratification. However, we can manage the nutrient load that these flows contribute to the system and its seems logical that this is where management efforts such continue. It is important that a baseline biological and water quality monitoring programme continue but macroalgal monitoring can probably be fairly infrequent. It would be more prudent to place effort into understanding and monitoring the phytoplankton productivity, since this will respond first to changes to nutrient loading and hydrodynamics of the system. Determination of the assimilative capacity of the upper reaches of the system is important if we are to establish appropriate catchment management criteria.

Finally, given the likelyhood that algal blooms are here to stay and that catchment management alone can only go so far towards managing the system, it may be appropriate to begin investigating 'in-estuary' or 'interventionist' management options. These might include measures such as sediment ammendment or deliberate tannin additions to the system to control either the blooms or nutrient cycling in the upper reaches.



The Swan-Canning Estuary.
Locations of water quality monitoring sites are shown and generalised macrophyte distributions. FIGURE 1



Dissolved Oxygen concentration profiles (mg/L) in the Swan River Estuary upstream of the Causeway.

FIGURE 2.

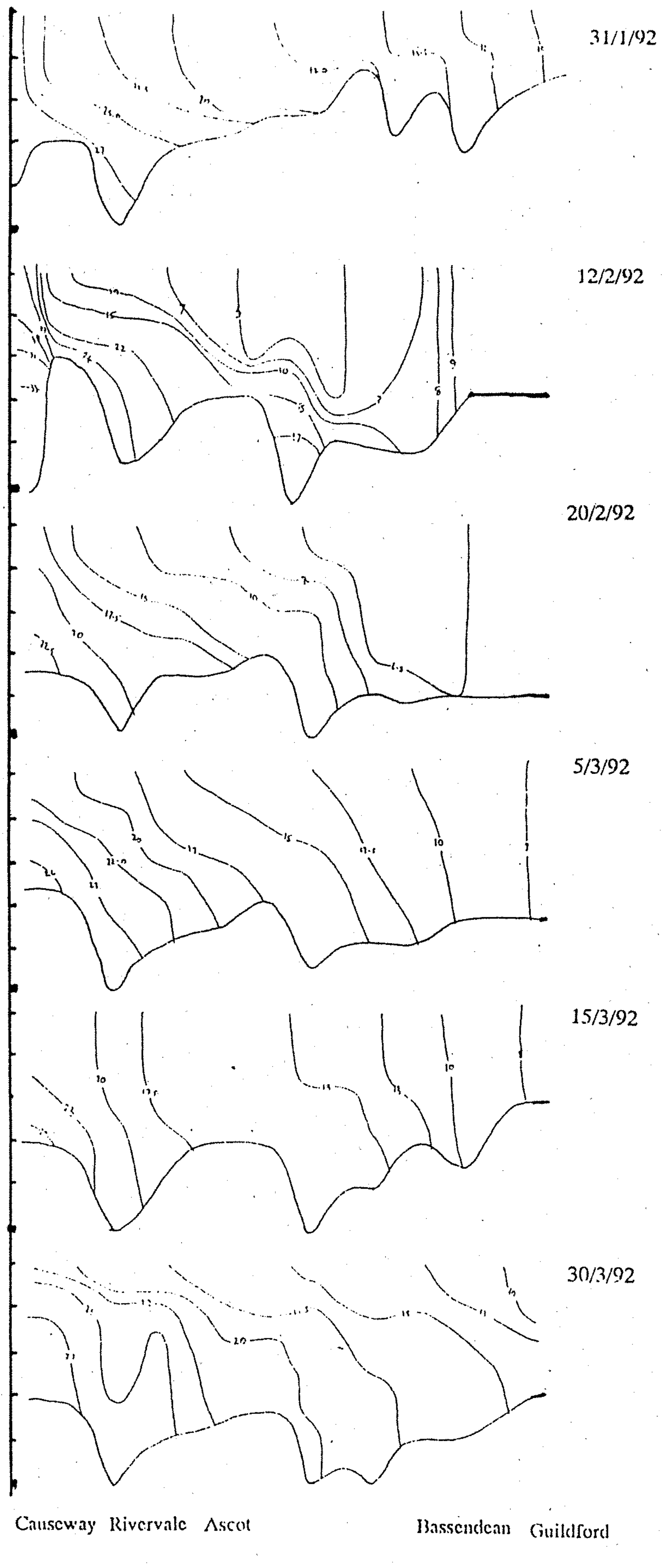


Figure 3a Salinity profiles for the Swan River (Causeway to Guildford) for early 1992.

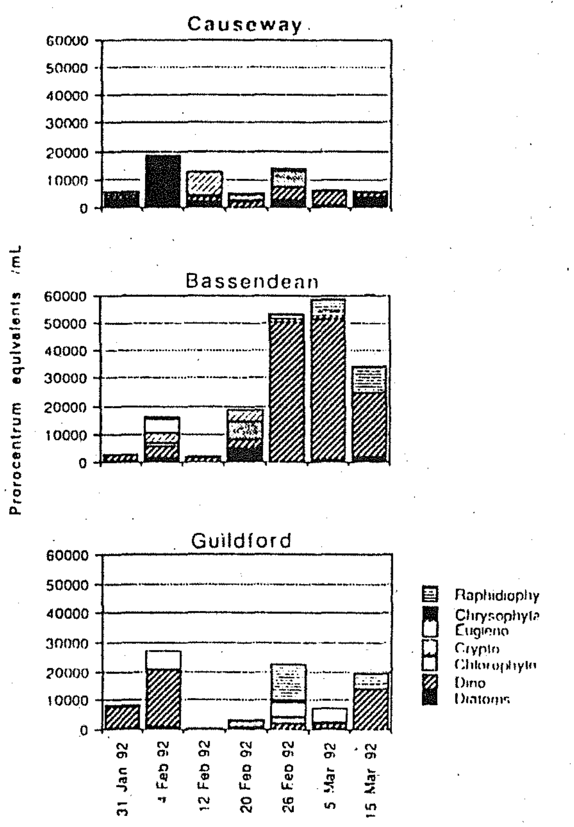


Figure 3.
Biomass of Phytoplankton in the Swan River.

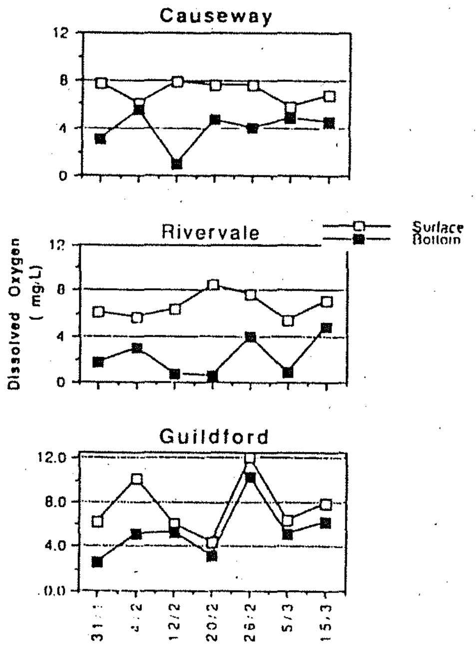


Figure 4.
Dissolved Oxygen Concentrations at three sites in the Swan River.

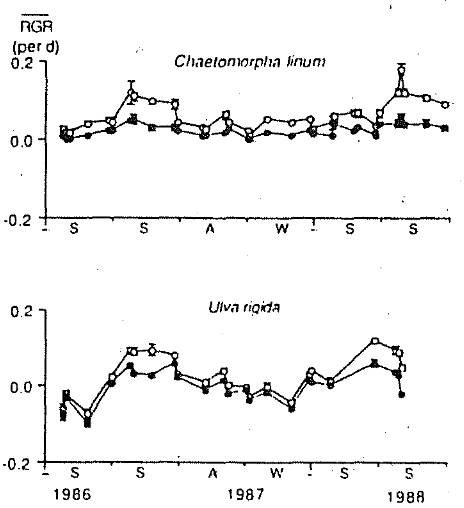


Figure 5.
Growth Rates of Macroalgae in the Peel Harvey Estuary.
(o) at the surface of the water column,
(•) at the bottom of the water column.

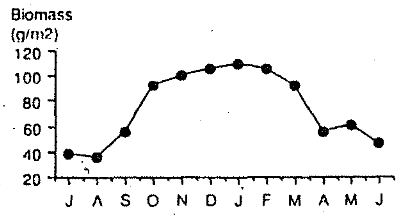


Figure 6.
Seasonal Change in Biomass of Chaectomorpha in Peel Inlet.

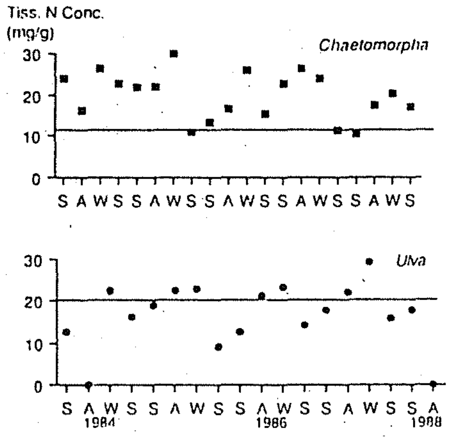


Figure 7.
Tissue Nitrogen Concentrations of Macroalgae in Peel Inlet 1984-1988.

Secondary production: bacteria to birds

Luke J. Pen and Thomas H. Rose

1. Introduction

1.1 The estuary and its fauna

The fauna of estuarine ecosystems is characterised by low species diversity and the abundance and productivity of a few species (Boesch 1974, Day 1981, Hodgkin & Lenanton 1981, McLusky 1981). Low diversity is often associated with stressed environments, and two of the major contributory factors are variation in salinity and dissolved oxygen (Sanders 1968, Day 1981, Pearson 1981, Hodgkin 1987, Grey 1989). As estuaries generally are richer in nutrients than either fresh waters or the ocean their flora can be highly productive and in turn their fauna prolific.

The hydrology of the Swan-Canning estuary is influenced by a Mediterranean climate (Spencer 1956). The estuary experiences major fluctuations in salinity during winter, with much of the system becoming fresh or brackish (0-20 ppt) at this time. By contrast, some regions such as Alfred Cove, can become hypersaline (>35ppt) and marine conditions can extend as far as Guildford on the Swan and Kent St. Weir on the Canning during summer (Chalmer *et al.* 1976, Lenanton 1978, Thurlow *et al.* 1986, Hodgkin 1987).

The penetration of marine and estuarine animals into the middle and upper regions of the Swan-Canning estuary is dependent upon previous winter rainfall. Thus species diversity increases in the estuary when marine salinities influence the fauna for extended periods (Chalmer *et al.* 1976, Hodgkin 1987, Loneragan *et al.* 1987).

The estuary provides a diverse range of habitats characterised largely by variations in substrate, salinity, water depth and the degree of tidal inundation. Habitats within estuaries have been classified according to depth of water covering the bottom substrate, e.g. shallows including intertidal zones (<1 m), and deep habitats (>1 m). They are also classified by zonation within the water column, e.g. euphotic, or by the dominant flora typifying the habitat, e.g. seagrasses and macroalgae beds and emergent vegetation of the intertidal zone. In turn, fauna can be categorised by habitat utilisation (i.e. planktonic, benthic), feeding group (i.e. herbivore, carnivore, detritivore), method of feeding (ie. suspension feeder, deposit feeder), size (i.e. micro, meio and macro) and the degree of tolerance to variation in salinity (i.e. stenohaline, euryhaline and oligohaline).

1.2 Secondary production

The biomass of a population at any time is in dynamic balance with new material being added by growth of individuals and reproduction, and with loss of material as it is removed by predation, excretion, death and decay (Mann 1980).

Secondary production is defined as the excess energy of a heterotrophic organism or population left over after maintenance and respiration, which is available for growth, the production of energy reserves and reproduction (Smith 1977). The energy provided by plants and animals to the heterotrophic component of the ecosystem is called net production. The quantity of net production passed on from one population to another through herbivory and carnivory will vary with the nature of the organisms involved and the relative density of the populations (Smith 1977). Nutrients and energy will also be available for consumption in waste material, such as faecal pellets and in the corpses of dead animals and plants.

2. The estuarine fauna

2.1 Zooplankton

Estuarine holoplankton consists of a large range of tiny organisms such as foraminifera, ciliates, euphausids and copepods (Grindley 1981). The larvae of barnacles, polychaetes and decapod crustaceans typically constitute the meroplankton, while tychoplankton is typified by peracarid crustaceans such as amphipods, isopods and mysids. At times mysids and amphipods may be extremely abundant but copepods usually dominate the plankton.

Little work has been conducted on the zooplankton of the Swan-Canning estuary. Studies carried out in the 1970s showed that the euryhaline species *Sulcanus conflictus*, an omnivore, and *Gladioferens imparipes*, a herbivore, dominated the zooplankton in the spring and autumn, but that the former species became dominant in summer, possibly through predation of the nauplii of the latter species (Hodgkin & Rippengale 1971, Rippengale & Hodgkin 1974ab, 1977, Rippengale 1987). Two other species which have been commonly found in the Swan-Canning include *Oithonia nana* and *Acartia clausi* which are marine species usually restricted to the lower estuary.

Recent work on the macrozooplankton of the lower estuary showed that marine cladocera and copepods dominated the holoplankton with the cladoceran *Penila* sp. comprising 81% of the total zooplankton (Gaughan 1987). Bracyuran crab zoea and a shrimp, *Lucifer* sp., dominated the meroplankton respectively (Gaughan 1987). In the shallows of the middle estuary (<1.5 m), calanoids, amphipods and harpacticoids were numerically dominant (Rose, unpubl. data).

2.2 Benthic micro and meiofauna

Benthic microfauna consists of microscopic organisms such as heterotrophic bacteria, protozoa and fungi. They play a major role in the mineralization of organic matter and the return of nutrients to the water column by bioturbation (Mann 1980). Many are capable of anaerobic fermentation or sulphide reduction in anaerobic sediments. The meiofauna, which grazes upon the detritus and its associated microflora and fauna, chiefly consists of a range of tiny animals such as nematodes, harpacticoid copepods, ostracods and rotifera. The larvae of macrofauna may also be a temporary component of the meiofauna. To date, no work has been carried out on the micro or meiofauna of the Swan-Canning estuary.

2.3 Benthic macrofauna

In the Swan-Canning estuary the macro-benthic community is dominated by polychaete worms, bivalve molluscs and amphipods. Gastropods however, may be very abundant at certain locations in the Swan, e.g. *Velacumantus australis* (Kirke *et al.* 1987, Rose 1987). Seasonal quantitative data on the diversity, abundance and biomass of the benthic community in different regions of the estuary is limited. Most investigations have been been qualitative, taxonomic, physiological or restricted to unpublished honours or Ph.D. theses and technical reports. Much of this work contains limited regional, seasonal or quantitative data (Thomson 1946, Serventy 1955, Blackwell 1969, Chalmer *et al.* 1976, Wallace 1977, Shaw 86, Jones 1987, Rose 1987, 1990ab, 1992).

Based on the distribution of benthic molluscs Chalmer *et al.* (1976) distinguished three biotype regions of the Swan-Canning estuary, namely the upper, middle and lower. Wallace(1977) found 42 benthic species in the shallows and deep waters of the middle and upper estuary during the autumn of 1977, the large majority of which inhabited the shallower depths. Faunal diversity was greatest in the middle estuary and decreased progressively upstream in both rivers. Later studies have confirmed a greater species richness in shallow water benthos than in deep water benthos (Rose 1990ab). Furthermore, Shaw (1986) found that a seagrass bed of *Halophila ovalis* contained a greater density and biomass of benthic invertebrates than adjacent sandy habitat.

The macrobenthic species restricted to the benthic substrate have no direct commercial importance. However, the polychaete bloodworm (Eunicidae) is sought after as bait by recreational fisherpersons and mussels may be collected for food at times in the lower estuary.

2.4 Fish and other nektonic fauna

In contrast to the planktonic and benthic components of the estuarine fauna, quantitative data on the diversity, abundance and biomass of the fish community, including larval fish, in different regions throughout the year have been relatively well documented (Thomson 1957, Lenanton 1978, Chubb *et al.* 1979, Wallace 1979, Gaughan *et al.* 1990, Neira *et al.* 1991, see Potter *et al.* 1990 for other past and recent publications).

A total of 137 species of fish have been collected in the Swan Estuary with approximately 55% of these species classified as marine stragglers, the majority of which were found in the lower estuary (Loneragan *et al.* 1987). Approximately 27 to 37 species or 20 to 30% of the total fish fauna collected would be consistent visitors or permanent residents of the upper Swan-Canning estuary. Of these species only black bream, cobbler, mulloway, Perth herring and mullet species have any recreational or commercial value. Some of the marine visitors, such as sea mullet, utilise the estuary as nursery habitat. Most of the permanent residents, such as hardyheads (Atherinidae), gobies (Gobiidae), yellow tail trumpeter (Teraponidae) and Perth herring (Dorosomatinae) are relatively small and may be considered important consumers of meio and macrobenthos and as prey for larger piscivorous fish and birds.

In addition to the community studies a number of biological and ecological studies of individual fish species in the estuary have been conducted on cobbler, yellowtail trumpeter, gobbleguts, Perth herring, blowfish, the mullet species and the hardyhead species (Kowarsky 1975, Wallace 1979, Nel *et al.* 1985, Chrystal *et al.* 1985, Chubb and Potter 1984,1986, see Potter *et al.* 1990 for other past and recent publications).

Fish are not the only component of the estuarine nekton. The jellyfishes *Phyllorhiza punctata* and *Aurelia aurita* are particularly conspicuous in the Swan-Canning estuary during the summer and autumn. Jellyfishes may be extremely important in cropping phytoplankton and zooplankton and therefore are important in influencing the survival of larval fishes (Hienle 1966, Miller & Williams 1972, Kremer 1976). Large crustaceans are also a component of the nekton and are discussed below.

2.5 Large crustaceans

The western king prawn and the blue manna crab are marine-estuarine opportunists which visit the estuary during its more saline phase, feeding and using it as nursery habitat for juveniles (Potter *et al.* 1983, 1991). The school prawn is capable of living entirely within the estuary (Potter *et al.* 1986, 1989). The estuary also supports four palaemonid shrimps, three of which are marine and one, *Palaemonetes australis*, is estuarine and riverine. This latter species has been studied in detail by Bray (1978). The prawns and crabs are sought after recreationally in the shallows of the estuary, particularly during summer and autumn.

2.6 Avifauna

Birds are exceptionally mobile animals capable of travelling long distances in short periods to exploit temporally and spatially fluctuating resources often outside the reach of many other animals (Siegfried 1981). The Swan-Canning estuary has a wide range of environments which support a total of 87 bird species and as many as 15,000 individuals on occasions (Jaensch 1987). The migratory waders, especially the red-necked stint and the curlew sandpiper, which mainly feed on intertidal zone invertebrates, are an important group, reaching numbers of up to 10,000 during the spring and autumn period. The estuary is especially important to waders in spring when, following winter, muddy shallows have yet to become available in nearby wetlands. Cormorants and coots may also be present on the estuary in large numbers.

2.7 Salt-marsh fauna

Huge numbers of mosquitoes breed in the fringing vegetated tidal flats throughout the year, but mostly in summer (Thurlow *et al.* 1986). Spiders, amphipods, grasshoppers and other insects such as midges may also reach large numbers (Brock & Pen 1984, Rose 1991). This rich invertebrate life provides a huge food source for fish and bird life (Smith 1977).

3. Food webs and nutrient cycling

3.1 Consumer groups and the food web

Estuarine fauna may be divided into a number of consumer groups. At the first level are herbivores which are preyed upon by primary carnivores, which are in turn preyed upon by secondary carnivores. Some consumers are omnivores and do not confine their feeding to one trophic level. Detritivores and decomposers feed upon the waste products of animals or on dead plant and animal material and they include microscopic organisms such as bacteria and fungi of the plankton and benthos, and larger animals such as polychaetes and fish. Some omnivores are microbial grazers, consuming the bacteria and fungi associated with detritus.

A simplified food web for the Swan-Canning estuary is shown in Figure 1. This illustrates the probable pathways for energy and nutrients within the estuarine ecosystem.

3.2 Nutrient cycling

Figure 2 shows the major compartments and pathways of the estuarine ecosystem related to nutrient processes. The main features of the model are the composition and nature of the inputs, the types of organisms and quantity of material within each compartment, the transfer rates between compartments and the physical and biological factors which regulate the transfers (Smith 1977, Webb 1981). The system will consist of nutrients either residing in the biomass of individual compartments, including individual animal populations, or being transferred via consumption, assimilation, excretion and mortality from one compartment to another at various rates of transfer. The transfer rates between compartments and the feedback mechanisms which regulate transfers are critically important in determining the magnitude and direction of major nutrient fluxes.

3.3 Nutrient gain and loss

In terms of secondary production, nutrients are gained and lost through animal migration together with consumption and through the harvesting of animal material by man (Figure 3). Humans, large crustaceans, fish and birds are the components of the estuarine ecosystem which have the most potential to contribute and remove nutrients from the estuary. Marine-estuarine opportunists, such as sea mullet and the king prawn, will bring nutrients into the system when they enter the estuary, and will remove nutrients when they depart after feeding and growing in the estuary. Those species which utilise the estuary as nursery habitat may be particularly important. Large numbers of visiting birds may also be important, especially as they feed from all trophic levels. For example, ducks and swans are primary consumers and carnivores, feeding on submerged plants and associated invertebrates, while waders and shorebirds feed predominantly on intertidal invertebrates. The herons, ibises, cormorants and pelicans are tertiary consumers, feeding on fish and large crustaceans. Commercial and recreational fishing for certain fish and large crustaceans will also remove nutrients from the estuary.

3.4 Nutrient regeneration

While an animal is living and growing or when it has just died nutrients bound within it are unavailable for primary production. Certain components of the estuarine fauna may play an important role in liberating much of these nutrients into the water column. For example zooplankton, in the process of feeding and excreting, are responsible for an appreciable recycling of nutrients, particularly of the major phytoplankton nutrients nitrogen and phosphorus (Parsons 1980). Similarly, microbial grazers, by consuming bacteria and fungi and thereby suppressing their populations, release nutrients which would otherwise be locked up in microbial biomass (Smith 1977). Some detritivores progressively degrade plant material which may initially resist invertebrate digestion (Mann 1980). Furthermore, a key ecosystem role of the benthos is mineralization of organic matter by aerobic and anaerobic microbes (Mann 1980). In a local context, Cheal (1983) found that seven invertebrate species in the Peel Harvey estuary contained 17% of the total biological phosphorus pool of the invertebrate animal community. This represented approximately 30 tonnes of phosphorus.

4. Trophic relationships and secondary production

4.1 Primary production and secondary production

In the zooplankton, an increase in phytoplankton levels has been shown to result in an increase in secondary production. However, as primary production increases, there is also a general loss of efficiency in transferring energy and nutrients to zooplankton (Figure 4). This is because as food intake increases assimilation decreases, giving rise to superfluous feeding (Parsons 1980). At this time faecal pellets will convey large amounts of nutrients to detritivores or, as in the case of zooplankton, directly to primary producers (see above).

Zooplankton may also determine the dominant form of the primary production. For example, in the Patuxent River estuary, USA, Heinle (1966) showed that at least half of the primary production was consumed by one copepod species during the summer months. Although he did not investigate whether grazing affected the composition of the phytoplankton, Lukatelich (1987) suggested that selective grazing of diatoms by zooplankton in the Peel-Harvey estuarine system may help to explain the collapse of winter diatom blooms and the subsequent dominance of *Nodularia* in spring in that system.

4.2 Secondary production and fish production

Zooplankton production may be a very important factor in the survival of larval fish. Large numbers of larvae can significantly reduce the standing crop of zooplankton and hence erode their own food supply (Thayer *et al.* 1974). For fish populations generally, establishing a relationship between fish biomass and secondary production is difficult as fish are highly mobile. However, studies have been conducted on relatively closed lake systems of variable trophic status (Parsons 1980). These studies have shown (Figure 5) that within each lake increasing fish biomass correlates with a suppression of zooplankton biomass. Among all the lakes there was a good general relationship between increased biomass of zooplankton and increased fish biomass up to some limiting value of zooplankton biomass. At that point the fish are apparently getting sufficient food to survive and some density dependent or independent factor then controls fish biomass (Parsons 1980).

4.3 Avifauna and secondary production

Just how estuarine secondary production determines or partially determines bird production is difficult to establish since birds are highly mobile and opportunistic. However, birds can have an impact on benthic invertebrate production. For example in the Ythan estuary, Scotland, birds consume about 69% of the net production of the mussel *Mytilis* with about 30% going to man (Table 1) (Milne 1974, cited in Siegfried 1981).

4.4 The importance of detritus

It has been estimated that over 90% of plant production is eventually contributed to the detritus in estuaries or exported from the system (Mann 1982). It is not surprising, therefore, that 80 - 90% of the fauna of estuaries have been found to be detrital feeders (Day & Grindley 1981). In temperate Australian estuaries the importance of the detritus based food chain is likewise reflected in the abundance of detritivores. Rainer (1982) found that 61% of the species present in the benthos of a NSW estuary were detrital feeders. Also, during a study of the shallow water fish fauna of the Swan-Canning estuary, detrital feeders were found to represent 33.5% of the total number of fish caught, and when considered as biomass they contributed 64.5% (Table 2)(Loneragan 1981). In the case of the Swan-Canning system detritus is commonly derived from seagrasses and macroalgae and their attached epiphytes, which are found in the shallows of the estuary (Allender 1981, Thurlow *et al.* 1986, Hillman 1987).

4.5 Man and secondary production

Dredging. Dredging activity can cause localised oxygen depletion, suspension of fine particulate matter and release of nutrients, pesticides and heavy metals, all of which can affect benthic communities. Loss of shallow areas, which are very productive, may reduce the carrying capacity of the estuary for waterbirds and affect the composition of the benthic community. In some studies of dredging the benthic community has recovered within a few months to a year (Kaplan *et al.* 1975, Stickney & Perlmutter 1975, Van Dolah *et al.* 1984). However, in other studies the benthos has taken several years to recover or has not recovered at all (Sykes & Hall 1970, Wallace 1977, Bonsdorff 1980).

Reclamation. Large areas of the intertidal zone have been lost along the Swan-Canning estuary through reclamation which has reduced habitat for benthic invertebrates and hence feeding areas for birds and fish. Thus, the carrying capacity of the estuary for waterbirds may have declined. Further reclamation may ultimately reduce the carrying capacity of the estuary for fish.

Catchment modification. Clearing and agriculture increase sediment loads carried by rivers. This inturn increases the amount of adsorbed nutrients, pesticides and heavy metals entering the estuary (Thurlow *et al.* 1986). Because many southwest estuaries are extremely shallow, increased sediment loads caused through human activities may lead to accelerated sedimentation rates which may ultimately shorten the life of many of these estuaries (Hodgkin & Lenanton 1981, Hodgkin & Kendrick 1984).

Pollution. Dissolved pollutants are rapidly taken up into the food web where they may progressively accumulate along the food chain, ultimately accumulating in top order carnivores such as sea eagles and man. Table 3 illustrates the effects of biomagnification. Some pollutants may be recycled back to the sediments through deposition of faecal pellets and dead organisms. They may also be transported and deposited in the deeper and non-euphotic regions of the estuary.

Mosquito control. Pesticides may contaminate the food web, but in relation to secondary production the removal of huge quantities of food in the form of insect larvae may have a greater effect on the estuarine food web.

Fishing. Up until the late 1970's the taking of fish and large crustaceans was not believed to have affected the Swan-Canning fishery. To date, the commercial fishery has remained fairly steady (Lenanton 1978, Chubb *et al.* 1981, Loneragan *et al.* 1987, Steckis 1991). However, heavy fishing can suppress the biomass and possibly the productivity of fish and large invertebrate populations. For example, it is believed that excessive recreational harvesting of bivalves in a NSW estuary led to low biomass of suspension feeders. This was particularly striking since there was a massive under-utilisation of potential food available to suspension feeders (Rainer 1982).

Nutrient enrichment. Eutrophication can cause ecological changes which favour certain populations over others (Pearson & Rosenberg 1978). With reference to the food chain model shown in Figure 1, nutrient enrichment may increase biomass within some compartments and result in no increase in others or even a decline. For example, there may be an increase in the biomass of zooplankton but no change in the overall biomass of primary producers. This is because the zooplankton have been able to quickly respond to the increase in food and thereby increase, through predation and excretion, the rate of transfer of nutrients and energy between compartments. Rose (1992) has found that in the benthos of the Peel-Harvey estuarine system, eutrophication led to a massive decline in the diversity and biomass of bivalves and an increase in smaller and less heavy opportunistic invertebrate species, e.g. polychaetes and amphipods. Other effects of eutrophication include physiological stress due to depletion of oxygen and the development of toxic algae blooms, which have recently occurred in the upper Swan estuary.

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Table 1: Total net production of *Mytilus* mussel and the amounts consumed by a number of waterbirds and by man in the Ythan estuary, Scotland.

Category	Production (kcal m^{-2} yr^{-1})	%
Total net production	700	100
Eider ducks	275	39
Oystercatchers	100	14
Gulls	110	16
Man	210	30
Other	5	1

(Taken from Milne 1974)

Table 2: Proportion of total fish catch in different feeding groups for the shallows of the Swan-Canning estuary.

Feeding group	Percentage total numbers	Percentage total biomass
Herbivores	11.4	1.7
Carnivores	49.5	16.1
Omnivores	5.6	17.7
Detritivores	33.5	64.5

(Taken from Loneragan 1981)

Table 3: Pesticide levels in water and estuarine fauna from Long Island, USA, in the mid-1960's.

Category	Pesticide concentration (ppm)
Water	0.00005
Plankton	0.04
Shrimp	0.16
Eel	0.28
Predatory fish	2.07
Seagulls	75.00

(Taken from Woodwell *et al.* 1967 cited in Smith 1977)

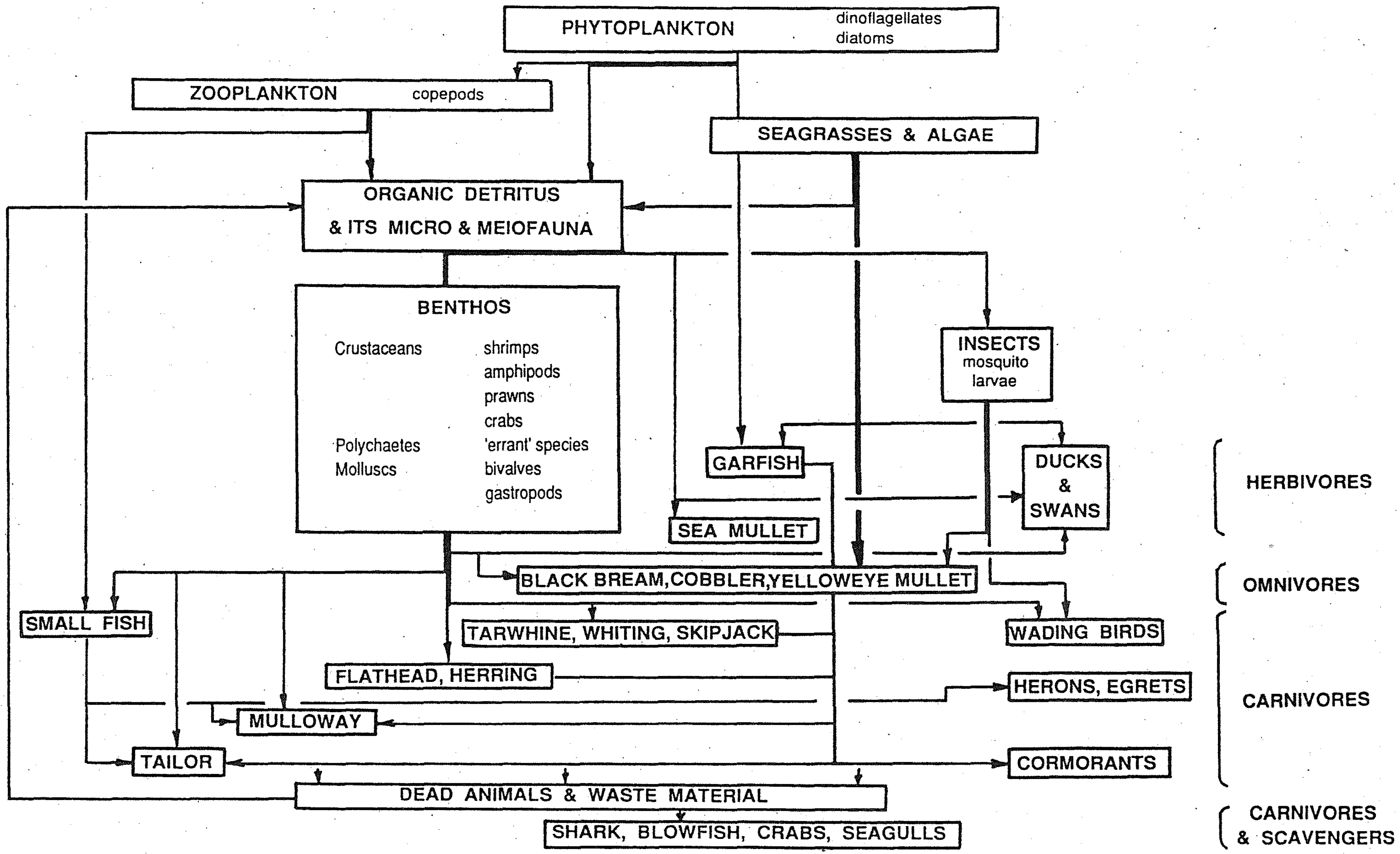

Figure 1: Simplified concept for the food chain of the Swan-Canning estuary (modified from Lenanton 1974).

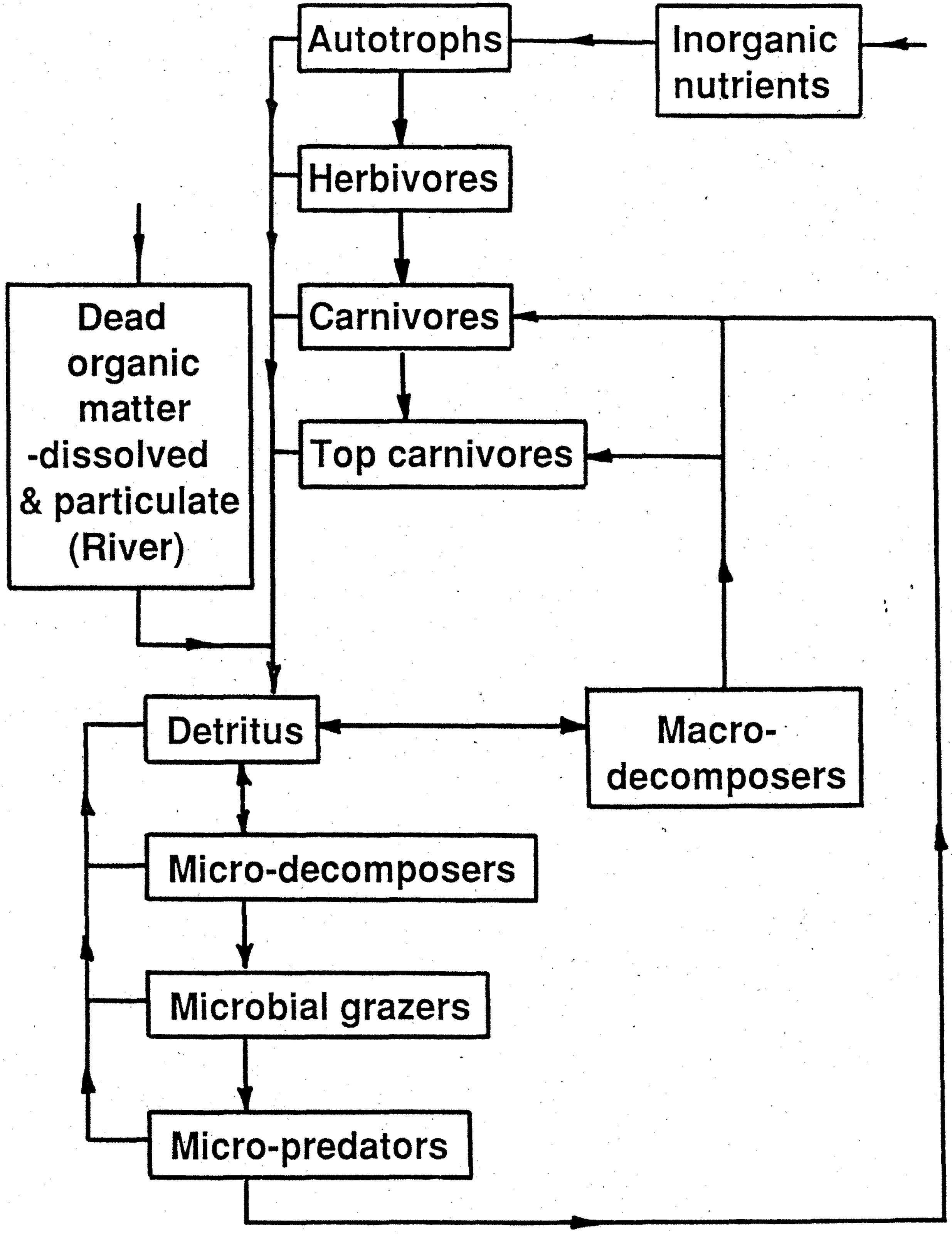

Figure 2: Model of the major compartments of the estuarine food chain related to nutrient processes.

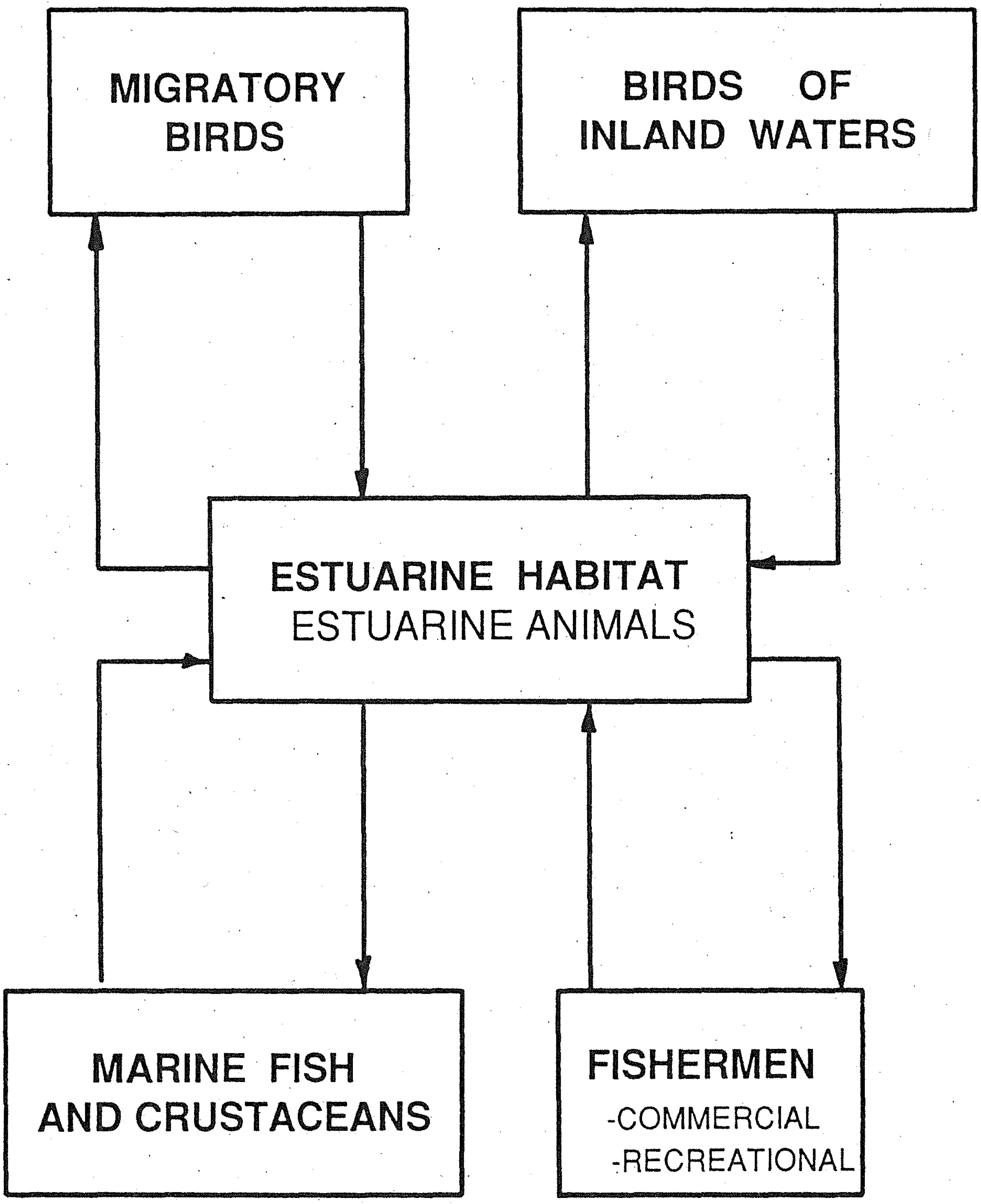

Figure 3: Gain and loss of animal material in the estuarine ecosystem (modified from Lenanton 1974).

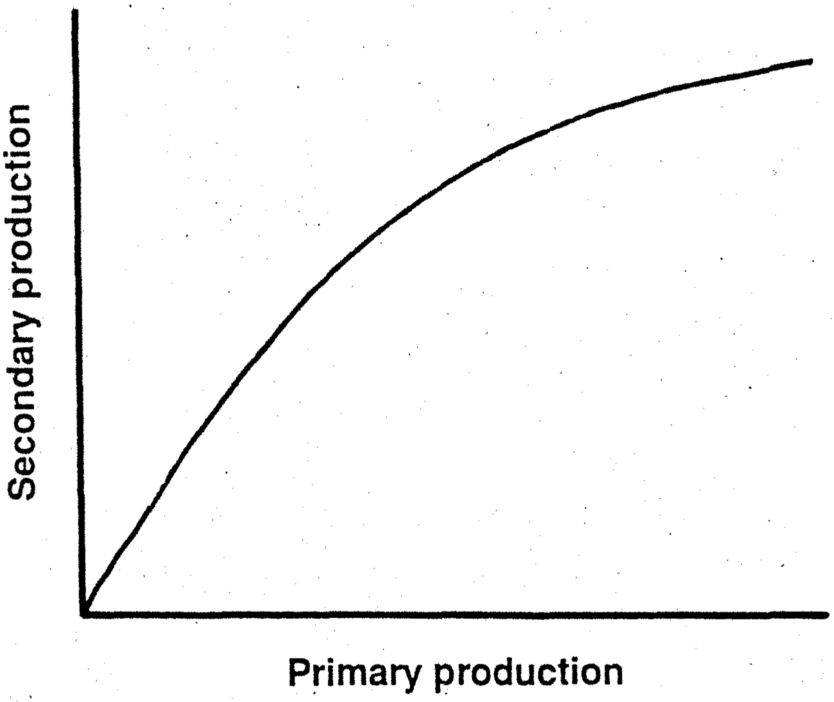

Figure 4: A relationship between secondary production and primary production (from Parson 1980).

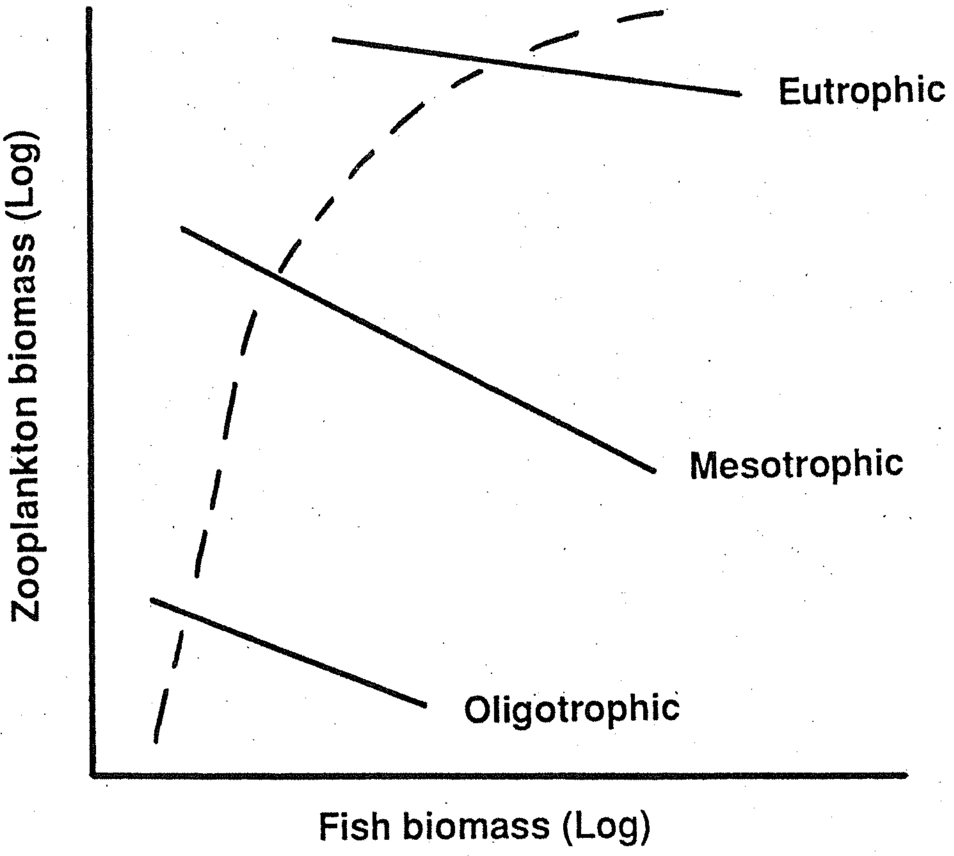

Figure 5: Relationship between the biomass of zooplankton and fish within lakes (solid lines) and between lakes (dashed lines) (from Parsons 1980).

4.0
Visions for the future

Early Warnings using "Health" indicators

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1.0 INTRODUCTION

A simple definition of ecosystem health could be "that state in which the components and processes remain well within specified limits of system integrity".

The health of the Swan estuary of water is strongly influenced by activities in its catchment as well as exchanges from the sea. Consequently any management of the estuary implicitly involves a management of the larger ecosystem of which the estuary is only a part. However, the health of the estuary can be measured directly.

2.0 TRADITIONAL YARDSTICKS FOR INDICATIONS OF ENVIRONMENTAL "HEALTH"

A number of procedures have been used for measuring environmental health water quality criteria.

2.1 Water quality criteria

The application of water quality criteria (WQC) has been the world wide method for establishing the level of "health" of bodies of water. One of the first comprehensive sets of criteria were developed in the USA (California) in the late 1960's. Since then, virtually all regulatory authorities around the world have developed their own criteria, and in general, they do not differ greatly. The development of WQC was the first recognition of the fact that the control of effluents using effluent standards only was inadequate for the protection of waterbodies (eg. phosphorus discharges to the Great Lakes).

The numbers contained in WQC have been developed from a variety of sources, including experience (field data), toxicological studies, and various field and laboratory microcosm studies. Criteria based on field data (eg. oxygen levels, temperature) are normally less conservative than those based on toxicological and eco-toxicological data.

One of the better sets of WQC available internationally is Bulletin 103: Water Quality Criteria for marine and estuarine waters of Western Australia (1981). This document has been used worldwide, and with minor revisions, still remains an important reference.

There a number of features which limit the use of only WQC for the management of waterbodies. The first is that WQC do not include natural variations with space and especially time, such as seasonal variations. The second is that WQC do not include the effects of important recycling processes of sediment/water interaction. Various attempts have been made internationally to develop sediment criteria (largely in support of London Dumping Convention Regulations) for mobile or "bio-available" materials, but none have been very successful.

The third and most serious limitation is that WQC concentrates on water column conditions, and not on the ecological responses.

2.2 Biological indicators

A variety of techniques have been developed to use natural biological communities for measuring environmental condition. Most involve identifying and counting the various species present, and then undertaking some simple calculations which identify dominant species, or indicate species diversity and abundance. One of the better known is the saprobic index system which uses diatomaceous algae as indicators of organic contamination. This system may have application in the upper Swan estuary.

2.3 Index systems

Various empirical index systems exist for collating and summarising a suite of water quality determinants and arriving at a single value which expresses environmental condition or health.

a) Freshwater

Index systems have been developed for fresh water in New Zealand and South Africa. Determinants included in the index system are: dissolved oxygen, pH, temperature, suspended solids, turbidity, chlorophyll a, and faecal coliforms. Numerical index values are assigned to each of these determinants, multiplied by a "significance" or weighting factor, and then summed. The answer obtained is then compared within a rating scheme.

Index systems are extremely useful for water quality assessment. They can be readily adapted to account for regional or seasonal variations, and are amenable to trend analysis.

b) Marine

Fewer index systems for assessing marine contamination have been developed and used. This is probably due to the difficulty of determining gradients of contamination in areas where multiple release points exist, and where dispersion and dilution is so rapid it is difficult to distinguish between natural and induced changes.

An interesting scale of marine contamination was developed as part of the Southern Californian Coastal Waters Research Programme (SCCWRP). The scale extends from 1 (pristine) to 10 (contaminated), with finer distinctions at the lower end of the scale.

The scale includes three principal criteria; namely, percent volatile solids in the top 2cm of sediment, number of benthic infaunal species, and the amount of synthetic organic chemicals in the livers of fish. An additional criterion is also described: the amount of unneeded metals on the liver metallothionein of fish. An example of the application of this scale is shown in Table 1.

2.4 Nutrient loading

Nutrients are being cycled continuously and are an essential requirement for aquatic productivity. Excessive nutrient loads cause eutrophication, consequently nutrient loading rates can be used to estimate the potential for eutrophication. Jaworski (1981) developed such a scale for various USA estuaries, and suggests that where the N/P ratio is above 16, and external phosphorus loadings are less than $1.0 gm^{-2} yr^{-1}$ "excessive" eutrophic conditions will not prevail. These data suggest that a "permissible" phosphorus load is less than $0.75 gm^{-2} yr^{-1}$.

For aquatic systems such as the Swan estuary, acceptable nutrient loadings would be more appropriately expressed on a volume basis, and would need to account for exchanges with the sea. In addition, acceptable nutrient loads would need to include seasonal considerations.

3.0 WATER QUALITY MONITORING

Whatever the limitations of using WQC, or other similar yardsticks, water quality monitoring has been, and will continue to be a standard component of any process for environmental quality monitoring.

Unfortunately the literature is replete with examples of poorly planned, very expensive and uninformative water quality monitoring programmes.

The objective here is not to further the cause of such profligate exercises, but rather to examine what features should be contained in a well designed WQ monitoring programme.

In particular, these are:

- a sensible selection of determinants,
- a sensible selection of frequency of sampling,
- appropriate data handling and manipulation capabilities,
- regular review and revision, and
- clear objectives and decision-making protocols.

4.0 MANAGEMENT OF WATERBODIES: USE OF MODELS

There is no simple procedure for managing a body of water such as the Swan estuary which is in the centre of a large city and subject to a number of influences which vary in intensity. Measuring water quality alone is clearly insufficient. A management strategy must contain three main components:

- well defined goals and objectives,
- a suitable understanding of the main processes occurring within the waterbody, and
- an appropriate monitoring programme which reflects the consequences of management programmes.

Invariably and inevitably this requires the development of a computer based model of the system.

The first requirement for a sensible model is that the important processes (physical, biological, chemical) are sufficiently well understood and documented. After this, an appropriate model of the system can be prepared. Models can vary from very simple box models which assume steady state conditions to extremely complex models where small variations in time and space are represented.

The use of models requires iterative validation and refinement to improve their ability to represent and predict conditions. The predictions of models should never be believed; field measurements should be relied upon instead.

The great value of models is their ability to be consistent (as compared to human judgement) and to resolve complex situations rapidly. The most effective models are usually developed by scientists with broad field experience who can distinguish the significant processes and ensure their appropriate representation in the model. The results from models and field measurements must be compared with previously established goals or objectives. From this the success of management can be determined and further management strategies can be implemented.

Finally, models <u>must</u> <u>be</u> <u>used</u> to be effective for management. Water quality modelling, as an activity on its own, runs the risk of being irrelevant.

Table 1. Scale of Marine Contamination. Most values are relative to control medians or CM. At least 6 control stations samples at depths corresponding to those in the scaled area are required.

		Scale Value	Percent area not affected	Percent Volatile Solids in upper 2 cm of bottom	Example	Median number of benthic invertebrate species larger than 1 mm in grab	Example	Total Synthetic Organic Chemical in livers of fish (ppm)	Example		Total unneeded metals in metallothionein in livers of fish (ppb)	Example
Good	Pristine	1	100	same as control		same as control		0			Control value or less	
	Control median	2	100	control median value=CM	2.8	control median value=CM	>70	control median value=CM	2.0		control median value=CM	< 25
	Within Control Range	3	100	highest control value	3.8	>95% CM	>66	<CM× 3	< 6.0	Low mol. wt fraction	<CM× 2	< 50
Contaminated	Minor changes	4	>95	<2×CM	< 5.6	>90% CM	>63	<CM×10	<20.0		<CM× 4	<100
	Ordinary Disposal Operations	5	>95	<3×CM	< 8.4	>70% CM	>48	<CM×20	<40.0		<CM× 8	<200
	Action required	6	>90	<4×CM	<11.2	>50% CM	>35	<CM×50	<100.0		<CM×16	<400
Polluted	10% of area	7	>90	<5×CM	<14.0	<50% CM	<35	>CM×50	>100.0	High mol. wt fraction	>100	>100
	25%	8	>75	>5×CM	>14.0	<50% CM	<35	>CM×50	>100.0		>100	>100
	50%	9	>50	>5×CM	>14.0	<50% CM	<35	>CM×50	>100.0		>100	>100
	100%	10	0	>5×CM	>14.0	<50% CM	<35	>CM×50	>100.0		>100	>100

A SWAN RIVER TRUST VISION - MAKING IT HAPPEN

by
Robert Atkins

2nd April 1992

INTRODUCTION - THE PAST

Traditionally the monitoring of estuaries has had a strong focus on water quality (chemistry, phytoplankton and bacteriological counts). Sampling has been carried out on the open waters of the estuary and the main drains that discharge into it. Measurement of parameters has almost exclusively been in concentration units. The reasons for this approach are easily understood when one recalls press reports of yesteryear, which focussed attention on pollution from industry, sewage treatment and algae fouling popular beaches.

This early work lead to many point sources of pollution being cleaned up or diverted away from the river. Water quality monitoring, based on this approach is still the mainstay of many waterways monitoring programs.

A review of these programs lead to the conclusion, that over a long period a basic understanding of water quality had been gained. However it was not likely that very much more could be learnt by continuing these types of programs, which only provide a snapshot of part of the estuarine system, rather than a broader picture of the health of the whole system over time.

While the program enabled managers to report on the current condition of the waterway, there was only limited, if any ability to report on possible trends in water quality. An understanding of the processes governing algal growth was largely lacking. With the clean up of industry discharges, that is still progressing successfully, the main water quality issue is now algal blooms.

TODAY'S ISSUES

Pollution of the waterways from industry is only an issue in two estuaries in the south west of Western Australia. Strategies are in place to manage them, so the pollution risk is diminishing all the time. However there remains a public perception that the river is polluted by chemicals. Often poor water quality related to algal blooms is blamed on chemical pollution.

The main issue relevant to the Swan Canning is nutrient enrichment which leads to a diminution of water quality from phytoplankton blooms and a loss of amenity from excessive accumulations of macro algae on beaches and shallow flats. Some chemical contamination occurs, but this is low level pollution from a wide range of urban sources and occasional spillages.

The long history of management of the Swan Canning River System has resulted in very tight management of point source pollution. The emerging risk for this system and an already developed problem in other south west waterways, is nutrient enrichment from diffuse or non point sources.

Waterways in the south west of the State with existing or developing nutrient/algal problems have catchments that have been largely cleared for agriculture. It has taken several decades of farming based on the use of phosphatic fertilisers, for these problems to develop.

With the increasing urbanisation of estuaries in the south west of WA, urban pollution loads of both nutrients and toxic substances are a growing issue. This is reflected in the move to design new urban developments to reduce the discharge of storm water and the level of pollutants in storm water.

Traditional approaches to water quality monitoring are not sufficient to enable managers to initiate management strategies and advise land planners on approaches to reduce nutrient inputs to the waterways to a level that can be accomodated without causing water quality and algal problems. The advice all too often is simply that nutrient loads need to be reduced. Decision makers need to have something to aim for, for example a target loading that cannot be exceeded by the combined catchment inputs. Waterways managers also need to know the annual loads to the waterway in relation to the "assimilative capacity" of the waterway as a means of assessing trends either towards developing water quality problems, or an improvement in water quality.

THE TRUST'S OBJECTIVES

Although the Trust's Corporate Plan, which includes the management objectives and strategies, is still being refined, it is indicative of the vision that the Trust has for the future. This section presents the general objectives and strategies that relate to the need for monitoring and research.

Objectives

Prepare and implement management plans and programs for the conservation and good management of the river environment.

Provide advice to the Minister, Department of Planning And Urban Development and local government authorities on planning an development applications, which results in their decisions being influenced to ensure the conservation and good management of the Swan -Canning River System.

Educate and involve the Western Australian community in issues affecting the swan-Canning River environment.

Improve and maintain the quality of the water in the Swan-Canning River System.

Strategies

Develop planning policies for the Trust, against which proposals for change or development are assessed to gauge their impact on the health of the waterways and as a result of which conditions are set and advice provided to decision making bodies.

Develop and implement management programs and plans, which identify areas requiring protection and rehabilitation and which guide the conservation and management of the Swan-Canning River environment and ensure the maintenance of viable nature reserves and ecosystems.

Conduct community education projects and the planned involvement of the public in the Trust's activities to increase awareness of waterways issues.

Conduct broad spectrum monitoring throughout the Swan and Canning Rivers and associated drains to identify and control pollutants which may have an adverse affect (eg., pesticides and heavy metals) and investigate and control waste water discharge from industry and other sources.

The Division of Environmental Investigations and Assessments undertakes investigations, monitoring and promotes research of the Swan-Canning System for the Trust. The Division's corporate objective and key activity areas are presented here to show these are achieved.

Objective

To improve the Western Australian community's understanding of its waterways, to enable it to make informed judgements on the directions and success of waterways management strategies and to identify potential or actual problems with the waterways.

Key Activities

provide advice on the impact of development and land-use activities on the Swan River System (ENVIRONMENTAL IMPACT ASSESSMENT)

monitor the impact of industrial waste and advise on the impact of these on the waterways; enforce pollution control legislation under delegation from the Environmental Protection Authority (POLLUTION CONTROL)

conduct environmental investigations and monitor waterways and their drainage inputs (INVESTIGATIONS)

provide technical support to the Trust and committees and the management planning process (TECHNICAL SUPPORT)

WILL PAST METHODS SERVE THE FUTURE?

There is little value in continuing to rely on routine traditional water quality monitoring. We are not learning anything new by doing so. These data simply show how this year compares with the trend for past years. Managers are able to answer parliamentary questions, demonstrating that they are monitoring the waterways and looking after the environment! This is of course a necessary function, but it is not contributing very much to our understanding of estuarine processes and only provides a limited capacity to predict the response of the estuary to management actions or development proposals.

Waterways managers are still faced with the prospect of being surprised by the occurrence of algal blooms that cause water quality and wider environmental problems (eg., fish kills). The *Nodularia* bloom that occurs in the Peel Harvey Estuary is one of the few events that can be predicted. That is based on the winter flows that preceed it, so it only allows time to implement contingency plans (health warnings and monitoring)!

With the growing need to introduce land use management controls and guidelines and to place development conditions on proposals, waterways managers must be able to predict the outcome of these decisions, rather than live in the hope that they will work. Proponents putting such controls into practice, whether it is a single development or general farming, must have confidence that what they have been asked to do is going to be effective in meeting waterways management objectives.

Traditional monitoring programs will continue to identify pollution events from point sources, such as industry and road accidents. The assessment of the more insidious sub-lethal impact of toxic substances is largely reliant upon overseas toxicology research. While there is a need for local research, the relatively low risk to waterways in WA, compared to that from nutrient enrichment, ranks local research in this field as a lower priority.

Much work is currently being done to improve estimates of nutrient loads to the waterways. This will lead on to looking at ways of arriving at more reliable estimates of the "assimilative capacity" for the waterways. This alone will not satisfy the needs of managers. It is vital to improve our understanding of algal bloom initiation and growth.

Traditional monitoring approaches need to be revised and research focussed on management problems.

NEEDS OF MANAGEMENT DECISIONS - A NEW DIRECTION

Waterways management today must have strong links to catchment management. Activities in the catchments can have an immediate (within the same year) or a longer term (years, decades) effect on waterways. An understanding of the processes that link catchment use with the quality of waterways is perhaps the most important management tool that managers need.

There is no likelihood of a return to pre-European nutrient status. So the estuary will remain in a nutrient enriched condition. Management has to include the control of blooms in waterways, as well as strategies to reduce nutrient loads to the system and possibly in the system. Research into the bio-stimulation of algal growth has to include factors other than the response to nutrients.

There will always be a need for routine monitoring of waterways and their catchment inflows. Traditionally this has used a large part of budgets. With the need to do more with less and to conduct the research referred to on this paper, monitoring methods that cost less, use less human resource but give a better picture of the behaviour of the waterway are required.

A new approach is needed, based on "health" monitoring, to provide information to answer questions and to monitor performance. A finger on the pulse if you like. We need to develop some predictive capability for managing water quality and more generally the overall ecological "health" of a waterway, especially an important one like the Swan Canning system.

THE VISION

The Swan River Trust in consultation with the community, intends establishing "beneficial uses" for the Swan and Canning Rivers. It is likely that there will be different priorities for "beneficial uses" in different parts of the system. "Water quality criteria" and "management objectives" will then be determined to meet the range of "beneficial uses". These will set the "bench marks" for monitoring the condition of the waterways.

Having established the waterways management objectives, target catchment loads for nutrients and other pollutants can be set. The concept of "assimilative capacity" is one of the tools that will be used to relate catchment loads to the response in the waterway, even though this may be crude in the beginning. These then form the basis for catchment management objectives used by both planners and managers. It is obvious that the whole exercise has to be co-ordinated through the Integrated Catchment Management process, as each part is linked to the next.

Monitoring programs will be changed so that the condition of the waterway can be measured against these criteria. Reports to the community will be produced each year. These will compare indicators with management objectives as well as reporting on the waterway's response to catchment management actions.

The Trust will also provide more comprehensive advice on catchment management initiatives and the likely impacts of development proposals on the waterways. It will also be better placed to participate in land use and development planning.

5.0

Planning for the future Open Forum

PLANNING FOR THE FUTURE

Open Forum

This forum was intended as a management oriented discussion to establish important priorities for the future research and monitoring of waterways, particularly the Swan and Canning Rivers. The audience, which comprised representatives in waterways research, monitoring and management, was asked to focus on whether current research and monitoring were sufficient for effective management and to address any gaps. The session was divided into four themes on which discussion leaders presented a general introduction. This was followed by a fifteen minute interactive audience discussion addressing that topic. The first of these, led by David Deeley examined the catchment, its monitoring, management and land usage. The second considered the monitoring and management of the estuary and was led by Robert Atkins. Research requirements, associated processes and applied research were examined as the third topic presented by Professor Arthur McComb and the final topic, presented by Dr. Bruce Hamilton, was entitled "Bringing it together". This addressed the means of establishing a cohesive outlook and presenting it to the government. For each topic the introductory address is presented here, together with a summary of the ensuing discussion expressed as the main points raised rather than an attempt at a verbatim report.

Mr Ron Davies, Chairman of the Swan River Trust, chaired the Forum and introduced it by providing a political perspective of the means by which the outcome of the Swan River workshop could be presented to the government to provide maximum attention and effect.

Using the data - the political perspective

Mr R. Davies
Session Chairman

What you would probably like me to say in regard to this title is that politicians, especially those in government, are eagerly awaiting to process and to put into effect any data and research which becomes available to them. Alas, this is rarely the case. However, it is wrong to infer that they are completely disinterested. Their interest and subsequent action can depend on many factors such as timing, public pressure, departmental persistence and government priorities. However, there is a time when success is likely to come more easily.

Every four years at least, the public in this state is invited to elect a government and in the six months or so prior to this, the major political parties are looking for things that are going to have public appeal. They hope that by talking to Ministers, talking to the various departments, talking to pressure groups and monitoring the media, to find out what are the real matters of concern which are likely to bring support at the polls. What's rather strange to me, as a long timer in the political game, is that these days no one pays any attention to their printed platform. Having fought for matters to go into platform and perhaps fought to the death at state conferences to win your point and get it included in the platform, these are forgotten. As far as I can see, printed political platforms are of little relevance these days. However it is at that time, the time of going to elections, that politicians are looking for inspiration, looking for arguments that will advance their cause, that will help them get their ideas established. I'm not suggesting that governments only become motivated by coming elections. During the whole of the term, if they have any common sense, governments or their Ministers will be listening to and taking guidance from their departments, because that really is where the ideas should be coming from. But if they decide to act, if they decide they want to do something, its not just a matter of doing it. There are a series hurdles which must be jumped.

First of all, can the proposal be contained within the existing budget? Can money be found if required? Can it be done 'in-house'? Does it require Cabinet approval? Does it require legislation? Where does it fit in the list of government priorities? These are just a few of the hurdles with which the Minister has to contend, but if he is armed with good data, then he can and is more likely to succeed. There are, however, still more hurdles to be overcome. Are you popular with the Premier? Have you got the numbers in Cabinet? Do those with the numbers have priorities which are different to yours? All of these things are very relevant to the outcome. But, if by some chance the issue has popular electorate appeal, which can be translated into votes, then the chances of successful advancement of the cause increases dramatically. A cynical view, you might say, but I have seen a few of you nodding in agreement. I would agree with you, it is a cynical view but it's the politics of remaining in power, the politics of issues, the politics of pragmatism.

Just recently, in a small volume called 'Buzzwords', I read the definition of pragmatism: "Ignoring party policy to stay in power. Politics, is the art of the possible, pragmatism is doing what is possible without the pain of losing office. To put it another way, it is political expediency; one eye on the constituency and one eye on the swag.". I don't think I've heard it better expressed anywhere else.

So today we are considering what we can do to establish important priorities for the future research and monitoring of our waterways so that we might bring these to the attention of the politicians. I haven't got any answers but I hope that during the discussion afterwards that you may have answers.

The catchment: monitoring, management and land use planning

David Deeley

There are a number of things that the Trust could do over the next few years in relation to the catchment water quality monitoring. We can make our monitoring a little more representative by focussing on the major sources. We can identify the first flushes, peak flow and loading times and monitor these to a greater extent. However, it is important that we focus on management because nutrients don't get into the waterways by themselves, its water that's pushing them around the landscape. We have to take account of water sensitive design and planning in urban and rural areas and view the entire catchment in a holistic sense. For example, in urban areas the run-off contains a very high proportion of organic particles and there is considerable potential for the use of compensating basins which are able to drop out some of that. In rural areas the nutrients are mostly dissolved, but there is considerable potential to improve fertiliser effectiveness, through soil testing, alternative cropping, drain modification and land capability studies. It's been mentioned today that when you have a cleared catchment that is largely comprised of sandy soils and you're fertilising it, then ultimately you're going to have a eutrophic water body. The only variable is the time in which that is going to happen. As planners, developers, managers, we need tools to avoid this or at least put off the time when that is going to happen.

Open discussion

- **Catchment water balance**

  Catchment water balance was seen as an important issue and it was felt that there was a crucial need to understand the relationship between catchment clearing, land use, water balance and water quality. It was suggested that a predictive model was required to determine what the likely effects of land use changes were and that this might be established by monitoring water balance.

- **Clearing and nutrient export**

  There was concern over the relationship between catchment clearing and nutrient runoff. It was shown that runoff increased exponentially when clearing exceeded 70% in conventional land use areas. The comment was made that where that was the case then reaforrestation should be considered in those areas. It was also thought necessary to establish what was achievable in nutrient runoff management in both rural and urban areas.

- **Ellen Brook - need for action**

  The point was made that there was enough known about Ellen Brook nutrient problems to embark on a detailed analyses of current and future land use practices so that changes could be made.

- **Fringing vegetation**

  The removal of fringing vegetation was seen to have enhanced problems associated with eutrophication and sediment transport. It was proposed that there be an inventory of existing riparian vegetation and an identification of it role and importance to the estuary.

- **Management objectives**

  Overall there was general agreement that catchment management objectives could not be set until water quality and management objectives for the estuary itself had been established.

The estuary: monitoring and management

Robert Atkins

The Swan River Trust has a long history, of physico-chemical, nutrient and phytoplankton water quality monitoring for the estuary. That program was stopped about five years ago when we turned our resources to the catchment nutrient loading work. We didn't have enough resources, both financial and human, to do both. The Trust is still doing opportunistic phytoplankton monitoring when blooms occur and obvious water quality problems come up. However, I think that's a fairly dangerous position to be in as we're relying on a data base that is a few years old now.

So the questions I would like us to address in this session are: what sort of in-estuary monitoring program should a management agency like the Trust conduct; to keep a finger on the pulse, to measure performance, to measure the response to catchment actions, to generally measure the health of the system, to achieve the management needs of providing information for assessing the impact of various activities and also to measure the success of management strategies.

Open discussion

- ### Management Targets

  In order to establish estuarine water quality and management objectives it was considered essential to first define the assimilative capacity of the estuary and to determine what a 'healthy' estuary was in terms of water quality, conservation value and community perception and usage. The first step in this process is to develop a vision for what we want the estuary to be in the future. This would be approved through establishing "beneficial uses" for the estuary.

- ### Health Indices

  Indices were generally considered to be important tools for monitoring estuarine health. Some delegates felt that it might be possible to identify an indicator that was representative of the overall environmental quality of the estuary but this would need to be statistically valid. However, it was argued that it would be necessary to pursue base line studies of a potential indicator first, so that any spatial and temporal variation was identified and documented prior to its use in monitoring. There was some suggestion that the community perception of estuarine health was different from that of scientists and that monitoring should, to some extent, measure parameters that the public could understand. The abundance of prawns was offered as an example.

- ### Algal blooms

  Algal blooms and the ensuing low oxygen concentrations and fish kills were considered to be a major problem in the estuary and therefore it was suggested that monitoring programmes should address means of providing early warnings of this. Monitoring in the upper estuary could incorporate depth profiles of parameters such as oxygen, light, salinity and temperature as this might illustrate the relationship between the stratification of these physical parameters and the occurrence of algal blooms. This sort of monitoring could be achieved cost effectively through the use of electronic data loggers and a minimum of staff.

  It was pointed out that monitoring should incorporate parameters which measured the performance of management changes to the system including the effects of interventionalist techniques for managing algal blooms such as dredging.

- **Public Education**

Public education was viewed as an important issue. The Swan River Trust produces an annual report which relates the status of the Swan/Canning environment and its management to the community. It was proposed that management targets for the estuary, which were easily understandable to the public, should be incorporated into that report. However, a number of delegates felt that public education should go further than the annual report. One suggestion was to provide the community with creative and regular measures of water quality in the estuary so that the public could address their contribution to the nutrient problem. Examples of this type of approach were the fire hazard and air pollution levels issued by C.A.L.M. and the E.P.A., respectively. Another suggestion was that all management authorities associated with the estuary join together in a massive media campaign to highlight the problems of litter and nutrient levels and encourage the public to reduce fertilizer usage until target levels are met. It was also argued that the public required more than nutrient targets to aim at, they needed to be provided with simple options such as, if they wanted to be able to catch prawns and fish, then they shouldn't fertilise their lawns.

Research needs, processes and applied research

Professor Arthur McComb

As a brief overview, the important components and processes which characterise an estuary include the catchment and groundwater which provides an external loading of nutrients; the estuarine basin in which there is nutrient trapping and recycling going on; the plant bio-mass which includes the macroalgae, seagrasses, phytoplankton and fringing plants as well as the benthic microscopic algae which must be important in aerating the sediment surface and preventing nutrient release in shallow water. Then we have the food webs which include the fish and birds. The sediments are important as they act as a permanent sink for nutrients but under the right conditions are a very important source for internal loading and nutrient recycling. In addition, we have losses to the ocean and other external losses.

As a suggestion of how we can proceed with discussion today, we might first examine research possibilities in terms of the plant bio-mass, the sediments and the ocean. I think we will perceive the physical processes as underpinning the whole of this and we should bare in mind the possibility of developing some kind of model. We need to ask ourselves whether or not our existing data are good enough to produce a model to describe the system, at least in a crude way

Open discussion

- ### Catchment - Urban processes

Many of the research projects suggested so far were associated with the catchment. These included the quantification of diffuse and point sources in terms of fluxes of nutrients to major tributaries. Also, the establishment of time scales over which phosphorus is transported through various soil profiles to the water. There was a general feeling that more research was required into groundwater movement particularly in relation to urban areas and it was suggested that management needed to be able to predict the effect of catchment changes on groundwater. From a sociological view point, it was proposed that there be some research into how to best develop a total catchment management policy.

- ### Littoral vegetation

Research topics that were related to the estuary included the quantification of the effectiveness of protecting the littoral vegetation in terms of its role in nutrient and metal trapping. This was then expanded to include research into the effectiveness of existing management methods in general.

- ### Algal blooms

A long term investigation of phytoplankton and macroalgal populations was proposed so that any increase or change in these could be documented. It was also suggested that some research be undertaken to establish why the Swan River did not get blue-green algal blooms. It was recognised that in order to establish useful indicators for monitoring it would be necessary to perform baseline investigations of how populations change and their timescale. Little was known about what triggers algal blooms.

- ### Health indicators

Need to determine the role and relevance of indicator species or determinants in the ecosystem. Also need to have a sufficient understanding of the system and its components to enable "acceptable" change to be defined by the community and decision makers

- ### Models

It was generally regarded that the development of a conceptual model incorporating physical, biological and chemical processes was essential as this would allow the investigation of the effects of any interventionalist techniques for management. As well this would allow the coordination of research and the integration of research and management in long term planning for the Swan/Canning system.

Bringing it together

Dr. Bruce Hamilton

In order to obtain funding from the government in the current political and economic climate it is essential to present the politicians with a clear vision and it must fit in with their political and electoral priorities. I believe the time is right. Waterways are a big issue in Australia at the moment and the Swan is a big issue for the government, and there is an election coming up. So, all the things that Ron Davies discussed from a political perspective, I see as timely from my perspective. What we must get out of today, as far as the Swan and other waterways are concerned is a clear vision to present to government. Then we can say to the politicians that if they can give us money to understand this system, we can better manage it and hence it is money well spent.

There are two key issues that have come out of today. Firstly, as part of a management programme, we need establish the objectives for the Swan and Canning River system in terms of what we want that system to be. It's important that that is done as an integrated process which involves the community, the politicians, the scientists and the managers. Secondly, we need a clear vision of a research plan with a sense of direction and outcome at the other end. This will provide us with a basis to go to government to request funding. It will also enable us to integrate and make the most effective use of both past and future research. This plan could also provide guidance to research organisations in terms of how their research fits in to a larger picture.

So in this session what we require are ideas as to how to present that vision for a research plan and the vision for the future state of the system to the government, which is ultimately going to be the source of the money.

Open discussion

- **Social Research**

  Delegates thought some social research would be required to establish what the community wanted in terms of the estuary environment and that this would be crucial to establishing management objectives for the waterway and the catchment.

- **Management objectives - Model - Cost benefit**

  Once the management objectives were defined, politicians could be presented with a broadly based cost-benefit analyses of achieving them. This could incorporate the cost of establishing a model which included physical, chemical and biological parameters and that would allow the effects of any estuarine manipulation to be estimated.

- **Integrated Catchment Management**

  Integrated catchment management was viewed as a fundamental component of a vision for the future of the Swan/Canning system which would ultimately have to undergo peer review and public assessment before it could be officially presented.

- **Research Reference Committee**

  It was generally accepted that a high level reference committee should be formed. This committee would investigate the coordination and integration of research and monitoring and come up with objectives for the research plan. Eventually a series of working groups could be established to tackle specific issues.

SUMMARY OR BROAD RESEARCH AND MANAGEMENT ISSUES

This is a check list of the main points compiled into a sequence that could be used as a starting point for a Research Plan for the Swan River Trust.

Social Research

Establish community desires and expectations for the future of the estuary.

Beneficial Uses

Develop a range of 'beneficial uses' or 'environmental values' that address the community's expectations for the future uses and well being of the estuary.

Management objectives

Develop management objectives and targets for both the estuary and the catchment that address the range of 'environmental values' and are measures that support management decision making.

Research Priority issues

These are not eshaustive, but were those most focussed on during the Open Forum.

- Social.
- Catchment water balance.
- Relationship between clearing, development and other land uses and nutrient export.
- Role and effectiveness of riparian vegetation.
- Ellen Brook - land use practices.
- Algal Blooms.
- Health indices.
- Physical, Chemical and Biological models

Health Indicators - Performance Monitoring

Develop a range of health indicators and a monitoring programme that enables managers to; measure the changes occurring in the estuary, response to management initiatives, success of management decisions and report to the community on a regular, meaningful and easily understood way.

Public Education

Use research and monitoring data to: improve the Community's understanding of the estuary, promote the estuary's value and facilitate desirable changes in people's habits for the better future integrity and amenity of the estuary in line with management objectives and the range of Environmental Values.

Integrated Catchment Management

Encourage the development and use of this process to reduce nutrient and pollution loads to the estuary, both in rural and urban catchments.

Conclusion

Ron Davies

On behalf of the Swan River Trust I would like to thank the speakers for their work, a great deal of effort has obviously gone into the papers. I also want to thank the session chairmen and the workshop facilitators for managing the speakers and guiding the discussion session. A particular thanks to Faye Jones and Diane Tracey at the Professional Education Office for organising the workshop and also, to Murdoch University thank you for hosting the function. Finally, thanks to Robert Atkins who took it upon himself to organise the seminar.

6.0
Appendix

THE SWAN RIVER ESTUARY - WATER QUALITY MONITORING AND MANAGEMENT

Robert Atkins, Waterways Commission, September 1991

Environmental monitoring, especially water quality monitoring has been carried out on the Swan River Estuary since the beginning of the century. The most comprehensive reporting of this early work is the *Swan River Reference Committee Report by Subcommittee on Pollution of Swan River, 1955.*

In these early years sampling was carried out for discrete periods and for a few selected determinants, e.g., dissolved oxygen bacteria and chloride ion. These programs were a response to water quality and algal events that had been causing a nuisance and were the subject of newspaper stories and letters since the 1870's.

Since these early studies, almost continuous and quite comprehensive water quality monitoring programs have been carried out. These still focussed on water chemistry and bacteriolgical sampling. The main programs were: 1944 - 1956 CSIRO, 1962 - 1978 , 1974 - 1975, 1979 - 1984 Government Chemical Laboratories for principally, the Swan River Conservation Board and the Swan River Management Authority. Most of these data were collected at three monthly intervals.

A review of these data lead to the conclusion that over a long period a basic understanding of water quality had been gained. However it was not likely that very much more could be learnt by continuing a program with a sampling frequency of three months. It had also become evident, from the Peel-Harvey experience, that catchment management is the key to water quality management of the estuary. Consequently the long term low frequency monitoring of water chemistry was discontinued.

This was replaced by both problem and management oriented monitoring. Examples are: the fate of heavy metals from the discharge of airconditioner waste in the estuary, pollution levels in the Bayswater Main Drain and the river, pesticide and heavy metal residues in fish, nutrient status of sediments and phytoplankton blooms. Resources were also redirected to measuring the nutrient loads coming into the estuary via the main drains streams and rivers.

This work is aimed at filling some of the gaps in our understanding of water quality related management issues. There is still a need to monitor the "health" of the estuary. This essentually was one of the reasons for the long term three monthly monitoring. However that program required considerable resources both financed and personnel. The Swan River Trust proposes to develop a "health indicator" based monitoring program. This is intended to be complimentary to the "problem" oriented programs.

Monitoring has shown that the Swan River Estuary is nutrient enriched and is showing signs of stress from external inputs. The upper reaches of the Swan and Canning rivers experience phytoplankton blooms which, on occassions cause undesirable water conditions. Although not directly attributed to these blooms, fish kills have also been observed. Heavy epiphytic growth on seagrasses and excessive accumulations of macroalgae in the shallows and along the foreshores occur in the middle and lower reaches of the estuary.

While some heavy metals have accumulated in the sediments and biota, with the exception in a few instances of copper and zinc all are below maximum public health residue limits.

The main threat to the ongoing maintenance of estuarine water quality is the nutrient loading to the estuary and the potential for this to increase with the expected population increase in the metropolitan area. It is vital that a better assessment of the assimilative capacity of the estuary is carried out together with a good understanding of nutrient loads from the different land uses and land forms in the catchment. Modeling should then be developed to enable some predictive capability to ensure that the future growth and development of the metropolitan area does not push the estuary beyond its assimilative capacity. The Swan River Trust is currently developing this approach. The Trust is intending to convene an estuarine workshop in November this year to review the approach to investigations and monitoring.

1. INTRODUCTION

Traditionally the monitoring of estuaries has had a strong focus on water quality (chemistry, phytoplankton and bacteriological counts). Sampling has been carried out on the open waters of the estuary and the main drains that discharge into it. Measurements of parameters has almost exclusively been in concentration units. The reasons for this approach are easily understood when one recalls early press reports of the day, which focussed attention on pollution from industry sewerage treatment and algae fouling popular beaches.

The approach of sampling for these things at regular (often infrequent) intervals at set sites has only told part of the story. Macrophytes (macroalgae and seagrasses) have not been monitored quantitatively because of difficult logistics and cost.

More recently attention has been paid to the role of nutrient release from sediments, particularly in regard to algal blooms. Low concentrations of nutrients in the water column can be deceptive when large amounts of nutrients can be released from the sediments under certain conditions stimulating algal blooms.

The Peel Harvey experience has led to a change in approach to water quality management and monitoring. The need for monitoring the nutrient loads from the catchment has become obvious. Although water quality monitoring had been carried out in the Swan for more than 20 years, little was known about catchment loads. It was decided that, because there were insufficient resources to commence a catchment monitoring program in addition to the water quality monitoring, the existing program would be discontinued.

The condition of the estuary has not been ignored. Event related monitoring has continued, collecting data on environmental events such as algal blooms. A three year study of the nutrient status of the sediments has been completed and monitoring the annual growth of algae and seagrasses will commence this year.

A catchment monitoring program was commenced in 1988 with a major review in 1992. The Trust has been conscious that no regular estuary monitoring has been done in the mean time. Although regular qualitative "inspections" and monitoring of observed events eg., algal blooms, has continued. The next phase is to develop a low level but informative "health indicator" monitoring program where key species and/or physico-chemical parameters are monitored. These would serve as a "finger on the pulse" or measure of the condition of the waterway and its response to either management strategies or events.

For this to be effective, species and parameters that are truly representative of the behaviour of the estuary need to be chosen. Not a simple task and one fraught with danger. The beneficial uses of the waterway need to be identified and measurable criteria suitable to meet these uses set. Coming to grips with the concept of assimilative capacity and developing an appropriate model for the Swan Canning is an integral part of this approach. These are the tasks currently facing the Trust!

2. HISTORICAL OVERVIEW

Nutrients

The long term phosphorus data are highly variable, although a general upwards trend can be seen, it is not likely to stand up to statistical analysis. Nitrogen levels do not show any trend at all. The improvements in chemical analytical techniques since the early years together with the low frequency of sampling both contribute to the poor definition of the data.

Nutrient levels are higher in the upper estuarine reaches of the river. This is a result of both the winter flows and the poorer flushing when there is no river flow. Salinity and oxygen stratification during the period when there is no river flow leads to the release of nutrients from the sediments stimulating the growth of algal blooms.

The estuary is nutrient enriched generally but to a higher level in the upper estuarine reaches. Although the time series plots of the long term data are not very revieling, meaned data for each estuarine reach and season give a better indication of the trophic status of the system.

Algae

Macroalgae

Macroalgae are confined mainly to the fringing shallows of the middle estuary. Nuisance accumulations vary, but are generally of a low level which is well catered for by the current management effort of the Swan River Trust. The Swan/Canning Estuary does not experience the same level of macro algal growth as the

Peel/Harvey mainly because of its bathymetary. While fifty percent of the Peel/Harvey Estuary consists of fringing shallows of less than half a metre deep with the entire estuary less than 2 ½ metres deep, the Swan/Canning has only seventeen percent of its area consisting of shallows less than two metres deep. Macroalgae and seagrass growth is restricted to this area, so that the estuary does not have the same potential to grow Macroalgae as Peel-Harvey.

Macroalgae do not grow to any extent in the upper reaches of the Swan River estuary because of poor light penetration as a result of highly coloured water and suspended material in the water. There are also few shallow banks in this reach of the estuary.

Phytoplankton

Phytoplankton blooms occur in the middle estuary, mainly in the late Winter/Spring period, however blooms do not reach nuisance proportions. They are rarely noticed by the public other than boating people noticing some colour change in the water at times. Phytoplankton blooms in the middle estuary do not cause an environmental problem or nuisance to the community.

However, in the upper estuary Phytoplankton blooms frequently occur as a result of higher nutrient levels from winter inflow and from release of nutrients from sediments particularly in late summer and autumn. These blooms can be as intense as those experienced in the Peel/Harvey estuary, although they tend not to last as long as those blooms. They are also rarely noticed by the public as they are masked by background turbidity and colour of the river, reducing their visual impact.

These blooms do not often cause a nuisance to the community however, over the past two summers blooms have been more intense and have led to a reduced level of water quality with a consequent loss of amenity. 1988/89 summer swimmers at Redcliffe complained of an oily substance adhering to their bodies when they emerged from the water. This was a residue from a phytoplankton bloom. Over the 1990/91 summer an extensive phytoplankton bloom caused the river to turn a rusty red colour which was quite noticeable. These blooms have not caused obvious environmental problems although small fish kills have been experienced on rare occasions.

There has not been enough detailed investigation to determine the level of environmental degeneration.

Pollution from stormwater drains

The majority of stormwater from the Eastern part of the Perth metropolitan area discharges into the upper estuarine reaches of both the Swan and Canning Rivers. These areas are characterised by poorly drained soils with a high water table. Development has been facilitated by the construction of a drainage network. Bacteria levels measured as *faecal coliforms,* only reach unsatisfactory levels in the river during winter as a result of runoff from the catchment. As this is a time when primary contact recreation is minimal the health issue is minor.

A number of the main urban stormwater drains discharging into the river have unsatisfactory bacteria counts from time to time. Among the worst is the Claisebrook drain where 60% of readings are classed as unsatisfactory. The Spring Street drain is also in this class while the Bannister Creek is typical of urban stormwater drains where unsatisfactory levels are reached in less than 50% of occasions. The Ellen Brook is notable for high bacteria counts from a rural catchment. In general bacterial contamination of river and drainage waters is not a significant management problem.

Low levels of a range of heavy metals have been measured in both river and drainage waters. The metals that are the most persistent and with the highest levels are Chromium, Copper, Zinc and Lead. Levels of these metals are highest in the Spring Street, Claisebrook, Bayswater, Kitchener Road and Belmont main drains. All of these drains drain either existing or old industrial areas and the central business district.

Copper and Zinc are the only metals that breach environmental criteria. Zinc exceeded health MRL's residue criteria for mussels on two occasions in 1980. The areas of greatest accumulation of metals in the river is adjacent to stormwater drains where the major sedimentation from stormwater occurs. Other locations include areas where organically rich sediments accumulate and adjacent to marina slip-ways. Runoff from slip-way boat maintenance areas include paint residues which contain these metals.

Dieldrin and Heptachlor residues are the only pesticides that have been measured above environmental criteria. However, no pesticide residues have approached health criteria. With the banning of the use of organochlorine pesticides, these levels are expected to reduce over time.

3. CURRENT SITUATION

Nutrient loads

The long term historical nutrient data has been calculated as estimates of total annual loading based on low frequency instantaneous loads. This approach has necessitated the use of a number of assumptions these, together with the low frequency of the data, means that estimates are subject to large errors. The estimated total phosphorous loading for the Swan/Canning Estuary is between 60 and 90 tonnes phosphorus per year. The theoretical assimilative capacity, that is the capacity of the estuary to accommodate nutrient loads whilst maintaining appropriate beneficial uses has been estimated at approximately 130 tonnes of phosphorus per year.

The large errors associated with this estimation means that the data are really only useful for getting a feel for the situation and the origins of phosphorus from the catchment. It is interesting to note that only 23% of the total annual phosphorus load comes from the vast Avon catchment. While nearly 50% of the phosphorus entering the estuary comes from the two coastal plain catchments of Southern River and Ellen Brook.

The Swan River Trust has been engaged in an intensive nutrient load monitoring programme of thirteen major inputs to the estuary since 1988. The Trust is currently estimating total annual nutrient loads from these data. This will be followed by a more rigorous review of the assimilative capacity of the estuary.

The Water Authority of Western Australia is studying ten urban catchments which include sewered and unsewered areas with different land use and land form types in the Perth metropolitan area.

CSIRO has been engaged to carry out a three year hills land use study, reporting at the end of 1992. This study aims to determine the nutrient loading from hills catchments mechanisms of nutrient transport and identify land use activities that contribute to this nutrient.

All of these studies will assist the Swan River Trust in formulating management strategies for maintaining the satisfactory water quality in the future.

Pesticides

Monitoring of organochlorine pesticides in fish has shown that both DDT and Dieldrin have been detected in a range of fish species and size classes throughout the Swan and Canning Estuary.

Residues have generally been low and have been well below health criteria. This is a pilot survey to scan a range of species with an emphasis on recreational and estuarine species. Sixty one fish flesh samples from eight species were collected between January and March 1991 and analysed. DDT and Dieldrin levels were found in eight of twenty nine samples in the Canning River and fifteen of thirty two samples in the Swan Estuary. No other organochlorines were detected. Further work is proposed to confirm these results.

Sediment Studies

A three year study comparing the sediments of the Swan/Canning, Peel/Harvey and Leschenault Estuarine systems has been completed and is in the final stages of reporting. Perhaps the most surprising finding was that the Swan/Canning estuary had the highest concentrations of all phosphorus fractions, the highest of which were in the sites of the upper estuarine reaches of the Swan River. More importantly these samples also showed the highest proportion (66%) of non-apatite phosphorus. This is the phosphorus fraction that is theoretically available for release from the sediments for algal growth. This has considerable implications indicating the great potential for algal blooms to occur in the Swan estuary.

Air conditioner waste water - Heavy metals

A study of the accumulation of heavy metals, principally Zinc and Chromium in the Swan estuary as a result of the discharge of air conditioner waste water from the central business district via stormwater drainage has been completed and is in the final reporting stages. The study showed that Chromium and Zinc exceeded water quality criteria within thirty five metres of the stormwater drainage outfalls. Zinc and Chromium also exceeded the soil criteria for contaminated soils in the sediments adjacent to stormwater outlets from the central business district. Heavy metal residues in fish flesh however, were all well below health criteria. Although no environmental criteria have been applied it is interesting to note that the gonads of Perth herring had the highest levels of Zinc of 890 milligrams per kilogram. Overall the study has shown that the criteria for waters and sediments are only exceeded near drainage outfalls. There is some evidence of bio-accumulation of Chromium and Zinc in the estuary but all levels are well below health criteria.

4. FUTURE DIRECTION

Health monitoring

There is little value in continuing routine water quality monitoring. We are not learning anything new by doing this. Its simply shows how the trend for this year compares with trends for past years. It enables answers to parliamentary questions to be prepared, demonstrating that we are monitoring the estuary and looking after the environment! This is a necessary function, but it is not contributing to our understanding of estuarine processes nor does it give us any capacity to predict the response of the estuary to management actions or development proposals.

A new approach is needed based on health monitoring to provide information to answer questions and to monitor performance. A finger on the pulse if you like. We need data and models to allow us to develop some predictive capacity for management water quality.

Currently some attempt is being made to fill gaps in our knowledge the sediment study and completion of the annual survey of macro algal growth is the first stage of this approach.

The Swan River Trust is surveying light industrial areas which contain many small industries which are not licensed nor should they be. However, collectively these industries are contributing to pollution levels in drains. The aim of the surveys is to identify poor housekeeping practices and illegal activities. When discovored action is taken to correct the situation.

The Swan River Trust has a policy of reducing the number of licensed industries discharging into the Swan estuary and to tighten up on conditions to improve the quality of effluent to those industries that remain. A basic premis is that if a discharge is not polluting or has no potential to pollute then it does not need to be licensed. Conversely, if it is licensed then treatment should be to the highest standards. The Trust also encourages industry to connect to sewer or when relocating to relocate to areas where sewer is available.

Models

A lot of work has been done measuring and understanding the different components of an estuarine system, e.g. water chemistry sediments, fish, algae and the like. Little if any work has been done on the processes that drive these components and link the components. Little or no work has been done on the development of systems models for the Swan/Canning estuary.

Modeling of physical aspects of the system including circulation, flushing, tidal wedge movement and mixing of layers is needed. A better understanding of nutrient fluxes between sediment and the water column and between the water column and both macro algae and *phytoplankton* is important. The importance of algal growth in the food chain and the role algal growth has in primary productivity needs to be better understood.

CONCLUSIONS

Monitoring and research on the Swan/Canning system to date has given us a long term but sparse data base. Analysis of these data suggests that the estuarine system is eutrophic however, it does not experience the same level of algal nuisance and other symptoms of eutrophication as other estuaries in the south west of Western Australia with comparable phosphorous loadings. There are many reasons suggested for this including the improved flushing through Fremantle harbour works, and the deeper estuarine basin with relatively narrow shallow marginal shelf.

The Trust needs to gain a better grasp of assimilative capacity and total nutrient loading in and out of the estuarine system in order to allow it to make more precise management decisions to maintain satisfactory water quality.

The great challenge for the next twenty years is to maintain the water quality of the estuarine system to satisfy its beneficial uses in the context of an increasing population and expanding urbanisation.

The urban growth needs to be designed and built on the basis of minimising nutrient and water loading to the estuary in order to meet these objectives. The Trust therefore has a responsibility to provide more precise data for urban designers.

THE SWAN RIVER ESTUARY - WATER QUALITY MONITORING AND MANAGEMENT

Dr Desmond Lord
Director, Environmental Sciences
WG Martinick & Associates Pty Ltd

Based on information presented at the workshop, and on subsequent discussions, I would like to take the opportunity of offering the following general views to you concerning the management of the Swan.

The Swan River and estuary is presently not dying, nor even close to it. If no further management were undertaken though, the ecosystem would probably continue to function, but degrade slowly and inexorably. If this occurred, it would be a huge task to reverse. Therefore continuous close management is essential.

The Swan system is an enormous asset to the City of Perth; probably its greatest asset. Managing the Swan for the protection of this quality is the goal.

The Swan System could be suitably divided into two segments; the upper riverine portion and the lower estuarine component. Management goals can be allocated to each of these, with goals expressed as uses or conditions which must be retained. For example, for the upper portion the goals could be, preservation of aquatic life and use for recreation as well as an x% reduction in phytoplankton blooms; for the lower portion the goals could be harvesting of edible organisms and the conduct of body contact (ie. immersion) recreation.

These goals can then be translated into a series of indicators measured with regard to seasonal and spatial change, with a detailed trend analysis continuously being undertaken, to indicate the success or otherwise of management practices.

Some thoughts following the workshop

by Dr Jacob John
Curtin University

1. **Dynamics, causes and consequences of phytoplankton blooms with special emphasis on Dinoflagellates in the Swan River.**

As an active member of several international algological societies, I have participated in several conferences and workshops on phytoplankton blooms - particularly dinoflagellate blooms. It is a growing problem in many parts of the world. It is increasingly on our agenda in the international scientific conferences. Currently I am working with the EPA Marine Division looking at phytoplankton in Cockburn and Warnbro Sound. We have identified several Dinoflagellate blooms in the Western Australian coastal waters. It is worthwhile looking at similar blooms in the Swan to see whether they are caused by identical species and to identify the 'triggering' factors.

It is quite likely that the upper estuary has become more saline over the years even in winter due to inland salinity increase caused by deforestation, agricultural practices and salt lakes in the catchment areas. Avon River - beyond the influence of the Swan estuary has definitely become more saline over the years. Probably the same can be said about other tributaries. My experience with the algae in these waterbodies support this.

We need to investigate
(i) concentration of 'Dino' cysts in the sediment,
(ii) N:P ratios coupled with levels of Fe and Mo in the sediment and water column,
(iii) blooms preceding the Dinoblooms to see whether we can identify any 'marker' (forewarning) species,
(iv) look at the tributaries for algal blooms and benthic algae as you monitor P and N in them,
(v) grazing by zooplankton as a factor regulating phytoplankton, and
(vi) the physics (hydrodynamics) of the water.

We need to integrate several aspects of the phytoplankton biology and ecology not only at the level of research work but also at the level of research personnel involved transcending the boundaries of government and tertiary institutions. We should aim at tapping the expertise of our local scientists, irrespective of their affiliations, for the common purpose of maintaining the quality of the Swan River.

2. **The use of reliable bioindicators of the River have to be explored. While any stable group of biota (fish, invertebrates, algae, etc) can be used as bioindicators (diversity indices), the success of the system relies upon (a) accurate identification of the species and (b) information on their tolerance and preference to the environmental factors.**

We at Curtin have been working on the use of bioindicators to classify our wetlands and have unique expertise on diatoms which I believe are the best bioindicators as they meet the above two criteria well. We can accurately identify all the diatom species in the River and we are accumulating lots of information on their tolerance and preferences to organic pollution, eutrophication, salinity, etc. I believe we should look at the merits and demerits of various systems of biomonitoring.

The River should not be looked at in isolation - we have to consider the marine link as well as the riverine link. Over several years of algological research we have accumulated a lot of information on blue-green algal blooms in the fresh water lakes in the Swan Coastal Plain.

Finally let me add that in any discussion on primary production, phytobenthos and the jellyfish need to be included (my colleague Dr Rippingale and his students have done some excellent work on jelly fish). The zooanthellae (symbiotic algae living in jellyfish) at times fix more carbon than the phytoplankton in the areas of the river where they occur. The overall interaction among phytoplankton, phytobenthos and macrophytes is very important in eutrophic estuaries.

By the way, I believe some of the papers presented in the symposium need to be carefully refereed before you actually publish the proceedings, as there were many factual errors in some of them.

Over the years, we (Curtin University) have used the Swan River as a laboratory to teach our undergraduate and graduate students many aspects of estuarine ecology and have accumulated substantial data on eutrophication of the River. Lots of my own research in the Swan River remain unpublished. I am in the process of writing some of them in the form of scientific papers to be presented in the international conferences as well as journals - copies of which will be made available to you.

The role of the phytoplankton in recycling minerals and during the ecosystem need to be emphasised. The nature and composition of phytoplankton blooms need to be used as a measure of the health of the River.

"SWAN RIVER THE FUTURE" WORKSHOP - LIST OF PARTICIPANTS

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Mr	Robert	Atkins	Swan River Trust
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Mr	Peter	Collins	La Provost Env. Consul.
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