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BLACKWOOD RIVER ESTUARY

AN ENVIRONMENTAL STUDY OF THE BLACKWOOD RIVER ESTUARY WESTERN AUSTRALIA 1974-75

Ernest P. Hodgkin

Report No. 1
Department of Conservation and Environment

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A REPORT TO THE
ESTUARINE AND MARINE ADVISORY COMMITTEE
OF THE
ENVIRONMENTAL PROTECTION AUTHORITY

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FOREWORD

When the Environmental Protection Authority requested the Estuarine and Marine Advisory Committee to undertake a study of the Blackwood River Estuary, it was indeed fortunate to have available the services of Dr. E. P. Hodgkin to co-ordinate the many facets of the work and present this appraisal of the research programmes and implications of the results obtained.

The environmental study was undertaken basically to assist Government in reaching a decision on an application to dredge parts of the Blackwood Estuary for mineral sands, but it also provided an opportunity for scientists from both Government and University Departments to understand better the dynamics of one of the State's estuarine systems.

The study was an example of scientists from a number of disciplines being prepared to co-operate to bring together their understanding of the social, biological and physical effects of a mining proposal. The mining company, too, at all times provided information it had available and entered into discussions thus increasing the effectiveness of this report.

As Chairman of the Estuarine and Marine Advisory Committee I would like to place on record my appreciation of Ernest Hodgkin and all those who contributed to the Environmental Study of the Blackwood River Estuary.

B. K. Bowen

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CHAPTER ONE INTRODUCTION

This study of the estuary of the Blackwood River was conducted during 1974 and the early part of 1975 and was financed by funds allocated to the Western Australian Department of Conservation and Environment by the Government of W.A. and the Australian Government. The study was directed by the Estuarine and Marine Advisory Committee (EMAC), a committee of the Environmental Protection Authority of W.A. (EPA).

I was appointed Research Coordinator for the study in January 1974 and the various members of our research team were subsequently invited to participate. Although individually responsible for their own segments the scientists involved have worked together to make this a successful cooperative effort. We believe the study gives a valuable understanding of the Blackwood River estuary and also provides the basis for more sophisticated studies of other estuarine ecosystems of south western Australia in the future.

Members of the research team have submitted their individual reports in respect of specific segments of the study and these Technical Reports are listed on page vii. Some have already been published and others will be published later in whole or in part.

The account which follows is a personal evaluation of these individual reports. They have provided most of the material on which it is based, even though constant cross reference to them has been avoided for ease in reading. My report is an attempt to put their data into the perspective of a general understanding of the estuarine ecosystem and man's influence on and response to it. It has been prepared with the cooperation of the team members and each has read and commented helpfully on the parts relevant to their studies. However, the responsibility for what is said here is mine.

Acknowledgements

This study of the Blackwood estuary has been a cooperative effort in which many people have participated. It has been my good fortune as Research Coordinator to lead an enthusiastic team of investigators who were intensely interested in the study. Interested not only in their own role in it but keen to make this assessment of the ecosystem the best possible within the time and resources available to them. The work reported here is mainly theirs and I am deeply grateful to them for their support throughout the investigation and in the preparation of this report. It has been a pleasure to work with them.

To the members of the Estuarine and Marine Advisory Committee, I would say thank you for constant help and encouragement and for showing very necessary patience at all times, and especially during the preparation of this report. I have relied heavily on the willing assistance of the Secretary to the Committee, Dr. Ross Field, throughout and owe much to him. The practical interest shown in the study by other colleagues in the Department of Conservation and Environment has been most helpful. Members of other Government Departments, State and Federal, have also given freely of their time most helpfully.

I speak not only for myself, but also for my team mates in saying that it has been a great pleasure to work with the people of Augusta. We have appreciated their interest in our work and their ready cooperation whenever we have sought it. Thank you for the friendship you have shown us. We are grateful too for the support given to the study by members and officials of the Augusta-Margaret River Shire Council.

There are many persons who I would like to thank individually, in other Government departments, State and Federal, at the University of W.A., Western Australian Institute of Technology, in industry, and others in their private capacity. To start to do so would certainly be to miss out some who should be thanked so I must simply express my gratitude to all who have helped in any way in this study of a "magnificent and peaceful river" (Georgiana Molloy in 1839).

1.1 History and Reasons for the Investigation

These are set out in detail in a report of the Department of Environmental Protection dated June 1973. The following is a brief background summary from that report.

Mining and dredging claims for heavy minerals were originally pegged in January 1970 in the Augusta area, but many of these were subsequently withdrawn. The present mining claims are in leached Quaternary sand dunes to the east of the Blackwood River near its mouth; the dredging claims are in the lower part of the estuary opposite Augusta and a few kilometres upstream (Fig. 1). In 1971, objections to the proposed mining and dredging were lodged by a number of citizen bodies and by two Government departments and the National Parks Board. These objections were based on social, aesthetic, and environmental grounds which stressed among other things the potential damage to fish and bird populations. In the report, these objections were summarised as follows:

(i) "The town of Augusta is developing as a retirement, tourist and holiday town and the encroachment upon this life style of a 'hard' industry is one of the major objections to the project."

(ii) "Aesthetic objections to the dredging are valid to some extent for the one year when the dredging would be near the townsite."

These points were further amplified:

> "Inspections of the area and assessment of the life-style of the permanent residents ... led to the impression being gained that the major objection to the proposed mining is fundamentally one of aesthetics and an objection to the unknown effect of such an industrial activity in such a quiet rural atmosphere. Such aesthetic objections cannot be quantified nor scientifically assessed. They remain very real objections nevertheless."

(iii) "Most of the objections to the proposed dredging in the estuary have claimed that it would destroy the natural fish and bird populations. In fact no scientific evidence for this exists for this area, and

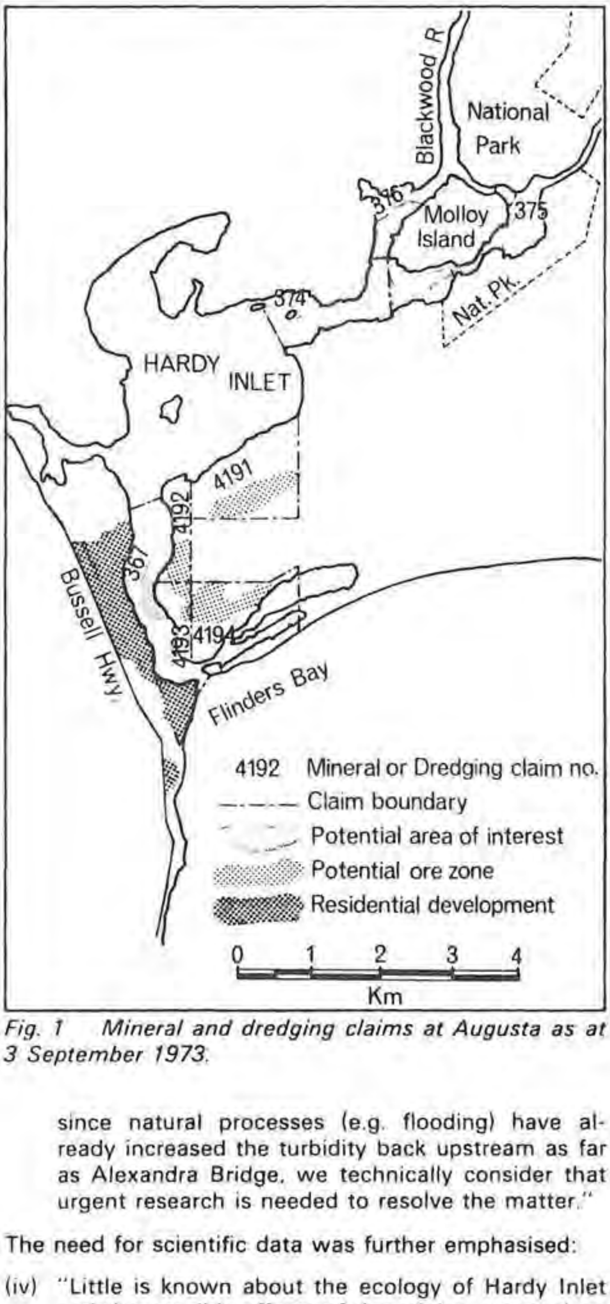


Fig. 1 Mineral and dredging claims at Augusta as at 3 September 1973.

since natural processes (e.g. flooding) have already increased the turbidity back upstream as far as Alexandra Bridge, we technically consider that urgent research is needed to resolve the matter."

The need for scientific data was further emphasised:

(iv) "Little is known about the ecology of Hardy Inlet and the possible effects of the mining proposal on it. No scientific references can be found relating to this particular estuary and only limited research has been done in other possibly comparable areas. Most of this latter work has been specific to particular organisms rather than the overall structure and balance of the estuary system."

Because of this dearth of scientific and sociological data about the estuary and surrounding area and the consequent inability to quantify ecological effects of the proposed dredging, the Environmental Protection Authority: "RECOMMENDED that no mining be allowed on these claims, and they not be listed for hearing in the Mining Warden's Court until further research has been undertaken." These recommendations were accepted by Government and EPA asked the Estuarine and Marine Advisory Committee to undertake a detailed investigation of the area.

EPA directed that:

"Such an investigation should include a study of the ecology of the estuary and its environs, and lead to an assessment of the multiple uses of the estuary with respect to such factors as commercial fishing, bird life, tourism, recreation, the mining proposal and the aesthetic effects for local residents."

It was envisaged that such a programme would entail at least one year of field studies.

1.2 Objectives of the Study

The study therefore had two objectives:

(a) Short term. To attempt to predict the probable effects of mining and dredging in the estuary and its environs.

(b) Long term. To understand the working of the Blackwood estuary ecosystem as the basis for making decisions about the management of this and other estuaries of south west Australia.

A separate report, "The Anticipated Effects of Dredging in the Blackwood River Estuary," has been prepared by EMAC and submitted to EPA.

THE PRESENT REPORT IS CONCERNED PRIMARILY WITH THE SECOND OBJECTIVE, THAT IS, WITH A GENERAL ASSESSMENT OF THE ESTUARINE ECOSYSTEM.

To make such an assessment, it was necessary to attempt to answer the following questions; "attempt" because it would be fanciful to suppose that complete answers to such comprehensive questions about a highly variable environment would be forthcoming within one year. But, however incomplete, the answers do furnish a substantial basis for making judgements about priorities in the Blackwood, and also in other estuaries of south western Australia. These questions are:

(i) What environmental factors determine change and continuity in the estuary and what is the magnitude and timescale of these changes? Such environmental factors include: physical dimensions of the estuary; current systems in the estuary and their relation to river flow, tidal exchange, and the impact of "weather" on water movements; the nature of the sediments and their transport and history; aquatic plants as sediment traps and nutrient sources.

How have these been influenced by man's activities in the past, and how might they be influenced by activities such as dredging in the future?

(ii) What fish and bird populations use the estuary, and what are the dynamics of these populations?

How are these populations influenced by environmental factors and changes in these, what changes have there been in these populations as the result of human activities, and how might they be influenced by human activities such as dredging?

(iii) What do the fish and birds feed on, where do these food organisms live, and what determines their abundance in different parts of the estuary and at different times of the year?

How might the distribution and abundance of these organisms be influenced by such human activities as dredging?

(iv) What part do the water plants play in maintaining the ecosystem, and what environmental influences determine the species composition and abundance of the aquatic flora?

How might human activities such as dredging influence the aquatic flora?

(v) What is the human usage of the estuary and what values are placed on it by people who use it or may use it in the future?

How might this usage and these values be influenced by dredging and mining or other similar human activities which will change the environment?

(vi) What other natural resources of the Augusta area should be taken into consideration when assessing the possible impact of dredging and mining and in planning the future development of the area?

1.3 Components of the Study

Areas of responsibility for particular parts of the investigations were as follows:

1. Hydrographic survey, ocean tide recording and prediction. Dr. W. S. Andrew, Mr. D. F. Wallace, and specialist staff. Harbours and Rivers Branch, Public Works Department.
2. Water characteristics, dynamics and sediment transport. Dr. J. Imberger, Mr. H. J. Agnew, and Dr. J. Billings, Departments of Mathematics and Mechanical Engineering, University of W.A., with assistance of Mr. E. M. Copley of Augusta.
3. Sedimentary studies; sedimentary history and granulometric analyses. Dr. B. W. Logan and Mr. Z. A. Sas, Geology Department, University of W.A. Sediment cores were taken by staff of the Harbours and Rivers Branch, Public Works Department.
4. Aquatic flora and plant nutrients. Mr. R. A. Congdon and Dr. A. J. McComb, Botany Department, University of W.A.
5. Invertebrate aquatic fauna. Mr. J. Wallace and Mr. R. C. J. Lenanton, W.A. Department of Fisheries and Wildlife.
6. Fish biology. Mr. R. C. J. Lenanton, W.A. Department of Fisheries and Wildlife.
7. Water birds. Mr. J. A. K. Lane, W.A. Department of Fisheries and Wildlife.
8. The fishery. Mr. R. C. J. Lenanton and Mr. N. Caputi with the assistance of Mr. G. Blowfield of Augusta to operate the 'Creel Census'.
9. Recreational use of the area; data from holiday log registers. Mr. N. Caputi and Mr. R. C. J. Lenanton, W.A. Department of Fisheries and Wildlife.
10. Tourism. Miss C. R. Bayley-Jones, School of Environmental and Life Sciences, Murdoch University.
11. Social and demographic characteristics and population attitudes. Mr. B. E. Wooller, Department of Social Work, and Mr. K. J. Frawley, Department of Geography, University of W.A.
12. Economic aspects. Mr F. A. Fulbrook, Department of Economics, University of W.A.
13. Coordination. Dr. E. P. Hodgkin, W.A. Department of Conservation and Environment.

It must be stressed that these were not watertight compartments; the success of the study depended on constant cooperation between all members of the team and frequent interchange of ideas, both in the field and in workshops held periodically to discuss progress. Success depended also on the loyal assistance of technical staff who are named in the Technical Reports.

1.4 Should Mining be Permitted?

The question: should mining and dredging be permitted in the area? did have to be answered, though it was not the responsibility of those conducting the investigation to answer it. It was our job to collect the information on which a decision could be made on rational grounds. An economic valuation has been placed on the commercial fishery and the tourist industry for comparison with the calculable value of the mining proposal, to Augusta and to the State. We have amassed a lot of valuable data about the physical environment, about the plants, and the dynamics of fish and bird populations. We have assessed as objectively as possible how dredging and mining will affect the natural environment, the estuary itself and the plants and animals which are a part of it, and what the long term results of dredging will be so that costs of mitigating potential damage may be estimated. However there are human values which cannot be estimated in dollars and cents: the peace of a natural environment which has undergone little change since Europeans first settled there in 1830; the beauty of centuries-old blackboys and grass trees and dense peppermint thickets; flocks of hundreds of swans and over fifty species of water birds that live here undisturbed; the recuperative value to a jaded city dweller of days spent with fishing line and bait; the reward to a retired person of the freedom from bustle afforded by village life.

In a State where a persistent pioneering urge is still pushing back the native bush for immediate economic gain with little thought for the welfare of future generations, these and other human values have somehow to be weighed against present gains to the community accruing from the extraction of heavy mineral sands.

Subsequent to preparation of this report for publication the EMAC report "The Anticipated Effects of Dredging in the Blackwood River Estuary" was considered by the Environmental Protection Authority. EPA recommended that the dredging and mining applications should not be approved. The mining company advised the Department of Mines that it did not wish to contest the various objections and, on its recommendation, the Mining Warden refused the applications on 12 January 1977.

CHAPTER TWO THE BLACKWOOD CATCHMENT

The catchment of the Blackwood River covers an area of about 23 000 km^2 and extends from Augusta about 325 km eastwards almost to Lake Grace. It is not the largest catchment of the rivers of the south west, but it lies in a region of relatively high rainfall and has the greatest discharge, 1 057 x 10^6 m^3 p.a., compared to 465 x 10^6 m^3 for the Swan River which has a much larger catchment.

2.1 Climate

Here, as elsewhere in south western Australia, weather is controlled largely by seasonal north-south movement of the anti-cyclonic belt of pressure systems; westerly winds bring heavy rain during winter and there is little rain in summer when winds are predominantly easterly, except in the extreme south west. Rainfall is heavy west of the Darling escarpment, but decreases progressively to the east. Climatic data from Cape Leeuwin and Bridgetown, the only two weather stations in the catchment, are summarised in Fig. 2.1. Rainfall data are available from many other stations.

Rainfall is measured daily at Augusta (West Bay) and recording instruments were operated as part of this study; air temperature at Lindberg House, barometric pressure at Point Irwin, and a recording anemometer on Thomas Island (charts only reduced for selected days).

Temperature

Augusta has a mild, equable climate with a small temperature range; the mean maximum for the hottest month (February) is only 23.2°C and the mean minimum for the coldest (August) 11.1°C (Perth, 29.7° and 9.0° respectively). The greater range at Bridgetown is evident from Fig. 2.1 and temperature extremes are of course even greater in the eastern catchment.

Rainfall

Isohyets and mean monthly rainfall data for representative localities in the catchment are shown in Fig. 2.2. In the lower catchment, west of the escarpment, rainfall is uniformly high with over 1 000 mm p.a. and a maximum recorded average of 1 270 mm at Rosa Brook. East of the scarp, rainfall decreases rapidly to less than 500 mm east of the Merredin Line. Summer thunderstorm rainfall in the eastern catchment results in occasional heavy falls and slightly increases the proportion of summer rainfall there. Although the resulting runoff only occasionally reaches the estuary, it may have a devastating effect on the biota of the river because of the great quantity of organic nutrients carried in from farmland.

Rainfall data for 1974 and 1975 are shown in Fig. 2.3. It will be noted that in 1974 rainfall was considerably in excess of normal in April, May and July, but was much below in June when there was a period of two weeks with no significant falls.

Evaporation

Evaporation is not measured at any station in the catchment and the data in Table 2.1 were read from Bureau of Meteorology maps and are therefore estimates only. It will be noted that evaporation, as measured from a free water surface, is approximately equal to rainfall at Cape Leeuwin. In the eastern part of the catchment (Wagin) evaporation greatly exceeds rainfall.

Winds

At Cape Leeuwin, winds are predominantly westerly in winter but tend south easterly in summer. In the immediate vicinity of Augusta, the wind is deflected by high ground of the Leeuwin peninsula. Dune blowouts and the characteristic deformation of coastal vegetation near Augusta reflect the direction of prevailing onshore winds; vegetation behind Point Frederick indicates a direction of 120°. Both native and garden plants in the Dukes Head area show abundant evidence of wind (salt) burn, but this is much less in the lee of this headland and in the town to the north of the hotel.

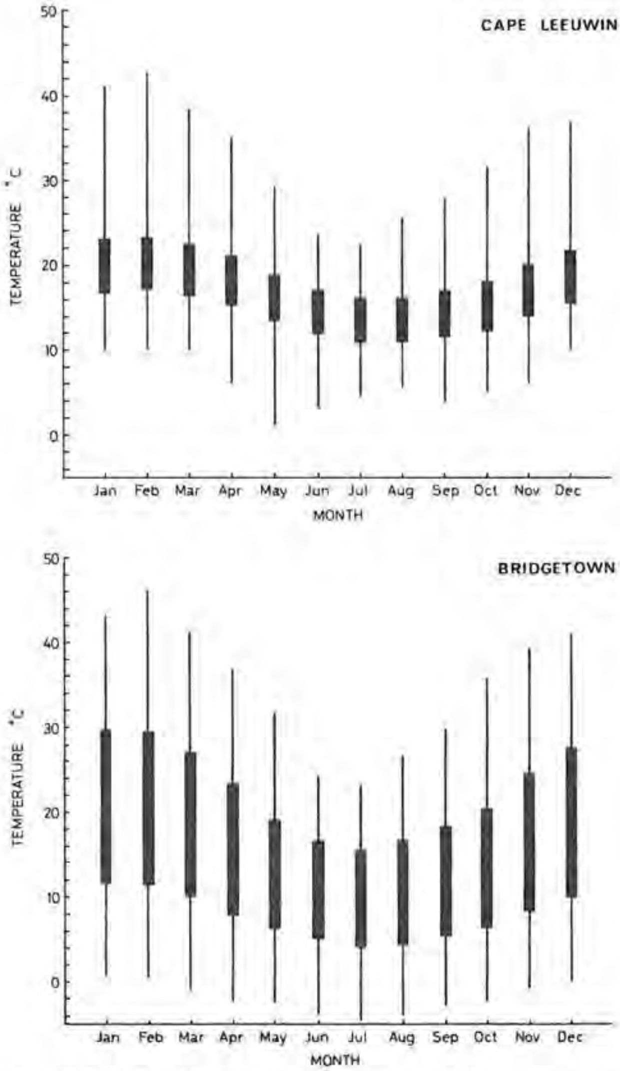


Fig. 2.1 Monthly means and extremes of temperature at Cape Leeuwin and Bridgetown. Source: Bureau of Meteorology.

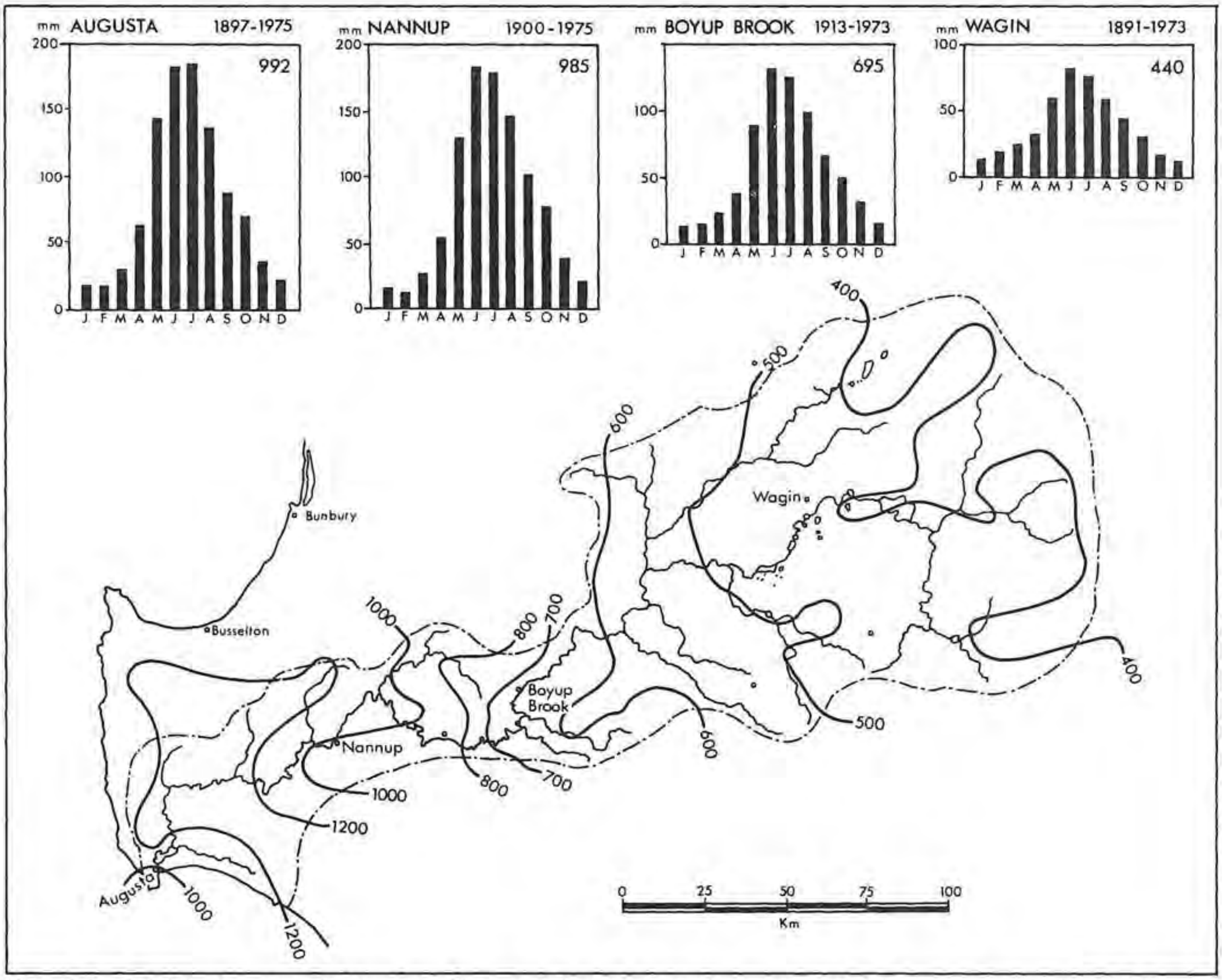


Fig. 2.2 Rainfall in the Blackwood River catchment—monthly mean rainfall, mean annual rainfall and isohyets—millimetres. Source: Bureau of Meteorology.

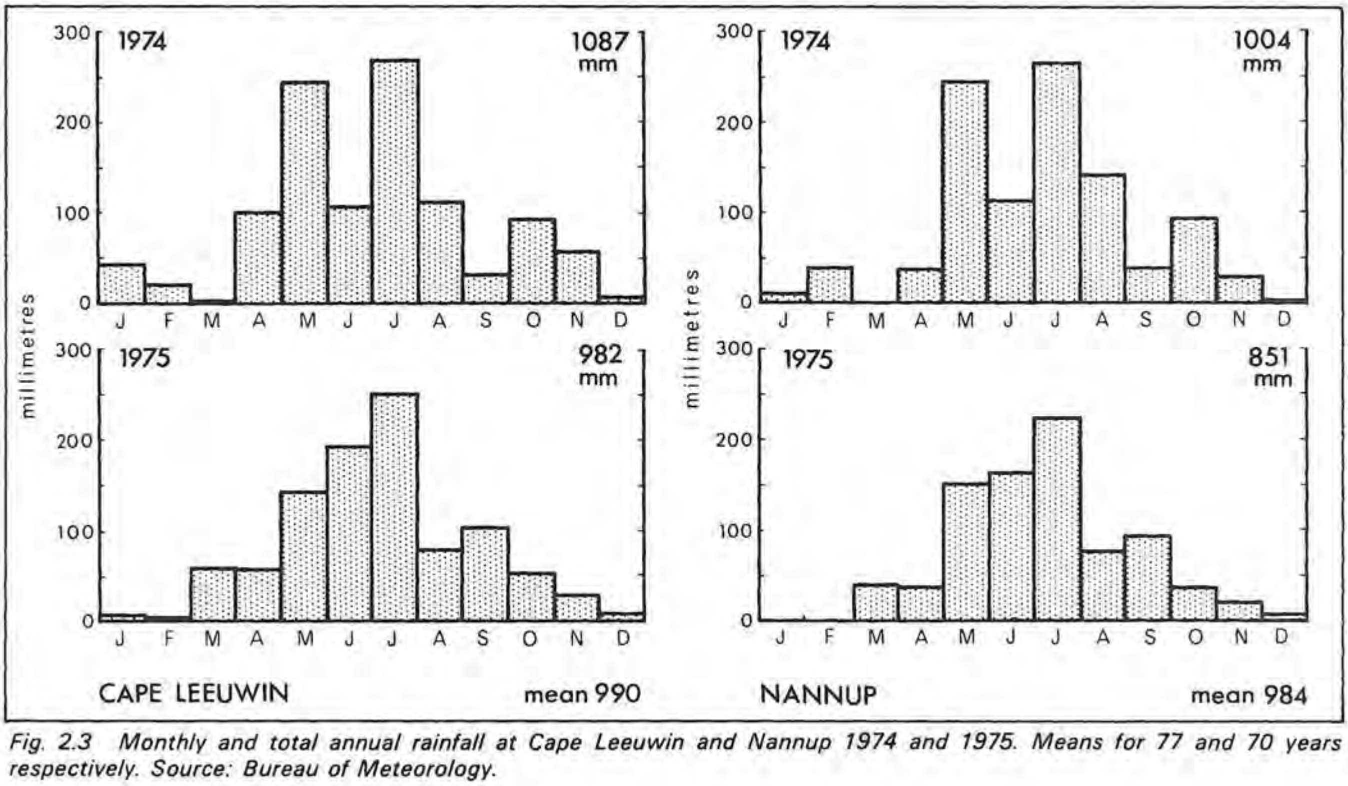


Fig. 2.3 Monthly and total annual rainfall at Cape Leeuwin and Nannup 1974 and 1975. Means for 77 and 70 years respectively. Source: Bureau of Meteorology.

Table 2.1—Evaporation in millimetres at three localities in the catchment of the Blackwood River. Figures approximate only
Source: Bureau of Meteorology maps.

	J	F	M	A	M	J	J	A	S	O	N	D	Total Rainfall
Cape Leeuwin	130	115	90	60	50	25	25	40	50	75	100	130	995
Bridgetown	180	150	130	75	60	40	25	40	60	90	140	165	853
Wagin	225	195	170	125	65	45	40	50	65	165	140	205	444

2.2 Geomorphology

The topography of the catchment is the result of the impact of past and present climatic forces on the geological substrate, further modified in the estuarine part by Pleistocene changes of sea level. The catchment lies principally in two very different geological regions and impinges upon a third. The upper catchment, east of the Darling Fault, lies on the Precambrian Shield, an ancient plateau which is here about 300 m above sea level. West of the Fault there is a sedimentary basin, the Bunbury Trough or Donnybrook Sunklands. This is bounded on the west by the Dunsborough Fault which separates it from the Naturaliste-Leeuwin block of Precambrian rocks along the west coast (Fig. 2.4).

The greater part of the catchment is on the Shield and must be presumed to be an ancient river system. Not only is the river valley deeply incised where it emerges from the plateau, but there is a well-developed submarine canyon through the continental shelf. Bettenay and Mulcahy (1972) recognise three drainage zones on the plateau.

The *zone of old drainage*, east of the Meckering Line, is gently undulating country with broad flat valleys, seldom more than 60 m below the uplands which surround them. These uplands are covered mainly by sandy (quartz) soils which overlie laterites; they are the product of deep weathering of the Precambrian rocks which they cover. In the valleys there are thin alluvial deposits, gradients are low (about 1 in 1 500 in valleys of the Avon catchment) and there are extensive salt lakes. Drainage is poor, evaporation high and the rivers flow infrequently, following heavier than average rainfall. In a wet winter there may be considerable flow; 1974 was such a winter.

A middle *zone of mature drainage* has U-shaped valleys with relatively flat floors and low gradient. Here the laterite which underlies the sandy soil of the plateau is extensively exposed. Rainfall is 450 to 700 mm and the rivers are seasonal, flowing in clearly incised courses during the winter but drying to strings of brackish pools in summer (about 10 000 p.p.m., Morrissy, 1975).

In the *zone of rejuvenated drainage*, the lowest part of the catchment on the Shield, the rivers flow in deeply incised, V-shaped valleys, commonly cut 60 to 200 m below the laterite uplands and exposing granitic basement rock. Rainfall in this zone is 700 to 1 000 mm and runoff is much greater than from the two more extensive zones to the east. However, even though some streams flow throughout the year, summer flow is a negligible part of annual discharge.

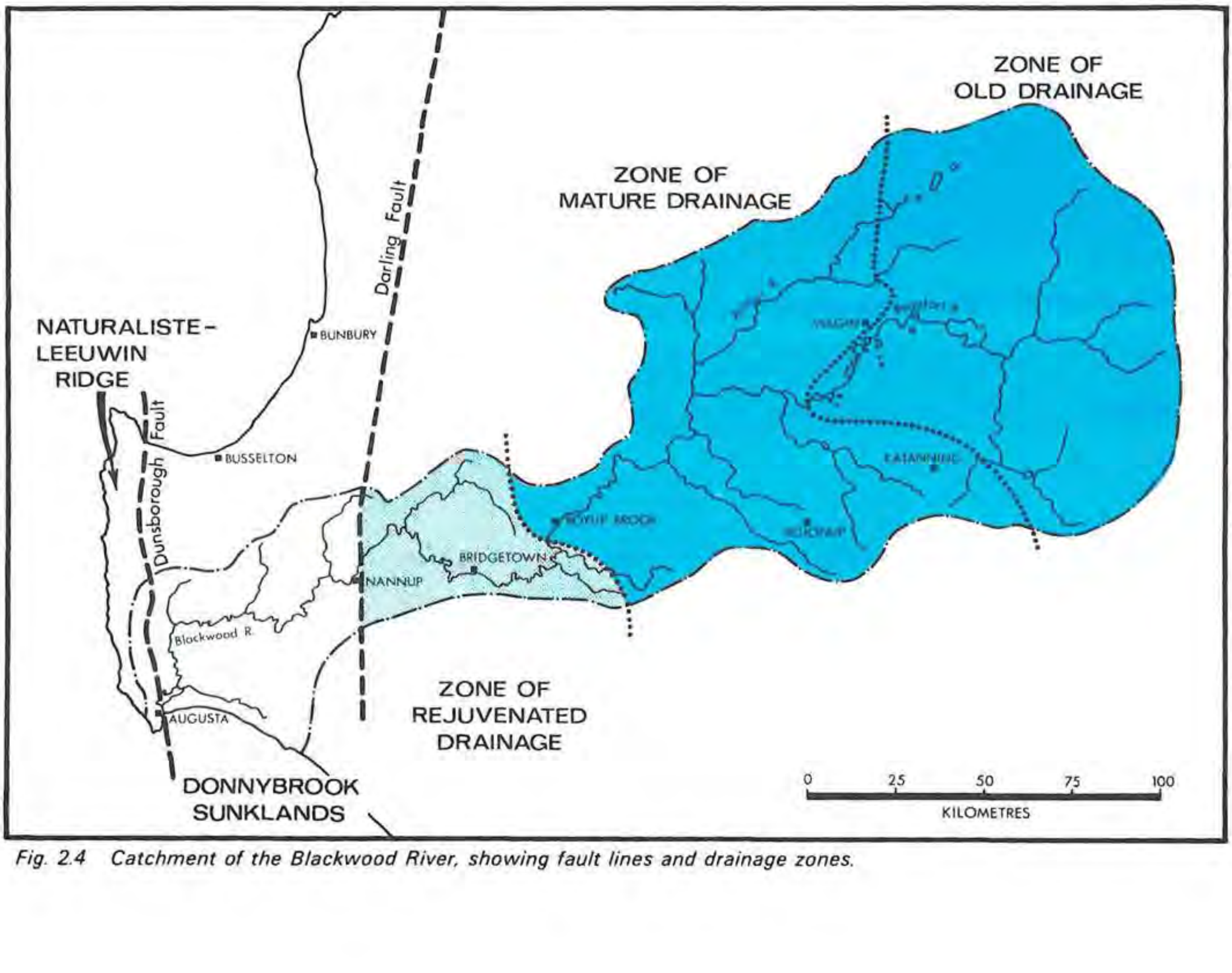


Fig. 2.4 Catchment of the Blackwood River, showing fault lines and drainage zones.

The *sunkland of the Bunbury Trough*, the deep graben between the Darling and Dunsborough Faults, has sandy sedimentary rocks which have accumulated over a long time, from late Palaeozoic to lower Cretaceous period (Lowry, 1967). These rocks are, however, covered by a thin surface layer of Quaternary laterites and associated quartz sands at an altitude of about 100 m. At Nannup, the river is 60 m above sea level and between here and the estuary the Blackwood and its tributaries have cut meandering courses in relatively deep channels, with steep banks, through gently undulating country where drainage is generally poor. Rainfall over the sunklands part of the catchment ranges from 1 000 to 1 300 mm.

In the southern part of the sunkland, south of the Brockman Highway, drainage is to the Scott River, streams are ill-defined, profiles are low and there is often sheet drainage in winter. Four Pleistocene shorelines are recognised here and off-shore reefs may represent yet others. The dunes of the two older shorelines, north of the Scott River, have been leached and much modified in topography, leaving an acid peaty quartz soil. The Scott River itself flows parallel to the coast through a broad flat valley, the Scott River plain, which represents an interdune depression. The two shorelines to the south of the river are still largely typical calcareous dunes with coastal limestone (calcarenite).

The main accumulation of heavy minerals appears to have been deposited along the old shorelines, from sediments transported by the Blackwood. The mining claims and the dredging claim opposite Augusta, are in littoral deposits of this nature; however minerals in the dredging claims round Molloy Island are thought to have been reworked from older shorelines and deposited where river flow slackened.

Quaternary surface deposits similar to those of the sunkland also overlie Precambrian rocks of the Naturaliste-Leeuwin block.

An account of the geology, mineral potential, and hydrogeology of the lower part of the catchment is contained in a report from the Geological Survey of W.A. (Tech. Rep. 14).

The following points with respect to mining may be stressed here. At the present time, heavy minerals, principally ilmenite, are the only significant mining prospect in the vicinity of the estuary. Deposits in the Scott River basin, some miles to the east of the estuary, contain the largest known mineral reserves. The sands of mining and dredging claims considered here (Fig. 1) contain approximately 6 per cent. heavy minerals, with an estimated total of some 3 million tonnes contained ilmenite (Project Mining Corporation, pers. comm.).

2.3 Hydrogeology

The soils of a large part of the Precambrian Shield, particularly the pallid zone lateritic soils, have a high salt content. Dimmock *et al.* (1974) estimate this at 10^6 kg/ha total salts at Baker's Hill, in the Avon catchment, with a 600 mm p.a. rainfall. Under native hardwood forest, with its deep rooting and high transpiration spread over the whole year, little of this escapes to the rivers. However, following clearing of the forest and its replacement with annual crops and pasture, there has been an increase in river salinity. At Bridgetown, the salinity of river water has increased from 1 000 p.p.m. to 3 000 p.p.m. over a period of some 50 years (Peck *et al.*, 1973); 500 p.p.m. is usually regarded as the maximum for domestic purposes.

The stored salt is believed to be cyclic salt from rainfall and river water has much the same ionic content as sea water, except that it has higher bicarbonate and lower sulphate levels. It is calculated that at present rates of deposition, it could have accumulated within the last 17 000 years. Although leaching is rapid Peck & Hurle (1973) estimate that between 30 and 400 years will be required before runoff water from cleared land will be acceptable for drinking purposes.

Rainfall, salt content of rainwater, and runoff all decrease with distance from the coast; but soil salt storage increases greatly (Dimmock *et al.*, 1974) and so too does the proportion of cleared land (Table 2.2). For rivers which have their headwaters in the wheatbelt there is the anomalous situation that salinity is least where the river enters the estuary and increases progressively upstream, until in lake systems of the old plateau there is often crystalline salt on the surface. Morrissy (1975) has documented stream salinities for the Blackwood River (Fig. 2.5).

Streams of the sunkland part of the catchment have a low salt content, less than 1 000 p.p.m. (Morrissy, 1975). Salinity in Rosa Brook and the Scott River seldom exceeds 250 p.p.m. (Public Works Department, Water Resources Section 1972). However, river water (at Darradup) has an average salinity of 720 p.p.m. and following heavy rain in the upper catchment may exceed 2 000 p.p.m.

Table 2.2—Areas of cleared land within the catchment of the Blackwood River (1969-70). Figures are approximate only. Source: Australian Bureau of Statistics.

SHIRE	HECTARES x 10^3 Total	Privately owned	Cleared	Percent cleared	
1 Augusta-Margaret River	158	57	36	23)	12
2 Nannup	197	38	12	6)	
3 Donnybrook-Balingup	77	18	13	17)	
4 Bridgetown	90	37	29	32)	32
5 Boyup Brook	212	128	80	37)	
6 West Arthur	212	178	116	54)	66
7 Kojonup	196	193	151	77)	
8 Narrogin	108	98	89	83)	
9 Wagin	194	185	163	84)	
10 Woodanilling	112	104	87	78)	83
11 Katanning	153	142	129	85)	
12 Broomehill	39	38	36	93)	
13 Wickepin	100	95	86	86)	83
14 Dumbleyung	255	233	208	80)	

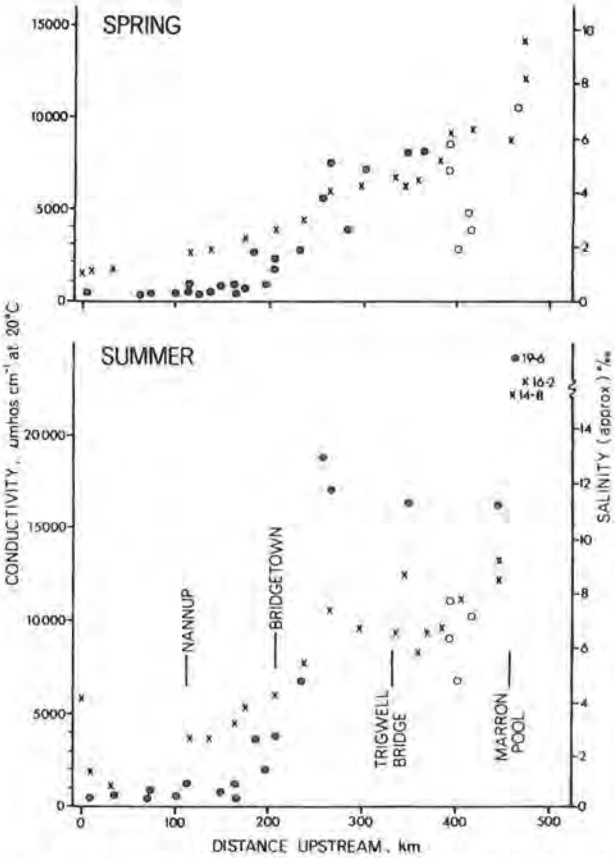


Fig. 2.5 Salinity of water in the Blackwood River and tributaries. Main river—x, tributaries—●, Hillman River—o. Source: Morrissy (1975)

Although total salt input to the Blackwood estuary from cleared land has increased greatly, it is unlikely to have had any significant influence on the biota. Dilution by sunklands runoff has allowed the freshwater fauna to continue to flourish in this part of the river (section 2.5). The increased nutrient load and metallic ions may have had some minor influence.

2.4 Vegetation of the Catchment

The natural vegetation varies from open sclerophyll woodland in the low rainfall (less than about 625 mm p.a.) eastern part of the catchment to thick jarrah-marri forest in high rainfall areas. The extent to which it has been cleared for agriculture varies greatly and little is now left of the sclerophyll woodland; some 83 per cent. of land in the eastern Shires having been cleared for grazing and wheat farming (Table 2.2).

The western, steeper part of the Shield has been less extensively cleared; woodland persists, particularly on hill tops and there is State forest of both native eucalypts and pines near the scarp. Clearing of alienated land continues with the result that river water has become increasingly saline and is useless for domestic purposes or for irrigation. Clearing has of course also increased erosion and seasonality of runoff. Agricultural land is used mainly for grazing and fruit growing.

The sunkland portion of the catchment, from which most runoff to the estuary derives, is still largely under forest, much of it State Forest. Some is being felled and replaced with pines, with temporary increase in runoff, but as yet this is only a small part of the Blackwood catchment. Much of the jarrah-marri forest is of poor quality, probably the result of poor soils, waterlogging, and frequent firing from early settlement days. There was also considerable burning by aboriginals even before settlement. Fire breaks cleared during the last 30 years have reduced the fire hazard but have helped to spread dieback *(Phytophthora)*, except on the richer riverine soils where the forest is less susceptible.

All land with drainage directly to the estuary (below Warner Glen Bridge) is alienated with the exception of small areas of State forest and National Park. In 1967, less than half had been cleared (map in Smith, 1973), but subsequently there has been extensive clearing for pasture close to the estuary and some of this has extended right to the river bank between Warner Glen and Alexandra Bridges. Uncleared land is mainly jarrah-marri forest.

The Scott River catchment grades from jarrah-marri forest through paperbark woodland, low scrubland and sedgeland, to coastal dune vegetation with peppermint scrub. The vegetation map of the area (Smith, 1973) is complex and there are patches of open jarrah-marri forest scattered throughout. There are also small areas of karri forest.

The Scott River plains are of botanical interest because many south coast species reach their western limit here and a number of plants are entirely or almost restricted to the plains, e.g. *Adenanthos detmoldii* and *Lambertia orbifolia* (Proteaceae). The Albany pitcher plant is also reported to grow here. Botanically the sedgelands are the most interesting feature and they are also the most susceptible to damage by clearing or draining (A. S. George, pers. comm.) The botanist James Drummond and ornithologist John Gilbert collected here in 1842 and it is probably the type locality for a number of plant species.

Much of the Scott River area is now being cleared for grazing, including some of the sedgelands, often with total destruction of all timber and other natural vegetation. Demands for better drainage are likely to be renewed following wetter winters than have been experienced in recent years.

The land immediately east of Augusta, with its thick groves of peppermint woodland (*Agonis flexuosa*), is gazetted town land, but as yet there has been little development on it, although some has been used for grazing for many years. Limited areas which have been cleared from time to time have regenerated to peppermint scrub.

2.5 Fauna of the River

No systematic study has been made either of the river, or of streams entering the estuary directly. The fresh part of the river, about to Bridgetown, has a normal, rather sparse, freshwater fauna with the mussel *Westralunio carteri*, marron (*Cherax tenuimanus*), and a variety of insects.

Marron and probably also *Westralunio* have disappeared from the upper reaches of the river, above Winnejup Ford near Bridgetown, following the increase in salinity and surface runoff of nutrients. As late as the 1930s marron were fished as far upstream as Marron Pool near Kojonup (Morrissy, 1974). In these upstream waters, a number of salt-tolerant animals are common, including cunac (*Cherax plebjus*), the shrimp *Palaemonetes australis*, various native fish (atherinids, galaxids, gobies, the cobbler *Tandanus bostocki*, pygmy perch *Edelia vittata*), and the predatory, introduced, redfin perch (*Perca fluviatalis*).

In two zooplankton surveys (November 1974 and February 1976) the brackish water copepod, *Sulcanus conflictus*, was abundant in middle reaches of the river (Duranillin to Winnejup), but was only sparse below Bridgetown.

CHAPTER THREE THE ESTUARY: PHYSICAL FACTORS

Few generalisations can be made about estuaries; there are so many exceptions that they are often of limited value only. This is particularly true when generalisations derived from studies of the drowned valley type of estuary are applied to Western Australian estuaries. *Estuary is here defined as the tidal part of a river system;* it is a region where fresh water and sea water mix, at some time of the year, and includes coastal lagoons which are continuous with it. This definition is appropriate to the Blackwood and other open and seasonally open estuaries of south western Australia.

These estuaries share certain characteristic features which are described in more detail below. They have developed on a coastal plain, across which a tidal river winds to discharge into a basin or lagoon behind Pleistocene dunes that restrict the mouth; the dunes having built up on a high energy coastline. In form the basins are similar to coastal "lakes" of south eastern Australia, but hydrologically they are very different because of the different climatic conditions.

The following terminology has been used in respect of the geomorphological features of the estuary, shown in Fig. 3.1. In Western Australia, the term "Inlet" has been applied to enclosed bodies of water in an ill-defined manner. As used here *Inlet* (with a capital letter) is a place name, applied to Hardy Inlet and includes both inlet and basin as defined below. The term *inlet* or *inlet channel* is used here in its geomorphological sense for the narrow part of the system connecting mouth and basin. It has been referred to as the "channel" in some of the Technical Reports.

The term *basin* is here used for the lagoonal part of the estuary between Point Irwin and Island Point. The term "lagoon' has been used for the same region in some Technical Reports. The shallow upper part of the basin is the river delta, or more usually simply *delta.*

The rest of the estuary upstream of the basin is termed the *tidal river.* The lower part of this around Molloy Island, with extensive shallow margins, is of a different character from the rest. The shallows of the lower part of the Scott River are the Molloy-Scott basins.

The hydrological characteristics of the estuaries of south western Australia are determined largely by the climatic pattern of winter wet and summer dry. For this reason Spencer (1956) termed the Swan estuary an "atidal climatic system" (the term "seasonal" is preferred here). In consequence, all open estuaries are fresh or of low salinity for varying periods during the winter rains and are saline during the dry season, even becoming slightly hypersaline to sea water at times.* Spencer calls these the "freshwater-dominated" and "marine-dominated phases." The transitional condition between marine and freshwater phases is seldom long, the recovery phase from fresh to marine may extend over several months. The simpler terms *fresh phase, saline phase,* and *recovery phase* are used here.

*The salinity of marine and estuarine water is conventionally measured in parts per thousand (‰ S); seawater is about 35‰ S; water containing less than 3‰ S is termed "fresh"; 0.5‰ S (500 p.p.m.) is usually regarded as the maximum for human consumption.

In Technical Report 1 the terms used are: "winter condition" for the period of highest river discharge, "summer condition" for the period of very low stream flow, and "salt wedge condition" for transitional periods between summer and winter states. These more adequately describe the dynamic states of the estuary.

The geomorphological characteristics are also to some extent the product of the climatic pattern; all the estuaries have sea bars which tend to close the mouths during the period of low river runoff. The estuaries of the west coast all lie on the Swan coastal plain with its Quaternary sediments and coastal dune systems. Those of the south coast are of somewhat different character; the basins lie behind high Pleistocene dunes, with aeolianite limestone cliffs that are often tied to granite headlands to the east of which the inlets open to the sea. In some respects the Blackwood is intermediate in character as well as location. The inlet opens against the Precambrian rocks of the Naturiste-Leeuwin ridge, but most of the estuary is bordered by Quaternary sediments and late Pleistocene and Holocene dunes in its lower part. All the permanently open estuaries have a lagoonal portion, Hardy Inlet is the smallest of these.

3.1 Geomorphology of the Blackwood Estuary (Fig. 3.2).

The tidal part of the Blackwood is considerably longer than that of any other river of the south west except the Swan. A rock bar, about 42 km from the mouth, appears to mark the up-stream limit of penetration of marine water but the river may be tidal to a ford at Carey's Flat (55 km). It is navigable as far as the rock bar (in an 8m boat), as indeed it was in May 1839 when Georgiana Molloy was "taken 30 miles up the Blackwood in a Whale Boat belonging to the ship *America,* Captn. Cole, then lying in the Bay. Beautiful our row was up that Magnificent and peaceful River ...." (Hasluck, 1955). The Swan is tidal for 60 km (to All Saints Church), though no longer navigable the whole distance as it was in 1827, when Captain Stirling was rowed up in a ship's longboat.

Mouth and Sea Bar. The river mouth breaches a wave-built barrier beach of mobile sand through which there is a narrow and fairly deep tidal channel. Breaking waves outside the mouth indicate how shallow the sea bar is there, less than 2m in summer. A depth of one fathom is shown on the Admiralty Chart of 1878.

In 1830, the mouth was where it is now, but during the decade 1925 to 1935 the bar silted up and the mouth moved rapidly eastward 2 km. It only returned to the present position in 1945 after the bar closed completely, causing flooding, and it was cut through again at the original site (Hodgkin, 1976). This is the only time the bar is known to have closed completely.

Deadwater and Swan Lake. Immediately east of the mouth of the estuary, and opening to it by a narrow channel, is the Deadwater and inland of this is Swan Lake. The Deadwater is the persistent river channel of the 1930-1945 period. It is up to 5 m deep in parts, but most of it is less than 2 m and it is shallowing progressively from its eastern end and seaward margin behind the foredunes.

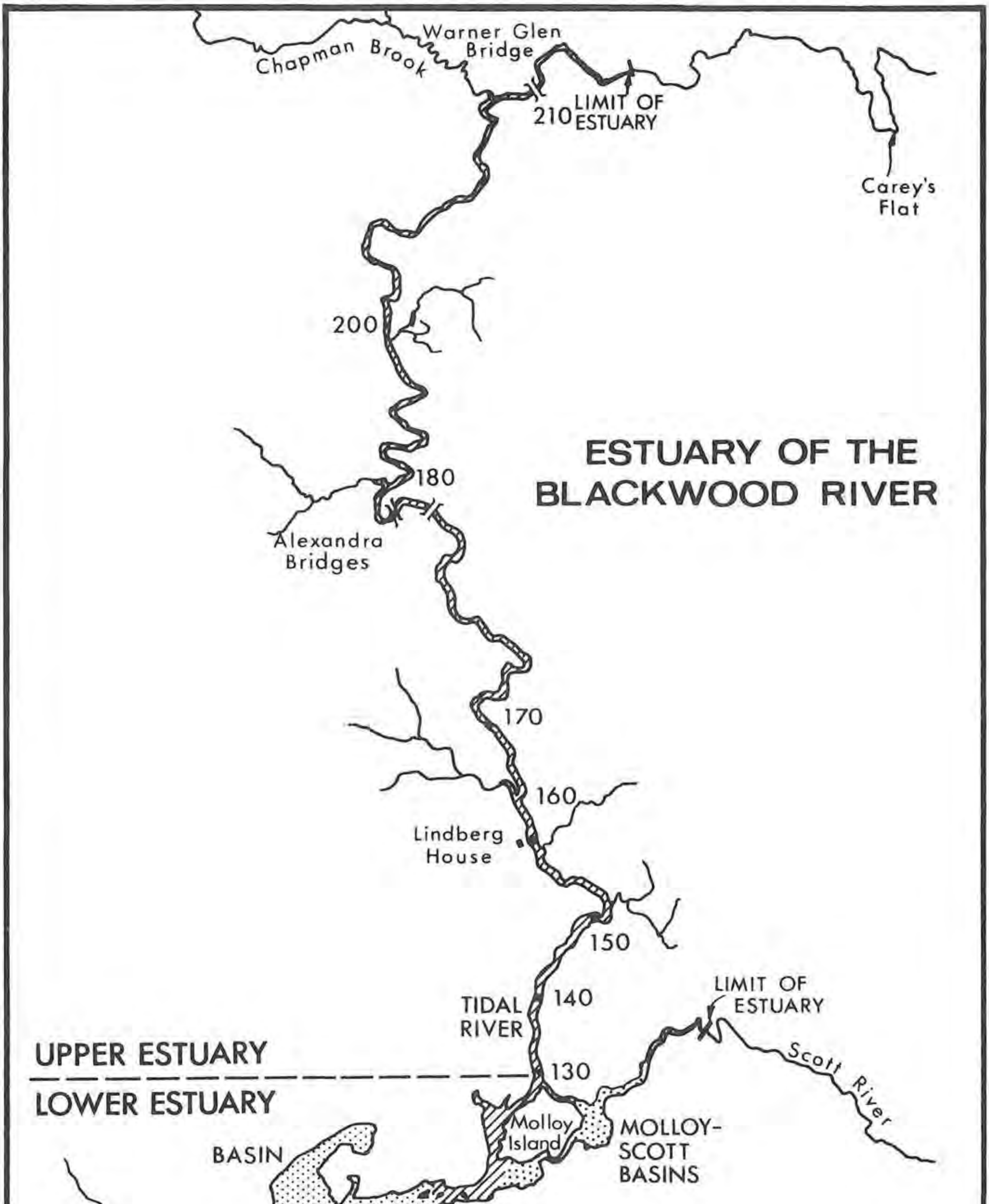


Fig. 3.1 Topographic terminology adopted in this report. Figures show station numbers.

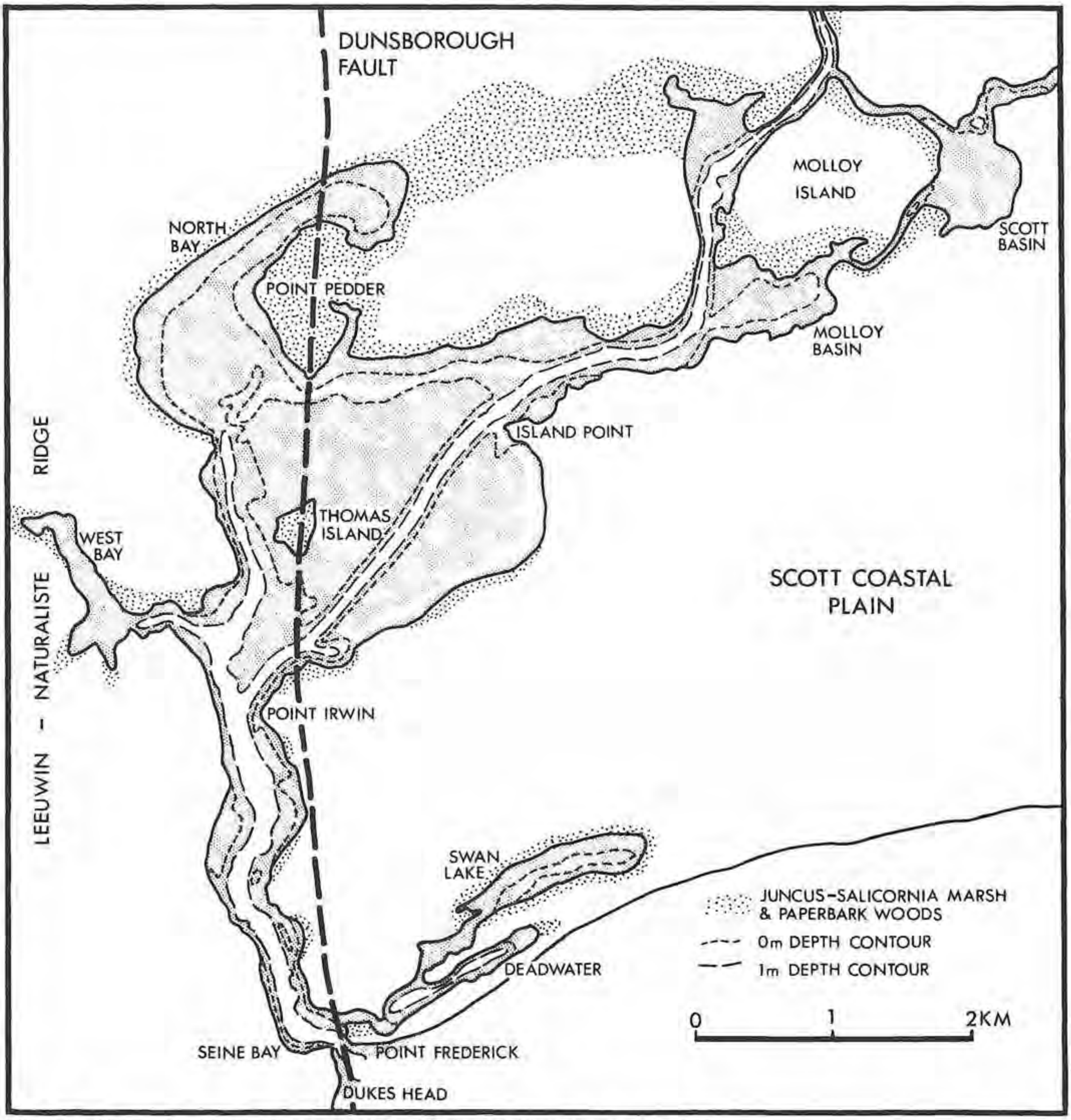


Fig. 3.2 Geomorphology of the estuary of the Blackwood River, lower estuary only.

Swan Lake was a shallow, seasonal, freshwater lake until the 1920s when the stream connecting it to the estuary was allowed to scour out and seawater flowed back into it. It now connects with the Deadwater by a winding tidal channel through dunes which have built up between them. The lake is shallow, probably not more than one metre throughout and has a rich growth of aquatic plants. To the east, there are small freshwater lakes which have been cut off by mobile dunes and are being filled in.

Inlet. The inlet is about 3 km long and ½ km wide. It has a central deep channel 2 to 8 m deep and 120 to 150 m wide and wide marginal platforms of less than one metre. In the upstream part of the inlet, these platforms are fairly stable and the 1974 hydrographic chart shows much the same depth contours as a chart made in 1925 (Fig. 3.3). However, there is a large bank of mobile sand in the lower part, opposite Seine Bay. There are considerable seasonal and long term changes of this and probably also of the bottom contours here.

As will be noted from Fig. 3.2, the inlet lies immediately to the west of the Dunsborough Fault and there is a small outcrop of granitic rock on the east bank at Point Irwin. The rest of the east bank is low-lying with sandy, rush-covered, supratidal platforms and limestone outcrops along the southern part. This rock is mainly coarse, flat-bedded beach material with marine fossils and is similar in composition to unconsolidated sands nearby. The exposed surface of the rock is about 3 m above low water. Most of the west bank is bounded by Precambrian rocks which rise steeply from the water's edge, except near the bar. The Lion Islands are small granitic outcrops which rise to 2 m.

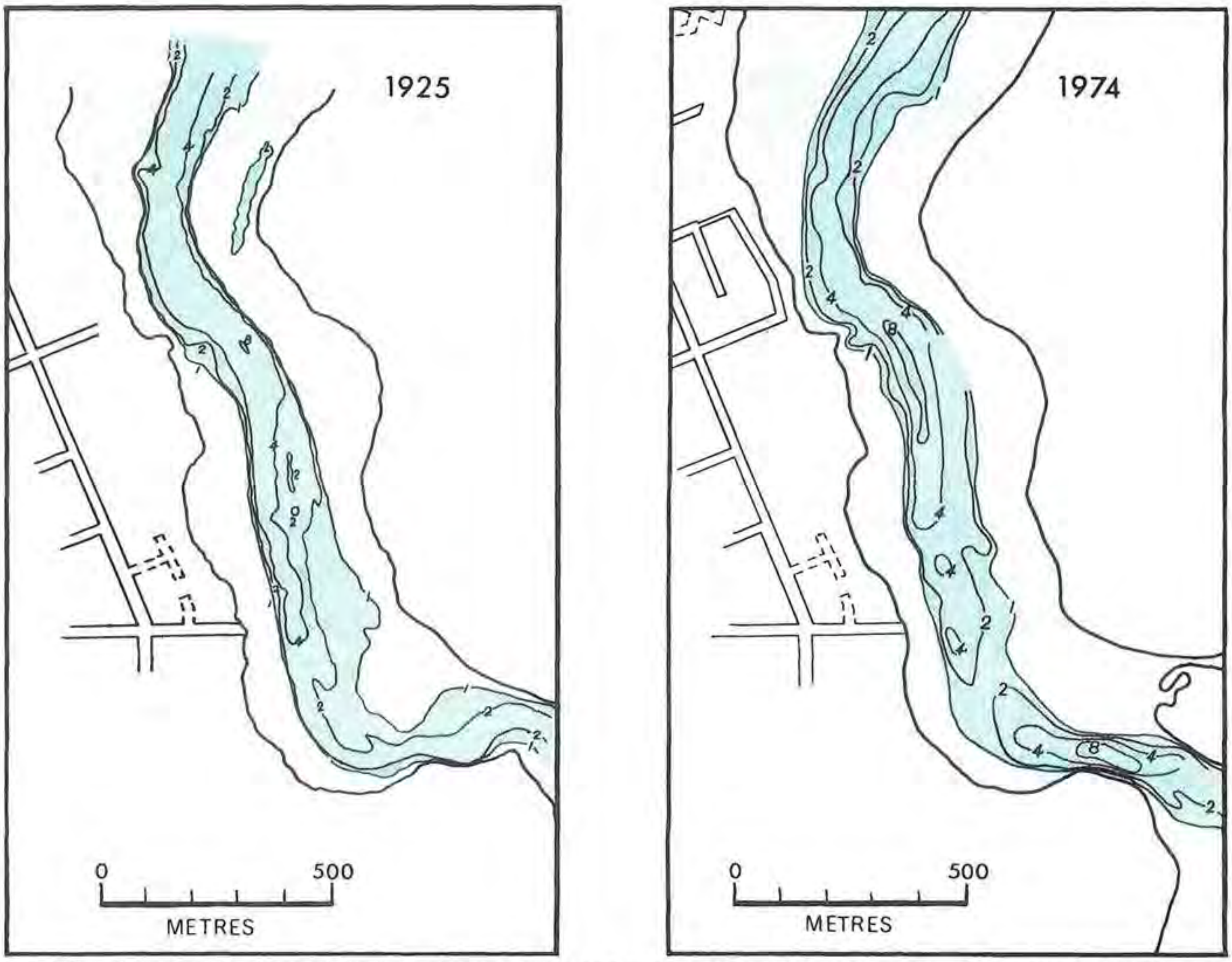


Fig. 3.3 Hydrographic charts of the inlet channel before and after diversion of river flow through the Deadwater. Source: Public Works Department, Harbours and Rivers Branch.

Basin. The total area of Hardy Inlet, from the mouth to Island Point, is about 890 ha at MSL. The basin is almost all shallow, less than 2 m, and about half is less than 0.5 m with extensive areas of delta shoals uncovered at low tide. Consequently the volume of the basin relative to that of the whole estuary is small when compared with other south west estuaries, with their large basins and smaller rivers. The small rush islets of the delta shoals are a feature of the basin. Natural channels run near the margins of the basin and were used by boats until construction of the boat channel. It is said that boats using the eastern channel always had to be dragged over rocks near Island Point at low tide and it is now only usable at high water levels. The channel along the north shore is also very shallow, but is said to have been deep over forty years ago, up to 30 feet off Turner's Jetty. Along the west shore there is a well defined channel 2 m deep.

The boat channel was first dredged in 1956 after an abortive attempt to blast a channel in the previous year. It followed approximately the line of a natural channel, which shows on the 1955 air photos. It was again dredged, on a slightly different alignment in 1973, to a depth of 6 feet at low water.

There is some granitic rock exposed along the western shore of the basin and on Thomas Island and there are patches of 'coffee rock' along the eastern shore, particularly at Island Point; however most of the margin of the basin is sandy with rushes and paperbark trees. This swampy margin below the 1.5 m contour is about 100 m wide in North Bay and along the north shore and includes the whole of Point Pedder.

Tidal River. From Island Point past Molloy Island to Station 130 this has some of the characteristics of the basin with extensive shallow areas round the island and wide intertidal swamps. However, the main river channel is clearly defined from Island Point; it is over 100 m wide and 5 to 10 m deep (Fig. 3.4). It is of similar dimensions between Molloy Island and Alexandra Bridge, with small lateral lagoons and swamps where tributaries enter. Between Alexandra Bridge and Warner Glen Bridge it is narrower but much of it is still 5 m deep. There are shallows and a rock bar which obstruct river flow (Fig. 3.5). The banks are high and steep at both bridges and continue so to well below Alexandra Bridge. They appear to be well consolidated to Molloy Island.

One remarkable feature is the presence of several deep holes in the river bed at sharp bends. The hole at Station 150 is 22 m deep. A grab sample taken from the bottom of it produced clean gravel.

The Scott River is also tidal for about 8 km from Molloy Island to an ironstone bar. The channel round the north side of the island is the deeper of the two channels. The southern one has built a small bar into Molloy Basin and is impassable by boat at low tide.

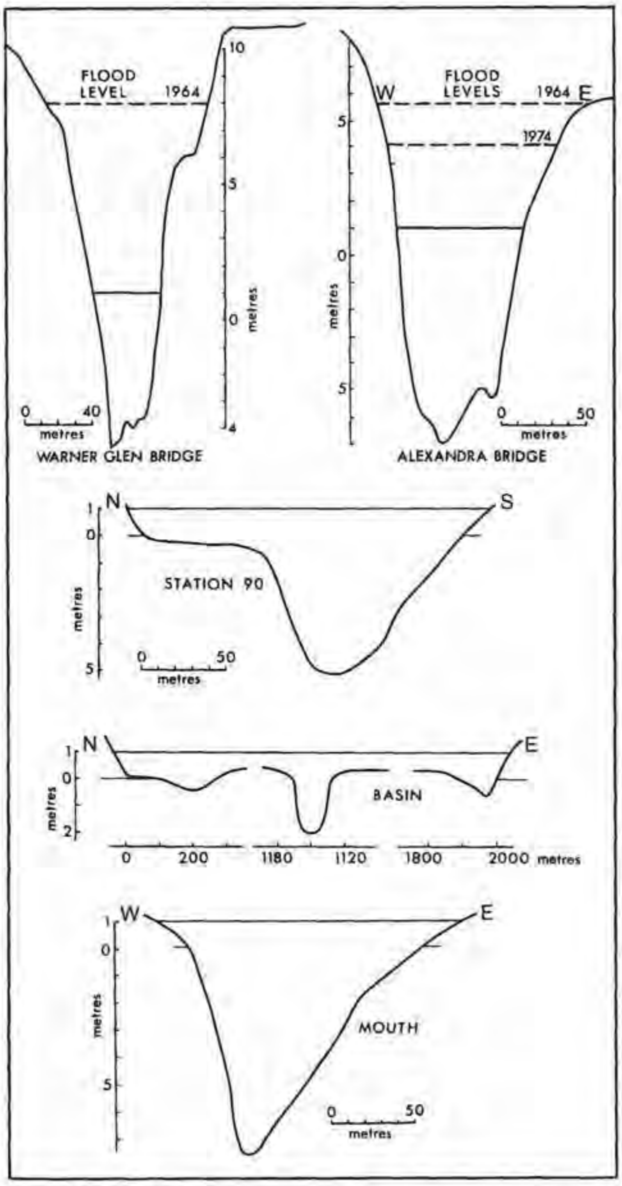


Fig. 3.4 Transects across the estuary at various points. Zero height is P.W.D. sounding datum. See Fig. 3.14 for tide levels.

3.2 Hydrographic Survey

This was undertaken by staff of the Harbours and Rivers Branch of P.W.D. The survey was made from a boat equipped with a recording echo sounder; the boat was positioned by a radio frequency distancing system giving accurate measurement to two shore stations. In water depths of less than 1.5 m it was necessary to operate from a shallow draught boat without the navigational equipment. Longitudinal river profiles were measured with an echo sounder, using an approximate shore survey for location reference. The boat travelled up the centre of the river and depths shown on the charts are not necessarily the maximum depth at any particular point on the river channel. Horizontal cross sections of the river and restricted shallow areas were carried out by hand lead sounding and levelling.

The hydrographic chart was prepared on a scale of 1:5 000 and covers the estuary from the mouth to Warner Glen Bridge (P.W.D., W.A. 48913). A chart of the lower part of the estuary has also been prepared at a reduced scale of 1:15 000 (P.W.D., W.A. 46913). Depths on these charts and those noted in the text, are relative to chart datum which is assessed at a low water mark, below which water level would rarely fall.

3.3 Sediments

It is essential when considering sedimentation in an estuarine environment to keep in mind the great changes of sea level associated with Pleistocene glaciation. Sea level has been constant, with perhaps minor fluctuations of up to 3 m during the last 5 000 years. However before that it rose rapidly from a glacial low some 15 000 years ago when it was 100 m below the present level. The shore line at Augusta must then have been considerably further south, beyond the islands, and the present estuary a valley, with the river running through it. It is evident from what follows that the estuary as we now see it has evolved during this post-glacial, Holocene, period. All the estuarine sediments have accumulated during this brief period of geological time. Moreover, the present is not a static situation; the same sedimentary processes are now at work as have been active throughout the Holocene, modified perhaps by human activities but still actively at work.

The estuarine sediments have a number of origins:

(i) river transport brings mainly siliceous sand, silt, clay, and organic detritus which drop out of suspension with decreased river flow and as a result of flocculation in contact with sea water;

(ii) similar material is reworked from the banks and eroded from adjacent land and redistributed by wave action;

(iii) marine sand, shelly material and organic debris are washed in with tidal flow;

(iv) organic matter is derived from plants and animals within the system, including fine organic mud at one extreme and skeletal materials (mollusc shells) at the other.

The sediment studies were confined to the lower part of the estuary, with the aim of answering three interrelated questions:

(a) the practical one, of how the sediments are likely to behave if they are disturbed by dredging;

(b) the historical one, of how they have accumulated since the last glaciation; and

(c) what trends can be seen in the present pattern of sedimentation.

Particular emphasis was laid on the role of environmental processes in deposition and in the construction of marginal platforms, and the river delta. To this end, 67 cores were taken with a vibrocorer with penetration into the sediment of up to 8 m and these cores were examined in the laboratory. The location of these is shown in Figure 3.6. Project Mining Corporation kindly supplied logs of cores taken in their claims on the east bank.

The following account derives mainly from Technical Report 2: Holocene Sedimentation, Blackwood River Estuary.

Nature of the sediments

The distribution of the surface sedimentary units is shown in Figure 3.7; cross sections of the inlet and basin are shown in Figure 3.8. The basement for the Holocene sediments of the estuarine basin is formed by a layer of sandy *Pleistocene soil*. On the west side of the basin, this is an orange to red material which has been derived by weathering from the granite below. This process has left a layer of pure kaolin in many places. On the east, the soil is composed of medium to coarse leached sands, derived from the Pleistocene dunes and is of unknown depth. During

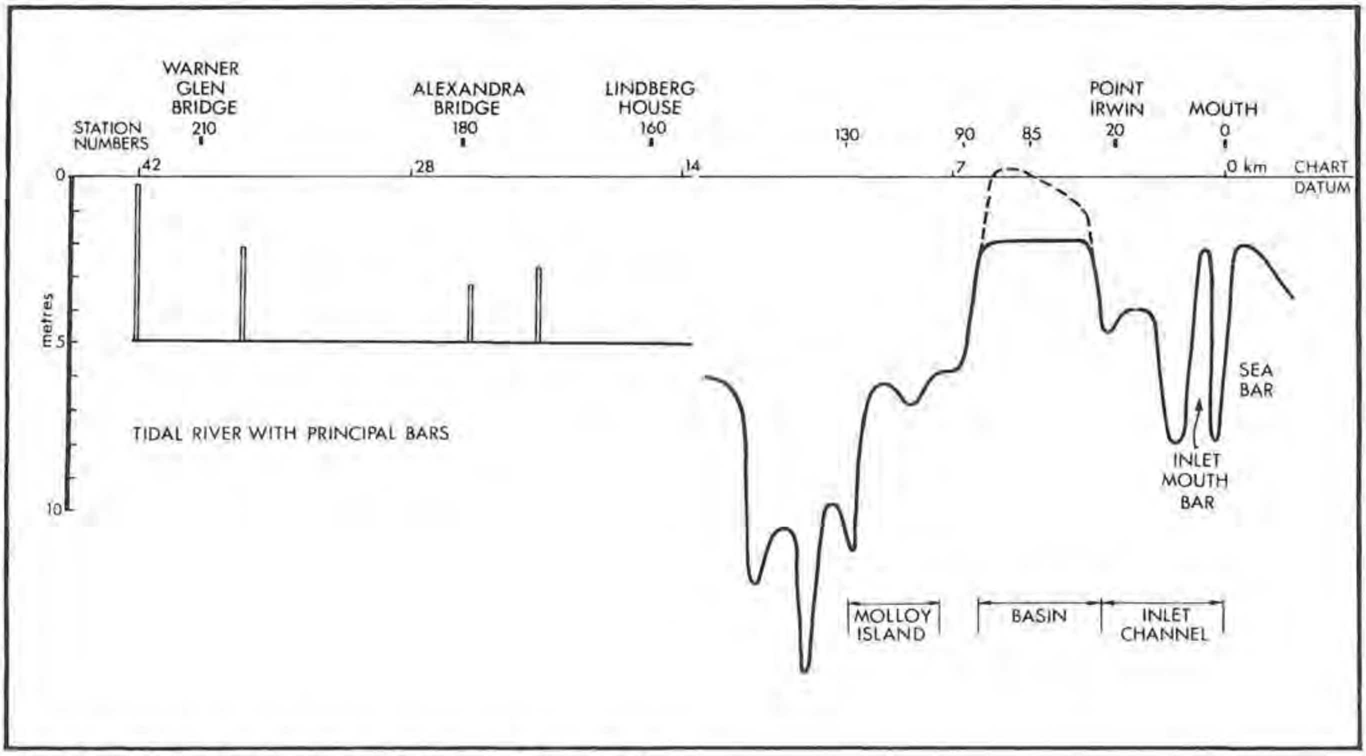


Fig. 3.5 Profile of the estuary, with location of principal bars.

the Holocene, a number of different estuarine sedimentation units have been deposited on top of this Pleistocene soil. These represent several phases and types of sedimentation, intergrading to some extent, but recognisable as the following distinct units.

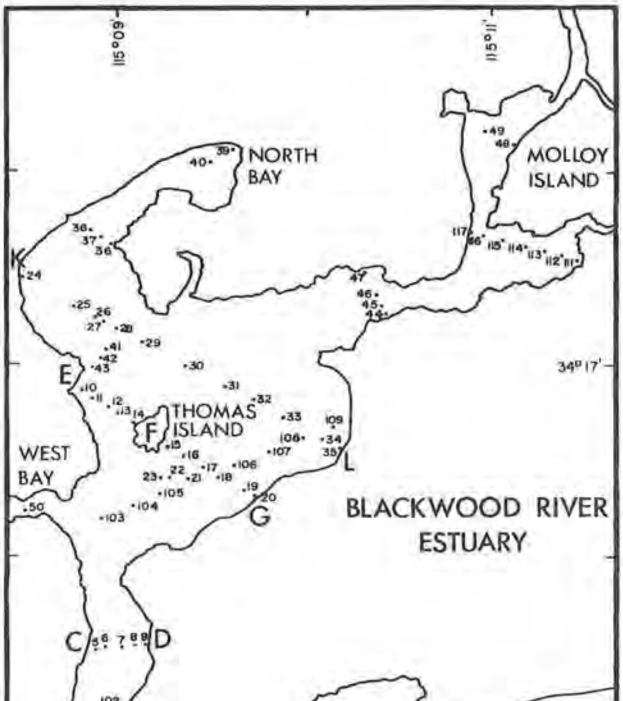


Fig. 3.6 Drill core locations in the Blackwood River estuary.

Basal sheet

With the progressive flooding of the estuary, the Pleistocene soils were reworked with new sediment to form a thin sheet (0.2 to 0.8 m), which extends throughout the inlet and basin. It contains roots and other remains of terrestrial plants and estuarine marine fossil material: Foraminifera, mollusc shells *(Ostrea, Nassarius, Niotha)* and faecal pellets which form up to 30% of the material.

Oyster unit.

This forms an extensive layer, more than 2 m thick in places, which overlies the Basal unit in the inlet and intrudes into the Basin unit in the lower part of the basin. It consists largely of bivalve mollusc shells, *Ostrea* (mud oyster) and *Chama,* in growth position. These and a variety of other bivalve and gastropod shells, are infilled with a matrix of black organic mud with silt-size skeletal fragments and detrital quartz. This is penetrated by large worm burrows. The fauna is that of a sheltered situation, considerably more marine than that of the present day estuary (Table 3.1). Shell samples (*Ostrea*) have been dated by the C14 technique: those from the base of the unit gave dates of 4 475 $\pm$ 105 and 4 070 $\pm$ 100 years B.P. (before present) while a sample from the basin mud was dated 3 880 $\pm$ 105 years B.P. The unit evidently represents an early phase of development of the estuary when sea water penetrated more freely.

Inlet-bar unit.

The bar itself and the bulk of the sediments of the inlet, are formed by this unit which grades into estuarine sediments in the basin. The sediment is largely marine in origin; beach sand mixed with re-worked sand from the Pleistocene dunes. It consists of whole and comminuted skeletal material (sponge spicules, mollusc shells, Foraminifera, echinoderm spines). Many of the whole mollusc shells are of species now living in the estuary, others are no longer represented here and come from somewhat more marine environments (Table 3.1). With this, there is fine quartz sand and coarser mineral sands (ilmenite, magnetite, zircon, red garnet). There is also some plant debris and lower levels tend to be muddy. It is 60 to 80% calcareous. Diagnostic of the unit are the abundant sponge spicules.

At Lion Islands, this unit is a thin layer lying directly on a marginal granite platform; elsewhere, it overlies the Basal sheet or Oyster unit, but in the lower part of the inlet no bottom was reached at 8 m below sea level on the eastern platform (Fig. 3.8). As noted above, this sedimentary unit is now fairly stable in the upper part of the inlet, but there is constant movement of the bar sediments both inside and outside the mouth.

Basin unit.

Throughout the basin, this estuarine mud forms a thick layer over the Basal sheet or lying directly on the Pleistocene soil. It is a black organic mud with about 20% fine quartz sand. Identifiable organic fragments include plant debris, with wood particles, faecal pellets,

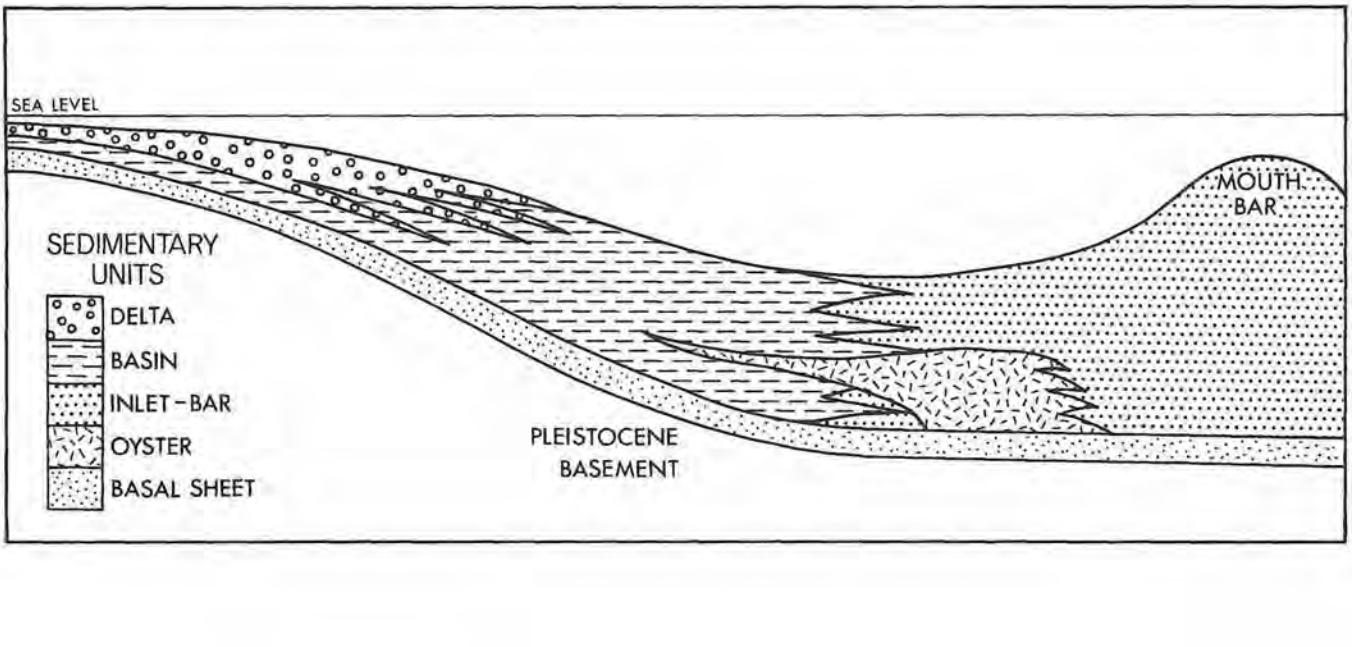
Fig. 3.7 Sediments of the Blackwood River estuary
Above—Surface sediments.
Below—An idealised stratigraphic section.

and broken and intact mollusc shells and calcareous worm tubes. It has been extensively burrowed by worms and other animals and consequently is generally well mixed. The shells are concentrated in two areas: in the Oyster unit, which protrudes into the Basin unit on the eastern side, and between Thomas Island and the western shore where there is a natural channel. Although a lot of the shells are of species

TABLE 3.1—Fossil Mollusca of the sedimentary units of the Blackwood River estuary

		Sedimentary Unit		
		Inlet Bar	Oyster	Basin
PELECYPODA				
MYTILIDAE	*Musculus paulucciae*			x
PECTINIDAE	*Chlamys aktinos*		x	
LIMIDAE	*Lima gemina*		x	
OSTREIDAE	*Ostrea angasi*		x	
LUCINIDAE	*Wallucina icterica*	x		x
	Anodontia perplexa	x	x	x
ERYCINIDAE	*Arthritica helmsii*	x		x
CHAMIDAE	*Chama ruderalis*	x	x	x
CARDIIDAE	*Laevicardium tenuicostatum*			x
TELLINIDAE	*Tellina deltoidalis**	x		x
	Tellina tenuilirata	x		
PSAMMOBIIDAE	*Sanguinolaria biradiata**	x		x
VENERIDAE	*Katelysia scalarina**	x		x
PHOLADIDAE	*Pholas* sp. cf. *australasiae*	x		
GASTROPODA				
TROCHIDAE	*Phasianotrochus apicinus*	x		
	Herpetopoma sp. cf. *aspersa*		x	
	Gibbula lehmanni	x		
	Thalotia sp. cf. *ramburi*	x		
	Thalotia sp. cf. *chlorostoma*	x		
PHASIANELLIDAE	*Phasianella australis*	x		
	Phasianella sp. cf. *variegata*	x		
ACMAEIDAE	Unindentified sp.			x
CYCLOSTREMATIDAE	*Elachorbis tatei*		x	
HYDROBIIDAE	*Hydrococcus graniformis**	x		x
	Potamopyrgus sp.*	x		x
DIASTOMATIDAE	*Obtortio* sp.	x		x
POTAMIDIDAE	*Batillaria estuarina*			x
CERITHIIDAE	*Bittium granarium**	x	x	
	Diala lauta	x	x	x
VERMETIDAE	*Serpulorbis* sp.	x		
NATICIDAE	*Proxiuber shorehami*	x	x	x
COLUMBELLIDAE	*Dentrimitrella* sp.			x
NASSARIDAE	*Nassarius burchardi*	x		x
	Niotha pyrrhus	x	x	x
BULLIDAE	*Bulla botanica*		x	
ATYIDAE	*Haminoea* sp. cf. *brevis*	x	x	x
	Haminoea sp. ct. *tenera*	x		
SCAPHOPODA				
DENTALIIDAE	*Dentalium* sp.	x		
SIPHONOIDAE	*Cadulus* sp.	x		x

* Species now living in the estuary



now living in the basin, others no longer live there and represent a more diverse and more marine fauna (Table 3.1). The number of species decreases and the more marine species become less abundant towards the upper levels.

Although much of this unit is now covered by the Delta unit it is still exposed in the lower part of the basin where accretion to it continues at the present time. It has also been exposed in the dredged boat channel. In parts of the eastern basin this unit is up to 6 m thick.

Delta unit.

This unit overlies the Basin unit in its upstream part and is interlayered with it at the contact between them. It consists mainly of medium to coarse river sand with sandy mud and plant debris. It is laminated with coarser and finer materials and pockets of mud and faecal pellets deposited by the varying discharge of the river and wave action redistributing it. There is little skeletal material other than that of Foraminifera. The sediment is coarsest at the surface, becoming finer with depth.

The unit is thickest at the upstream end (to 4 m) and thins out downstream. Small deltaic fans have formed at the downstream end both of the northern channel and the boat channel (dredged in 1973). Much of the delta is at a level where further vertical accretion is no longer possible and deposition is taking place on the downstream slope.

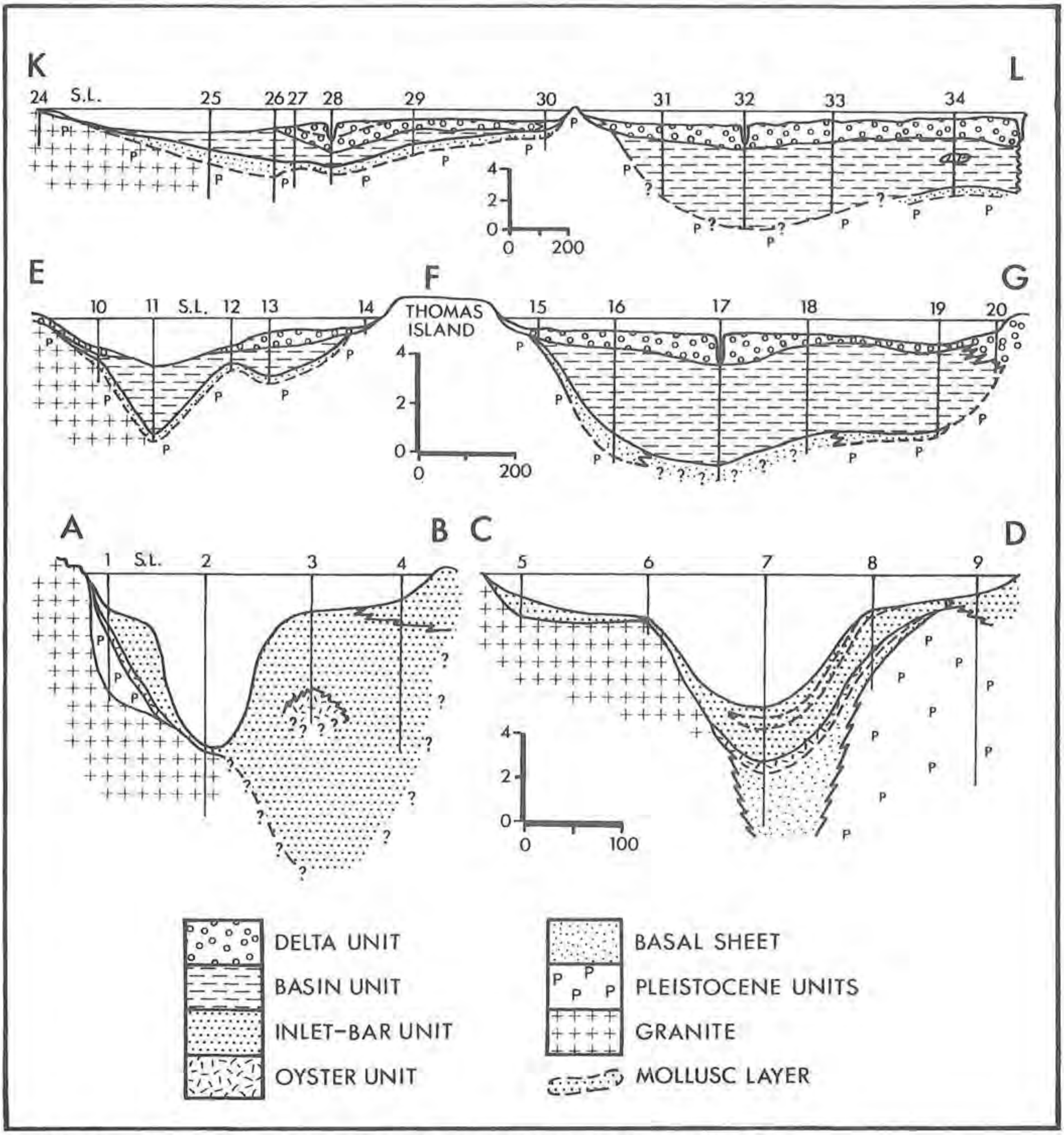


Fig. 3.8 Cross sections through the estuarine sediments at locations shown on Fig. 3.6.

Other sediment types.

Erosion from estuary shores has resulted in somewhat modified marginal sediments, in which are incorporated both coarse quartz sands and calcareous dune material. Marginal swamps were not cored, but one core from the Molloy Island shore may represent such conditions (49, Fig. 3.6). This core penetrated over 7 m of black organic mud with abundant plant material, but no macrofauna. The surface sediments of Swan Lake are also highly organic, but in this case are dominated by ostracod, gastropod, and foraminiferan shells (Quilty, 1977). Until the 1920s, this was a freshwater swamp and it may be expected to have a considerable depth of organic mud. It is a very different situation from the recently formed Deadwater with which it connects and where ostracods were completely absent from surface samples. No cores were taken from the upper estuary. Surface samples show a range of composition from coarse, well-rounded, pebbles and coarse, sharp sand (at Alexandra Bridge) to find well-compacted mud (Station 130).

Holocene history of the estuary.

With the gradual flooding of the Pleistocene basin some 5-7 000 years ago, the surface soils were reworked by wave action and burrowing animals with the new estuarine sediments to form the Basal sheet. The basin then had an estimated volume of $22 \times 10^6 m^3$ in contrast to the $1 \times 10^6 m^3$ of the present basin (Fig. 3.9). At first there must have been free entry of sea water at all times of the year, so that oysters could flourish for some 600 years at least in the lower estuary. The fauna is less diverse than that of Oyster Harbour at the present time, but represents a more marine environment than in Nornalup Inlet (compare 4.12). This condition subsequently gave place to the present extreme alternation of fresh and saline phases, as indicated by the progressively less diverse fauna.

The estuarine mud must have started to accumulate early and the rate of accumulation would have accelerated with progressive restriction of the mouth by the build up of the Inlet-bar unit. The average rate of accumulation is estimated at 1 480 m^3 p.a. The mud derives both from fine organic and inorganic material brought down by the river and from plants and animals of the estuary itself.

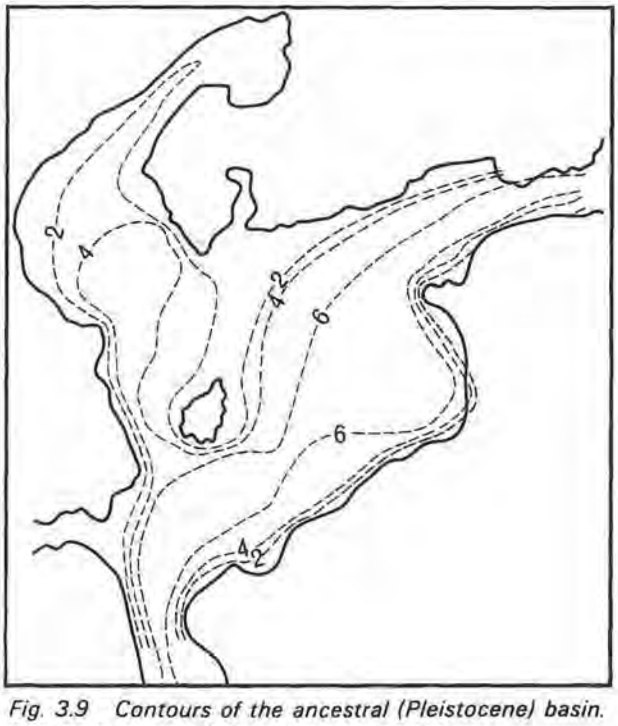


Fig. 3.9 Contours of the ancestral (Pleistocene) basin. Depths in metres below the present datum.

The Delta unit is a relatively thin layer (maximum of 4 m). Since it overlies the Basin unit it must be a more recent development and represents a change in the pattern of erosion and sedimentation. The two interfinger at the downstream edge of the Delta unit, where both units continue to accumulate.

At present the river carries little bed load and the delta sands are thought to be reworked material which has been scoured by winter floods from the Molloy Island region of the tidal river.

It cannot be assumed that the annual volume of river discharge to the estuary was constant throughout the Holocene, even within the 1 : 5 variation at present observed (section 3.4). Indeed there is accumulating evidence from Quaternary studies that there has been considerable climatic change. It is evident from the dynamic studies (section 3.6) that any significant change in volume and pattern of discharge to the estuary would have resulted in great changes in the nature of the erosive and sedimentary processes in the lower estuary, as well as of hydrological conditions.

The marine sediments of the Inlet-bar unit would first have had to infill the old river channel in the deep part of the present inlet. Cores did not reach to the bottom of the unit and the actual location of the Pleistocene river channel has not been identified.

It is unlikely that there has been any great change in form and areal dimensions of the lower estuary during the Holocene. Where sampled, there is Pleistocene soil at the margins so that there is unlikely to have been either extensive erosion of the banks or much prograding by the marginal swamps, except in a few restricted localities. The change has been one of infilling the Pleistocene basin, with the deposition of more than 8 m of sediments, and a massive accumulation of marine sand to infill the inlet, and form the bar, leaving a central flood channel and marginal platforms.

Historic times

The Holocene sedimentary processes continue at the present day. The estuarine mud continues to accumulate where it is relatively undisturbed in the deeper parts of the basin and delta sand continues to prograde over it. There is no evidence of the net rate of deposition at the present time; it can be quite rapid locally and the northern channel has silted up and become almost impassable in this century.

The most striking change which has taken place since 1830 has been the formation of the Deadwater and consequent incorporation of this and Swan Lake in the estuarine system (Hodgkin, 1976). This event and the observed movements of banks inside and outside the mouth, underline the great mobility of sands of the Inlet-bar unit here. On the other hand, the record also serves to emphasise the dynamic stability of sedimentary processes in the inlet. This leaves it an open question as to whether there is continued accretion to the Inlet-bar unit or whether this is now in equilibrium with the constructive forces of tidal transport and the destructive effects of the very varying winter flood discharge and storm waves.

Granulometric composition of the sediments

In order to be able to predict the probable behaviour of sediments if resuspended by dredging or any other process, it is necessary to determine the size composition of the material. However it should be noted that in their natural state, the fine particles are bound

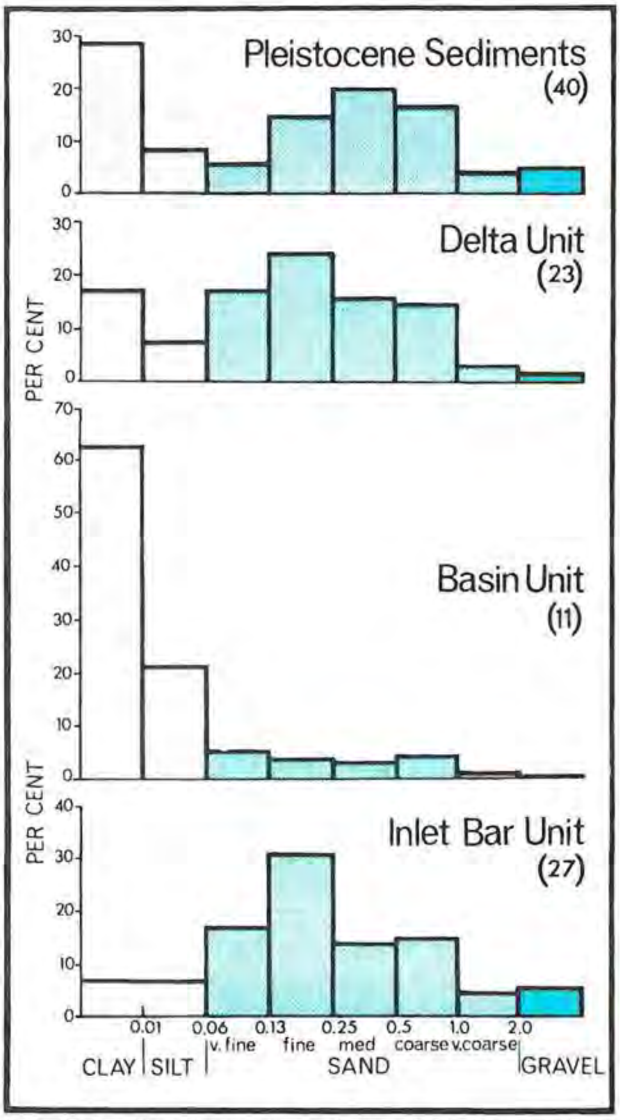


Fig. 3.10 Granulometric analyses of Blackwood River estuary sediments. Figures in brackets show number of samples averaged.

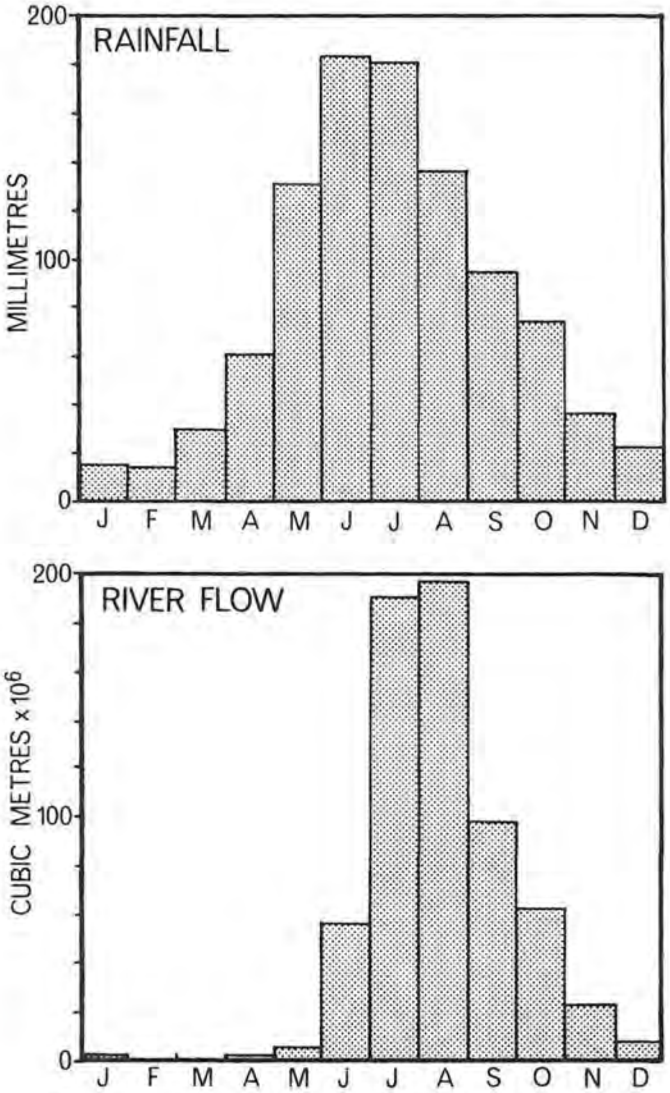


Fig. 3.11 Monthly mean rainfall and river flow at Darradup. Rainfall 1919-1973, river flow 1965-1974. Source: Bureau of Meteorolgy; Public Works Department, Water Resources Section.

by electrostatic forces and the biota also have a binding effect. The sediments are therefore much more resistant to shear forces from river flow than is implied from their granulometric composition alone. This aspect will be discussed more fully elsewhere.

The granulometric analyses were undertaken by Dr. B. W. Logan. Representative samples from the four principal stratigraphic units were taken from the cores. The coarser material was separated by sieving and material passing the 0.062 mm aperture sieve was processed in a cyclosizer to separate silt and clay particles. The average results are shown in Table 3.2 and Fig. 3.10.

From this data it will be seen that the Pleistocene unit consists of poorly sorted material. The Delta unit is predominantly sand size material, having been brought in by the river at relatively high flow rates. Nevertheless, it has a 25 per cent silt clay fraction.

The Basin unit which is largely of organic origin, deposited under low flow rate conditions, has over 80 per cent silt-clay fractions. Most of it (63 per cent) is clay size, particles less than 0.01mm diameter.

The Inlet Bar unit sediments are the best sorted, being predominantly medium to fine sand. However, even these have a substantial (13.5 per cent) silt-clay fraction.

Table 3.2—Granulometric analyses of Blackwood estuary sediments.

	GRAVEL	VERY COARSE SAND	COARSE SAND	MEDIUM SAND	FINE SAND	VERY FINE SAND	SILT	CLAY	NUMBER OF SAMPLES
	>2mm	2-1mm	1-0.5mm	0.5—0.25mm	0.25 — 0.125mm	0.125 — 0.062mm	0.062 — 0.011mm	<0.01mm	
PLEISTOCENE UNITS	4.7	3.7	15.9	19.4	14.6	5.7	8.4	28.3	42
DELTA UNIT	1.1	2.3	14.5	15.6	24.0	17.2	7.7	17.3	23
BASIN UNIT	0.2	0.6	4.0	3.1	3.2	4.8	20.9	62.8	11
INLET BAR UNIT	4.7	4.4	14.5	14.2	30.7	16.6		13.50	27

3.4 River Flow to the Estuary

Records of river flow in the Blackwood are available for Nannup (1940-1955) and Darradup (1965-1975) and the monthly averages are shown in Table 3.3. From these it will be seen that river flow is even more seasonal than rainfall; 97.5 per cent of runoff is during the six months June to November and there is a considerable lag between the early rains and response of river flow (Fig. 3.11). A small flow continues to the estuary throughout the summer and this is responsible for maintaining the estuarine stratification.

Rate and volume of runoff respond not only to immediately preceding rainfall, but to soil conditions at the time. There is considerable variation in volume of flow (Fig. 3.12); this is much greater than for rainfall, at least a fivefold difference between years of greatest and least discharge (Darradup 1974—58 mm, 1972—11 mm). In contrast, the greatest rainfall was little more than twice the least (1926—1371 mm, 1969—595 mm). The last serious flood was in August 1964 when water in the tidal river rose to the roadway at Alexandra Bridge and was over the handrails at Warner Glen Bridge, about 9 m above normal level. The flow rate recorded at Darradup on 6.8.1964 was 969 m^3/sec. Flooding is also reported to have taken place in 1955, 1945, and 1926.

Although the rainfall for 1974 was only average, winter river flow was the highest on record, partly because early rains saturated the ground and allowed maximum runoff of the heavy July-August rainfall.

Darradup lies 65 km upstream from Warner Glen Bridge and Nannup a further 43 km (Morrissy, 1974).

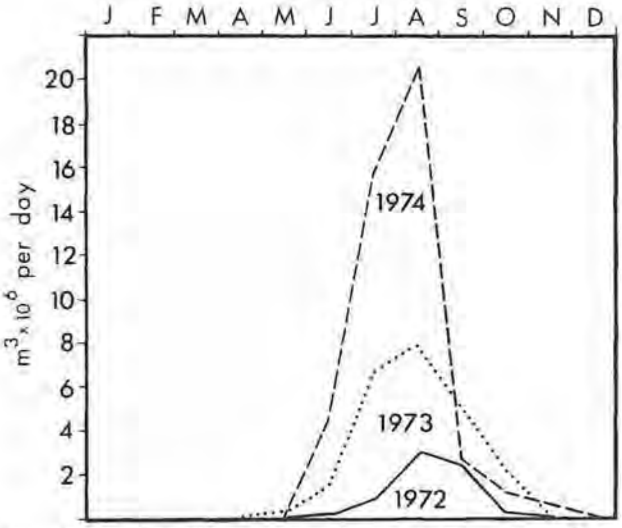


Fig. 3.12 Monthly stream flows at Darradup. 1972 was the year of least flow and 1974 of greatest flow on record (1965-1975). Source: P.W.D. Water Resources Section.

Although both are low in the catchment, it is estimated that some 80 per cent of water entering the estuary does so from rainfall to the sunklands part of the catchment, downstream of Nannup. Therefore while the Darradup gauge gives valuable data on river flow at that point, the figures are clearly not accurate for volume of discharge to the estuary. Two methods were used to estimate volume of flow which enters

TABLE 3.3—River flow in Blackwood River at Nannup and Darradup. Source: Public Works Department of WA, Water Resources Section.

BLACKWOOD RIVER AT NANNUP

CATCHMENT CHARACTERISTICS
CATCHMENT AREA: 19320 km^2
annual precipitation: 530 mm

NaCl BY TITRATION

number of samples:	490
weighted average:	871.81 ppm
90th percentile value:	1971.43 ppm
(median) 50th percentile value:	1228.57 ppm
10th percentile value:	795.00 ppm

FLOW SUMMARY
for period June '40 to Feb '55
MONTHLY FLOWS IN $m^3 \times 10^3$

MONTH	MAXIMUM RUNOFF	AVERAGE RUNOFF	MEDIAN RUNOFF
January	870	498	476
February	1 119	302	232
March	403	191	160
April	5 081	1 273	566
May	18 490	6 371	3 208
June	268 900	66 570	12 162
July	480 300	124 300	48 500
August	607 200	176 500	85 670
September	210 800	76 820	42 900
October	51 980	23 760	21 080
November	26 400	8 821	7 941
December	6 038	2 090	1 835
ANNUAL	1 600 000	367 900	183 000

BLACKWOOD RIVER AT DARRADUP

CATCHMENT CHARACTERISTICS
catchment area: 20 460 km^2
annual precipitation: 560 mm

NaCl BY TITRATION

number of samples:	505
weighted average:	719.05 ppm
90th percentile value:	1 730.00 ppm
(median) 50th percentile value:	1114.29 ppm
10th percentile value:	528.57 ppm

FLOW SUMMARY
for period May '65 to December '75
MONTHLY FLOWS IN $m^3 \times 10^3$

MONTH	MAXIMUM RUNOFF	AVERAGE RUNOFF	MEDIAN RUNOFF
January	4 474	1 531	1 148
February	1 353	773	830
March	1 195	829	643
April	2 939	1 807	1 560
May	10 040	5 047	4 158
June	144 600	53 870	38 710
July	510 000	185 200	157 600
August	637 300	197 600	123 200
September	159 400	95 830	77 270
October	147 500	58 840	41 930
November	85 920	20 610	12 470
December	22 920	6 666	3 402
ANNUAL	1 195 000	619 000	518 100

the river below Darradup (for details see Technical Report 1) and this is assumed to be 41.5 times the flow of Rosa Brook, the only tributary below Darradup which is gauged. Fig. 3.13 shows river flow to the estuary during the study period as estimated on this basis.

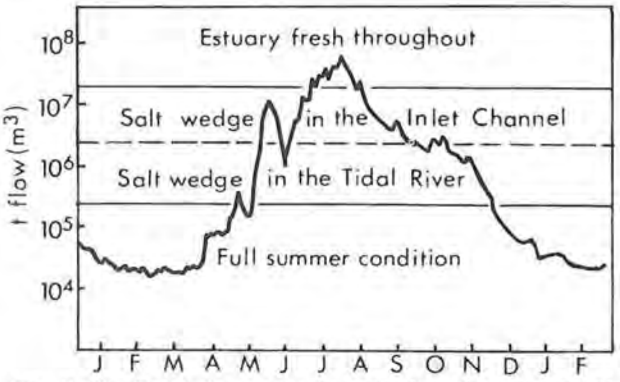


Fig. 3.13 Total flow per day entering the estuary at Warner Glen Bridge during 1973-1974.

3.5 Tides and Other Water Level Changes

Five tide recorders were operated during the survey at the following localities:

		Period of Operation Months	Distance From Mouth km
1.	Flinders Bay—PWD	6½	
2.	Seine Bay—PWD	12	0
3.	Station 20—University	11½	2.8
4.	Station 160—University	11	15
5.	Station 210—University	11	39

The following instruments were used: 1. bubbling gas paper punch recorder (recording at 5 minute intervals), 2. float continuous strip chart recorder, 3, 4 and 5. Rauchfuss air bellows transducers with strip chart recording (at 6 minute intervals). The method of operation of these instruments and a detailed presentation of the results will be found in Technical Report 1.

The tides of south western Australia are of small range and other non-tidal factors cause changes of water level of the same order of magnitude. Thus, although astronomic tides in the basin have a maximum range of only 70 cm, the extreme range of water level recorded at station 20 during the study was 1.3 m. These non-tidal factors are therefore as important as the astronomic tides in determining the characteristics of this shallow estuarine ecosystem. The various factors which cause changes of water level are summarised in Table 3.4.

Astronomic tides are similar to those of other parts of south western Australia, being predominantly of

Table 3.4—Causes, Periods and approximate ranges of changes of water level at Flinders Bay and Seine Bay. 4. and 5. are assumed to be the same as at Fremantle.

		Approx. maximum range, cm.		
		Period	Flinders Bay	Seine Bay
1.	Astronomic tides	12 hours	40 cm	20
		24 hours	100 cm	70
2.	Barometric pressure	5-9 days	60 cm	60
3.	River flow/mouth bar	irregular	0	30
4.	Isostatic sea level	1 year	30 cm	30
5.	? isostatic	10+ years	10	10

Recording tide gauge and barometer at Point Irwin. Mr. H. Agnew.

daily type but with the smaller semi-daily tide becoming apparent for a few days twice in each tropic lunar month (27¹/₃ days). These mixed tides are described and figured by Hodgkin and Di Lollo (1958). The ranges of the principal harmonic constants determined for the record from Flinders Bay were:

Daily: M_2—0.10 m Semi-daily: K_1—0.40 m
S_2—0.14 m O_1—0.30 m

The principal meteorological influence is that of barometric pressure. At Fremantle, the pressure factor is 1.8 cm/mb (Hamon, 1966), nearly twice the isostatic value. The figure for Augusta has not yet been calculated but is likely to be similar, possibly slightly less. The effect may be spectacular, as for example during the passage of cyclone Vanessa in January 1976, when the rock bar at the head of the estuary in Scott River was submerged allowing passage of a small boat upstream.

The seasonal change of water level is shown by Figure 3.14. The difference of 30 cm between summer and winter levels, though small, must be viewed in perspective of the shallow depth of the basin and low profile of its beaches, and also the height of the marginal rushes, about 50 cm.

The sea bar damps tidal exchange, reducing the range of astronomic tides and causing a phase lag. Daily tides in Seine Bay average about 70 per cent. of those in Flinders Bay and semi-daily tides 50 per cent; longer period 'tides' are undamped. Phase lag across the bar is 1 to 2 hours.

Under conditions of low river flow, the only significant further modification of tides within the estuary is attenuation across the shallow basin, especially at low water levels (Fig. 3.15). Propagation time, and consequent phase lag, of the tides along the estuary from Seine Bay to Warner Glen Bridge is approximately 2 hours at high water and 3 to 5 hours at low water.

Under high river flow conditions in winter, the tides are not propagated within the estuary and water level builds up considerably in the tidal river. In early August 1974, water level reached over 6 m above normal summer level at Warner Glen Bridge and in the 1964 floods both bridges were under water.

The tidal excursion in the tidal river part of the estuary is about 5 km up and down on a maximum range tide; however this is not simple and water bodies of different density may behave differently in this respect.

The analysis of tidal movements is discussed in full in Technical Report 1: The Dynamics of the Blackwood River System.

3.6 Dynamics of the Estuary

This part of the study is reported in full in Technical Report 1: The Dynamics of the Blackwood River System.

The long estuary, with its varying bottom topography and extreme seasonality of river flow experiences a complexity and variety of both space and time scales of water motion. Previous observations had shown that the Blackwood, like many other estuaries of south-western Australia, was strongly stratified during much of the year. It was therefore anticipated that the dynamics would be greatly influenced by buoyancy forces, as well as by river flow and tidal exchange which commonly dominate estuarine dynamics. The estuary is not easily classified in the traditional categories employed by previous authors and the investigation posed problems of unusual interest.

Aims and methods

The study aimed at an understanding of the dynamics of the estuarine water under the varying seasonal conditions: penetration of sea water into the estuary, its movements in relation to river runoff and the nature of the mixing process, circulation patterns within the basin and exchange of water with the bays and two coastal lagoons.

This part of the study also provided physical data of direct concern to other sections.

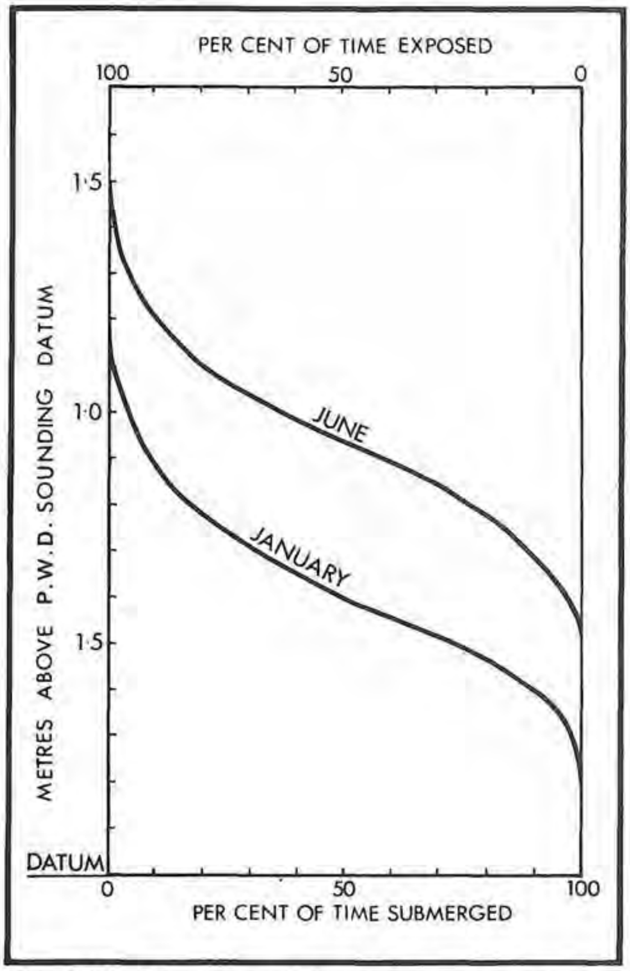


Fig. 3.14 Percentage of time submerged or exposed above datum.

The study necessarily involved investigation of phenomena on two very different time scales. Changes resulting from seasonal variation in river flow had to be observed over the whole year. Others, related more to tidal exchange, necessitated intensive study over short periods. In practice the two requirements were successfully met by a programme in which fixed recording instruments and periodic routine, boat-based,

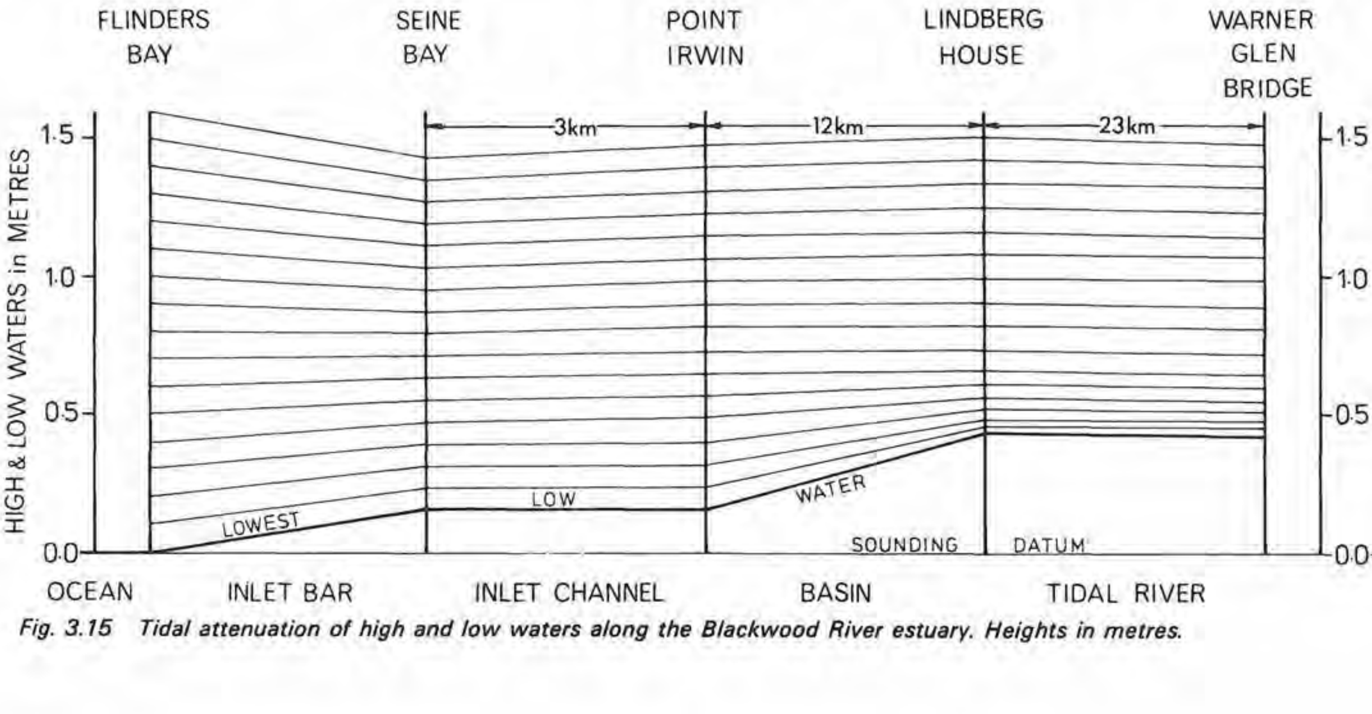


Fig. 3.15 Tidal attenuation of high and low waters along the Blackwood River estuary. Heights in metres.

observations were complemented by intensive investigation of specific phenomena at each of a number of field trips.

Such a programme required a concise formulation of the overall aim of the project and equally concise sub-aims had to be defined for each field excursion and within each field trip as the investigation proceeded. The underlying philosophy was to get a global feel for the estuary and to fill in details as the study proceeded, very often concentrating on resolving the unexpected rather than only documenting the expected.

For this reason the field programme was extremely flexible. After the first exploratory field trip, each subsequent trip was designed to investigate a particular phenomenon of the dynamics encountered at a previous trip, while at the same time providing the data for a routine analysis of the hydrodynamic situation. Even within one field trip the data collection was never on a routine basis; the data was always graphically displayed (by hand or automatically) as the trip proceeded and decisions about the type and frequency of data collected were made by one of the principal investigators. The frequency and dates of the field trips were fixed by the behaviour of the estuary, as judged and updated from previous trips. Even now at the conclusion of the study, the predictability of the hydrodynamic condition of the estuary is only as predictable as river flow, and valuable opportunities would have been missed and much useless data collected by rigid adherence to a predetermined sampling programme.

This flexibility was achieved by monitoring directly with boat-operated sensors and facilitated by processing all the data immediately after each field trip, and well before planning of the next trip began. Despite the penalty of increased man hours, this proved to be an extremely efficient and relatively cheap method of learning a great deal about the estuary.

This programme resulted in the following types of monitoring:

(a) five fixed stations giving continuous records of tides and meteorological data;

(b) periodic sampling at predetermined stations to obtain a synoptic picture of hydrodynamic conditions on each occasion;

(c) continuous short period sampling, usually for 24 hours;

(d) experiments involving large teams of participants over periods of a few days;

(e) additional sampling as problems arose.

Multiparameter probe measuring salinity, temperature, and current speed and direction.

The instruments employed in the study were:

Tide gauges as listed in section 3.5.

Multiparameter probes measuring salinity, temperature, and current speed as a function of depth, with manual readout.

Profiler measuring salinity and temperature continuously as a function of depth, with chart and magnetic tape data logger.

Dissolved oxygen and turbidity meters used for spot readings.

Fluorometer to record dye concentrations.

River flow data from the Darradup and Rosa Brook gauging stations operated by P.W.D. Water Resources Section were used to estimate freshwater discharge to the estuary.

Water movements

Water movements in and the hydrologic condition of the estuary are the result of interaction of a number of driving forces: first, the varying volume of fresh, low density, water entering from the river; second, density differences between fresh water and sea water; third, tidal and other changes of sea level causing a pumping action; fourth, turbulent mixing in shallow water and at the interface between different water bodies. These operate within, and their effects are modified by the physical dimensions of the estuary. They do not operate in isolation and the following analytic approach, in which they are discussed separately, is intended only as being contributory to a better understanding of the sequence of events described below. The hydrologic sequence is illustrated in Fig. 3.16.

1. River Flow. The volume of river discharge to the estuary varies by a factor of 1 000 (Fig. 3.13). During winter floods, river flow exceeds $20 \times 10^6 m^3$ per day (total flow to the estuary). The estuary is continuously flushed with fresh water and tidal influence is only appreciable in the lower estuary.

In contrast, during late summer there is negligible river flow and the currents are tidal throughout. At intermediate flow rates, sea water enters the estuary and penetrates upstream beneath the seaward-flowing fresh water, to a distance which is dependent principally on the volume of river discharge.

2. The sea water input. Because sea water is more dense than fresh water, it exerts a force which tends to carry it into an estuary beneath the fresh water, which it displaces seawards. This produces a two-layered structure in which the two water bodies tend to retain their identity. Such a "stratified" system, with a sharp halocline between the two bodies, exists in the Blackwood and other estuaries of south-western Australia, under low river flow conditions.

Density of estuary water depends both on the concentration of dissolved salts (salinity) and on the temperature. However, in this respect, 1‰ salinity is roughly equivalent to 4°C and temperature can be ignored because of the wide salinity range experienced. Therefore, salinity alone may be used as the measure of density in the present situation.

3. Changes of sea level. Whether these are caused by astronomic tides or by longer period barometric forces, sea level changes have the effect of pumping sea water in at the mouth, with rising tide, and expelling estuary water on the falling tide. This is seen in the tidal cycle shown in Fig. 3.20, in which sea water was pumped in over the bar with rising tide and some was retained behind it on the falling tide.

In a stratified situation, the two bodies of water may behave independently in respect of flow. Such a situation is seen in the record from the lower part of the tidal river, shown in Fig. 3.21, in which tidal movement affected almost solely the surface water, there being negligible movement in the deep water. On other occasions, the two bodies of water were observed to move in opposite directions.

4. Turbulent mixing. Several different forces operate to cause mixing between water bodies of different density in the estuary. Wind stress, generating wave action, is an effective mixing agent only in the large expanse of open water of the basin. Here the water is often stirred to the bottom, with resuspension of fine sediment. Elsewhere in the estuary, wind probably has little effect in mixing the water. Sharp haloclines persist in other estuaries of the south west at depths of only 30 cm.

Waters of different salinity are carried from the tidal river by the falling tide across the delta shallows. There they are mixed by turbulent flow and then returned by the rising tide to the tidal river as water of intermediate salinity. A similar process takes place over the sea bar and there is doubtless also mixing by ocean wave action outside the mouth of the estuary.

When water bodies of different density move independently of one another the shear generated between them may cause mixing at the interface. In the stratified tidal river this has the effect of stripping high density water from the surface of the sub-halocline water mass, thus entraining it into the low density water above. This is an important factor setting up the longitudinal salinity gradient in the surface water of the tidal river in summer (Fig. **3.16**, 11.4.74).

High flow rates in the entrance passage, between Dukes Head and Point Frederick, cause considerable turbulence and consequent mixing. The turbulence is readily observed by anyone in a boat; sand particles are held in suspension in the turbulent water and are transported by tidal or river flow.

Thermal mixing is important in maintaining homogeneity of surface water in the tidal river. Differential heating by day and surface cooling at night

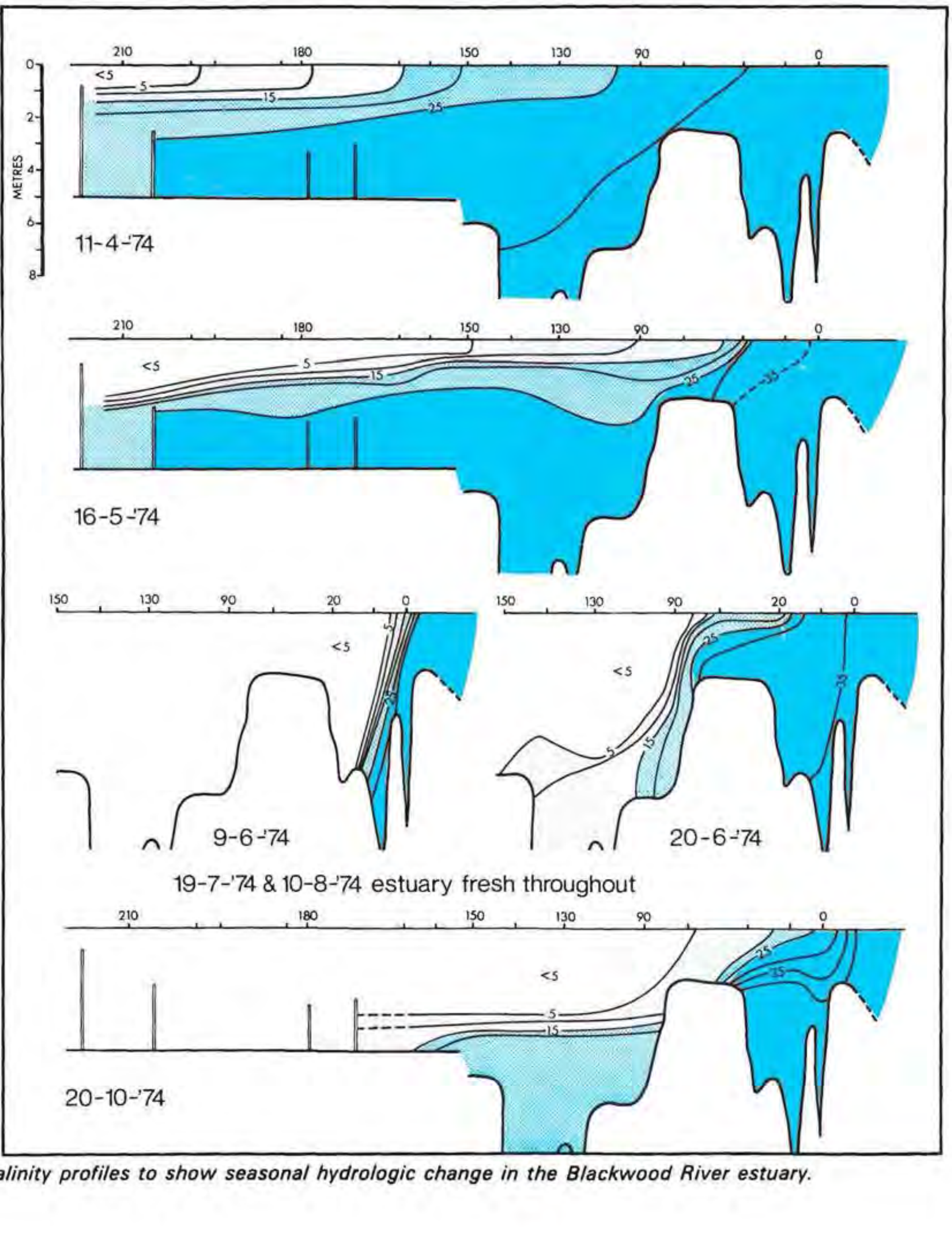


Fig. 3.16 Salinity profiles to show seasonal hydrologic change in the Blackwood River estuary.

cause a degree of convective mixing which keeps the surface water of uniform salinity throughout its depth. Thermal mixing does not take place across the halocline.

5. Dimensions of the estuary. The effects produced by the above forces are modified by, and to some extent determined by, the dimensions of the estuary. Current speeds (both river and tidal) vary inversely with cross sectional area (Fig. 3.4), which itself changes with water level, especially in the basin.

The river bars (Fig. 3.5) act as barriers which delay the passage of high salinity deep water upstream and again delay its return downstream, as seen in Fig. 3.16. As noted above, tidal mixing takes place in the shallow basin and there is also turbulent mixing where high or intermediate salinity water cascades from it into deep water beyond. The shallow basin also has a small throttling effect, as shown by the reduction in tidal range across it (Fig. 3.15).

The dynamic sequence

The following sequence of dynamic conditions has been observed in the estuary. When daily flow to the estuary exceeds about 20×10^6 m^3, the incursion of sea water is prevented and the estuary is fresh throughout. Although the lower estuary is still tidal, and flow through the mouth slackens on a rising tide, tidal currents are not strong enough to pump sea water against the river flow into the estuary. Indeed during this **winter condition,** the estuary can only be regarded as estuarine in the crudest geographical sense: it is a fast flowing river with a considerable head of water in the upper estuary (Fig. 3.17).

In the lower estuary, Scott River water joins the main flow from the Blackwood north and south of Molloy Islands. The contribution of the Scott River ranged between 5% and 10% of total river flow at this time. The two water bodies maintain their integrity; they are of different colour and the contact between them is sharp and only becomes blurred by turbulent mixing over the 3 km to the basin. Even there, the Scott water moves as a separate body down the eastern margin, while the Blackwood water flows over the northern and central part of the basin. This was dramatically shown by the August dye release experiment, in which the dye was only released into the Blackwood water (at station 90) and was not detected at all in the eastern part of the basin.

The river water flows across the basin via the three channels and over the submerged sand flats to the inlet and the sea. Measured velocities in the basin indicated maximum values of 50-80 cm/sec in the channels and minimum values of about half this (Fig. 3.18).

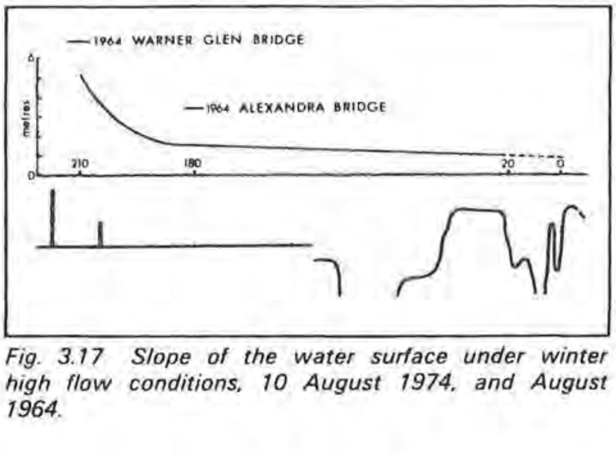


Fig. 3.17 Slope of the water surface under winter high flow conditions, 10 August 1974, and August 1964.

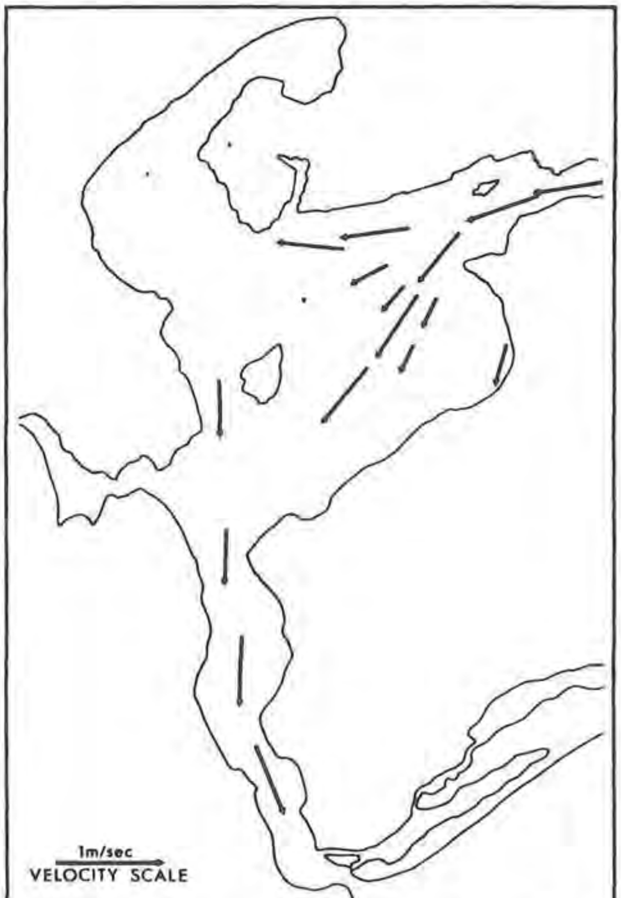


Fig. 3.18 Flow velocities in the lower estuary under high discharge conditions on 13 August 1974.

Velocities over the shallow areas were of the order of 20 cm/sec but lower values would occur during periods of rising tide. Even slower speeds are experienced in North and West Bays. The highest flow rate 1.0 m/sec, was measured at the mouth. Water velocities and friction velocities determined at various locations are shown in Table 3.5 and Fig. 3.19.

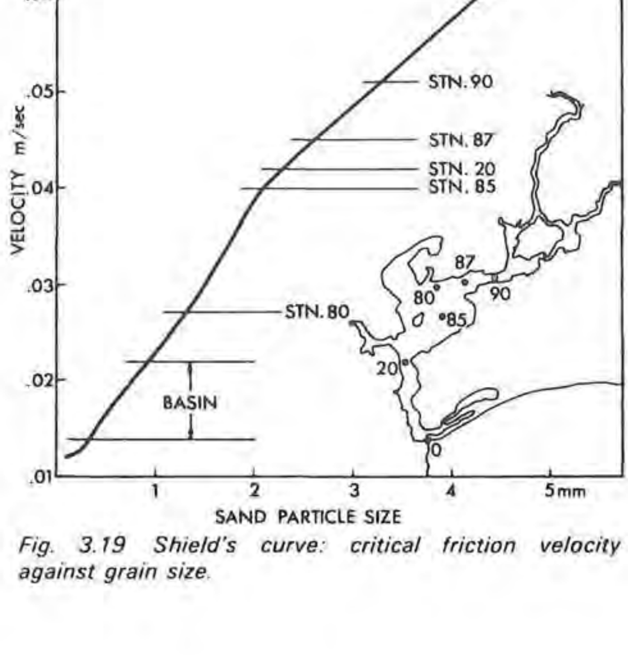


Fig. 3.19 Shield's curve: critical friction velocity against grain size.

The winter condition persisted for 6 to 8 weeks in July and August 1974. While it is convenient to use this term because of the normal seasonality of rainfall, it should be emphasised that this dynamic situation may supervene at any time if river flow exceeds 20 x 10^6 m^3 per day, and in some years it may occur as early as April. It is also probable that in years of low river discharge the flow rate never reaches this critical figure and the full winter condition does not develop at all.

When river flow decreases below this figure, the current is not strong enough to exclude sea water. This then flows into the estuary beneath the outflowing fresh water on the rising tide and, because of its greater density, forms a **salt wedge in the inlet channel** (Fig. 3.20 and Fig. 3.16 9.6.74). On the falling tide, the upper part of this is entrained with the outgoing surface flow, thus making the halocline between surface and deep water masses more abrupt. Mixing takes place outside the mouth and water of intermediate salinity returns. The dynamic response of the inlet channel to changes in river flow is rapid, about one day or less.

With further decrease in river flow, to less than

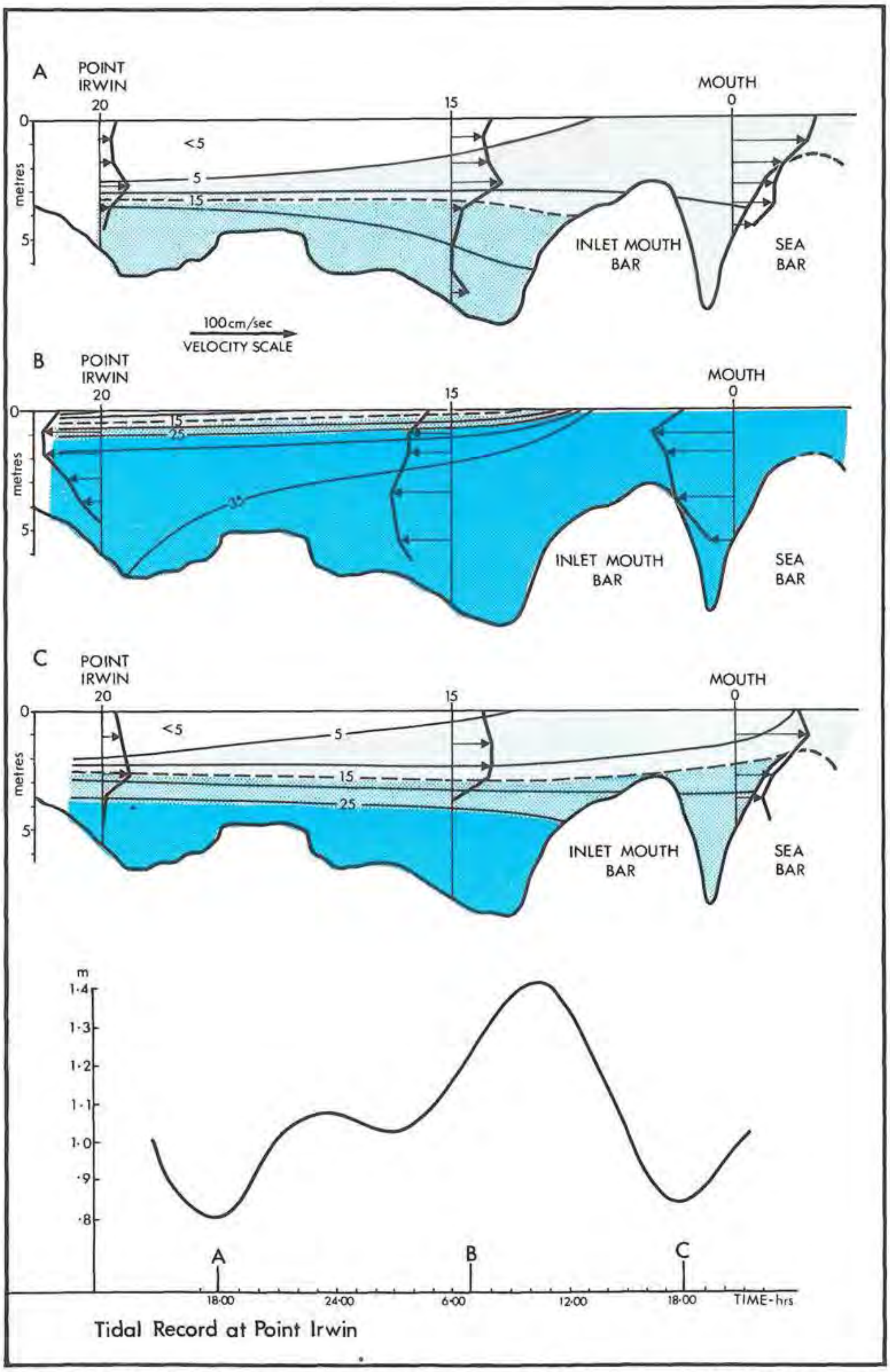


Fig. 3.20 Tidal changes in the inlet channel on 13 September 1974. Velocity and direction of flow shown by arrows.

Table 3.5—Current velocities and friction velocities under high discharge conditions on 13 August 1974.

	Distance from mouth km	Depth m	Average water velocity m/sec	Friction velocity m/sec
Stn. 90, tidal river	6.8	4.3	0.66	0.051
Stn. 87, entrance to basin	6.1	3.0	0.64	0.045
Stn. 85, dredged basin channel	4.8	2.0	0.55	0.040
Stn. 80, north basin channel		1.0	0.35	0.027
Basin shallows		0.7	0.30	0.020
Stn. 20, Point Irwin	2.9	4.1	0.51	0.042
Stn. 00, estuary mouth	0.0	3.5	1.00	0.081

about 2 x 10^6 m^3 per day, high salinity water from the inlet traverses the basin with rising tides and cascades into deep water upstream to form a **salt wedge in the tidal river** (Fig. 3.21 and Fig. 3.16 20.10.74). Because of the greater distances traversed and the throttling effect of the shallow basin, response to changes in river flow are slower than in the inlet channel and adjustment of the salt wedge to decreasing river flow is of the order of a few days to a week.

The accumulating high salinity water flows up the estuary beneath the outflowing fresh water, which depresses the isohalines, until limited by bottom topography. In Fig. 3.16, 20.10.74 this flow has been arrested at a bar between Stns. 170 and 180. As in the inlet, waters of different salinity are carried seawards by falling tides and mix in the shallow basin. The resulting intermediate salinity water is carried back by rising tides into the tidal river, where it sinks to its appropriate density level. There, it forces the isohalines apart and is propagated upstream as an intermediate level 'jet' flow. This replenishing jet can travel up to 10 km upstream on each rising tide. Intermediate salinity water is also entrained into the surface water by river and tidal flow, thus producing a salinity gradient in the surface water and making the halocline more abrupt.

Finally, when river flow is less than about 0.25 x 10^6 m^3 per day, it ceases to have any significant effect

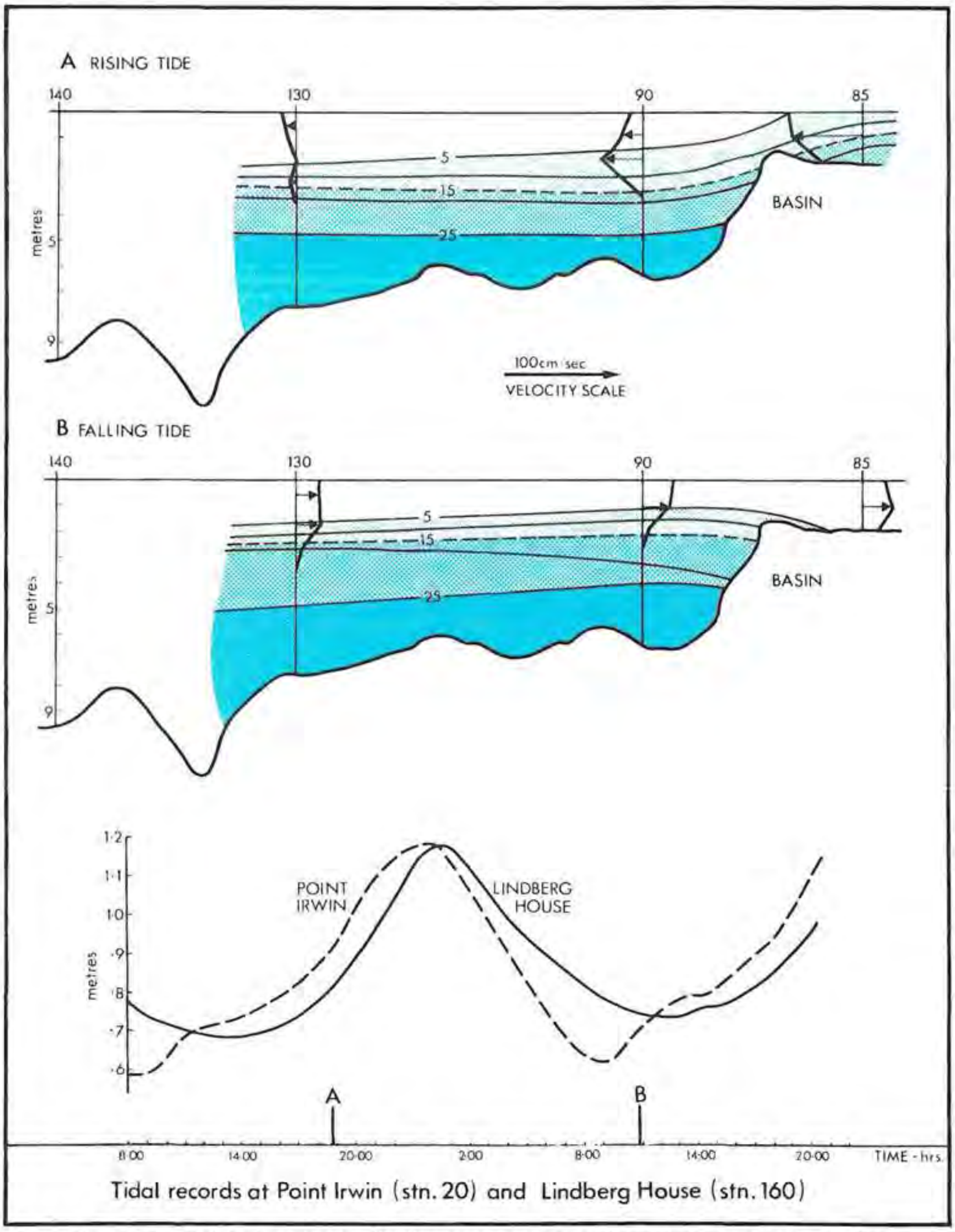


Fig. 3.21 Tidal changes in the lower part of the tidal river on 27 November 1974. Velocity and direction of flow shown by arrows.

on the dynamics of the system. The inlet is then virtually marine (30+‰ S). In the upper estuary, the flow is not strong enough to tilt the isohalines and the deep saline water flows over the bars to the head. Stratification is then extreme. This **summer condition** is shown in Fig. 3.16, 11.4.74 and in 1975 was probably established by early January.

The estuary is now tidal dominated and the small river flow has negligable effect on the currents in the lower estuary; they are tidal currents. The nature of these and their effect on circulation in the lower estuary, were investigated in the February dye release experiment and are illustrated in Fig. 3.22. At this time, water level in the basin was some 25 cm lower than during the winter dye release experiment, so that much of the delta was exposed or covered with only a few centimetres of water. In consequence, flow through the basin was concentrated in the dredged channel where a maximum flow rate of 0.55 m/sec was measured, in comparison with only 0.15 m/sec at Stn. 90. Only at the mouth were current speeds comparable with those observed during winter flow conditions; a maximum of 80 cm/sec.

Despite the relatively low current speeds, they do cause a considerable tidal shift up and down the estuary. Table 3.6 shows the extent of this and it is illustrated in Fig. 3.23 where salinity serves as a marker to record movement of the water mass. In the dye release experiment, sea water penetrated from the mouth through the inlet and into the basin (3+km), dye released at Stn. 20 reached Stn. 90 and covered much of the basin, and dye from Stn. 90 penetrated beyond Stn. 130 (a distance of 3 km) on the surface and probably to Stn. 150 (6.5 km) in the subsurface layer. Because the basin and inlet are of relatively small volume, there is a considerable volume of exchange with the sea on each tide. However, it must be remembered that often, in the absence of any strong ocean longshore currents or other mixing forces, much

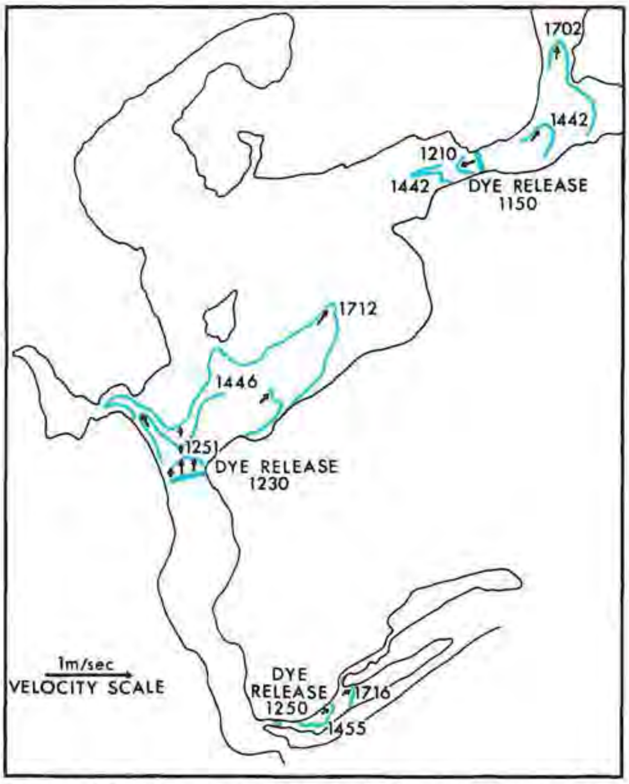


Fig. 3.22 Flow velocities and dye transport under tidal circulation conditions on 23 February 1975. Figures show times of observations of dye streaks.

Table 3.6—Water movement under summer tidal circulation conditions in the estuary.

Stations	Distance km.	Displacement time
00- 20	2.85	5-6 hours
15- 20	1.6	2-3 hours
20- 85	2.25	5-6 hours
85- 90	1.7	7-8 hrs upstream 2-4 hrs downstream
90-130	3.0	5-6 hrs upstream 3-4 hrs downstream

of the estuary water which goes out on a falling tide will return on the next rising tide.

The tidal currents cause water from the tidal river to mix in the basin, and the intermediate salinity water pumped back on the returning tide drives the jet flow in the tidal river. In the upper part, continued river flow maintains the low salinity surface layer which was about 1.3 m thick at Stn. 210 on 29.4.74. However, mixing forces, which here result mainly from differential flow between the layers, cause salt water to be entrained into the surface layer. This has the dual effect of making the halocline more abrupt and maintaining a longitudinal salinity gradient in the surface layer, from 2.4‰ at Stn. 210 to 15.6‰ at Stn. 130 on 29.4.74.

The differential tidal flows continue throughout the upper estuary, as shown in Fig. 3.24, though it is probable that here, in the upper reaches, the intermediate level flow is driven by the pressure field due to the density distribution rather than by tidal mixing in the basin as described above. With the slow upstream flow of this intermediate level water (the velocity at Stn. 195 was of the order of 0.02 m/sec on 6.2.75), there is a weak reverse, seaward flow, apparently both in the surface and deep water.

This intermediate depth flow also functions as a heat pump that induces a temperature gradient along the length of the estuary (Fig. 3.25 & 3.26). This water mass receives a small heat increment by solar heating each day, which it cannot lose at night because there is no mixing with the surface layer. A similar hot house effect, sometimes with deep water temperatures 7°C above those of surface water, is observed in other estuaries of the southwest but, because they are shorter there is not the same temperature gradient towards the head of the estuary.

When river flow increases again, usually in May or June, the isohalines are depressed in the upper reaches and low salinity surface water pushes seawards. In 1974, this effect was first seen on 16 May when a salt wedge condition had been re-established in the tidal river. The heavy rains of late May had a dramatic effect on the estuary and at the survey of 9 June the

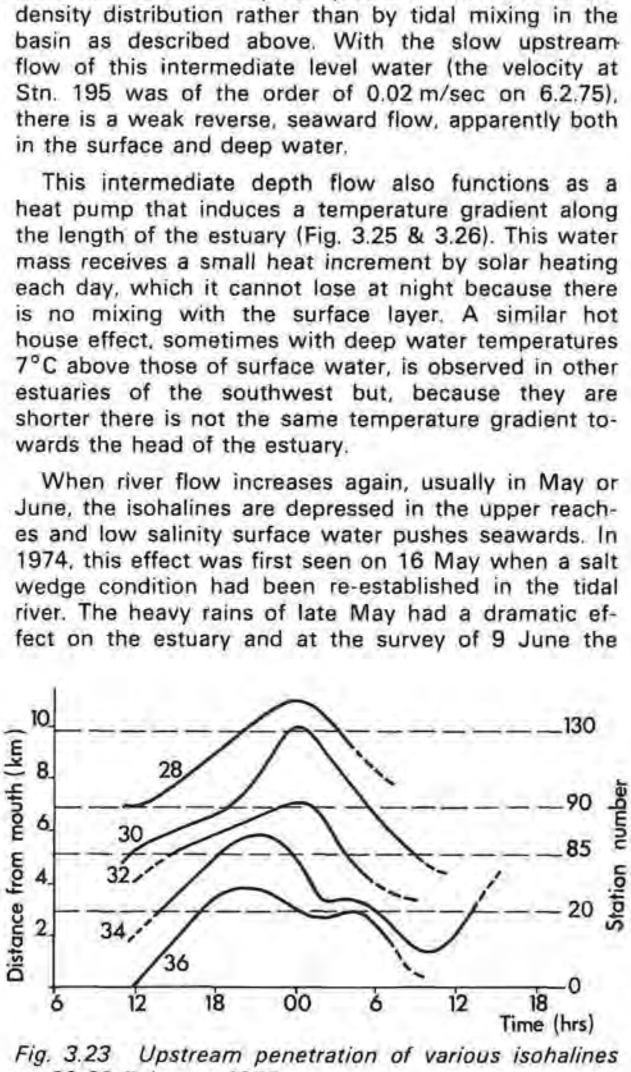


Fig. 3.23 Upstream penetration of various isohalines on 22-23 February 1975.

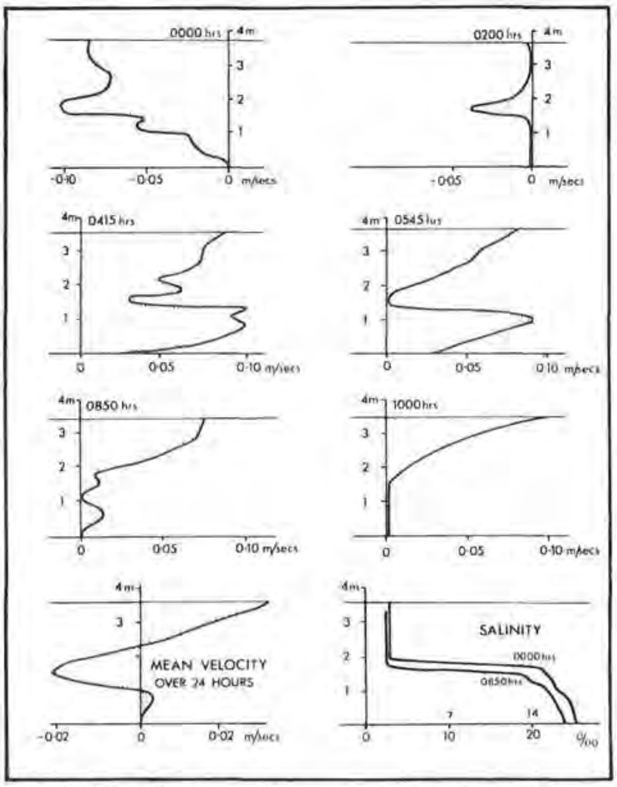


Fig. 3.24 Velocity profiles in the tidal river at Station 195 on 13 February 1975.

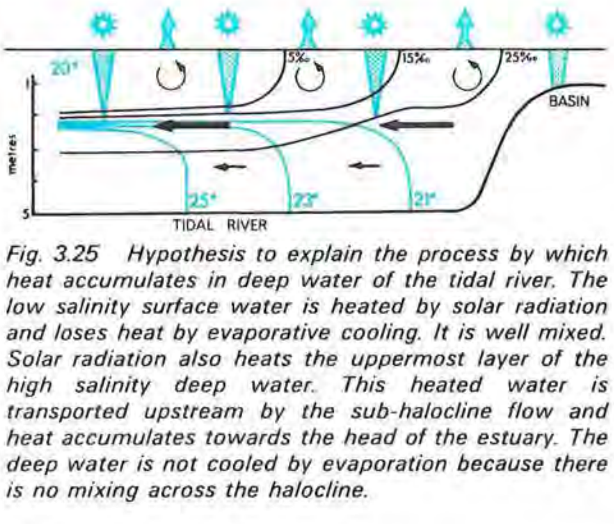


Fig. 3.25 Hypothesis to explain the process by which heat accumulates in deep water of the tidal river. The low salinity surface water is heated by solar radiation and loses heat by evaporative cooling. It is well mixed. Solar radiation also heats the uppermost layer of the high salinity deep water. This heated water is transported upstream by the sub-halocline flow and heat accumulates towards the head of the estuary. The deep water is not cooled by evaporation because there is no mixing across the halocline.

upper estuary and basin were fresh throughout and a salt wedge only persisted in the inlet (Fig. 3.16). The prolonged dry period which followed in early June, and consequent decreased river flow, allowed a brief re-establishment of a salt wedge in the tidal river (survey of 20.6.74), before the full winter condition was established by the end of July.

River discharge thus dominates the dynamic status of the estuary and its condition is predictable in terms of volume of flow to it (Fig. 3.27). It depends also on the seasonal history of flow, with a lag in response to changing volume of flow. This lag is not great in respect of surface water, but there is considerable delay in response by the deep, high salinity water (Fig. 3.28). The basin (and river bars) obstructs its passage and it is more slowly swept from the tidal river, with increasing flow, than is surface water. Similarly, with decreasing flow, re-establishment of the salt wedge is delayed by the shallows.

The Deadwater, Swan Lake, and bays

Although the Deadwater and Swan Lake are outside the main body of the estuary, they are an important part of the estuarine system. The Deadwater has a surface area of 34 ha and Swan Lake 42 ha.

There is free exchange between them and the inlet, limited only by the narrow entrance passages and shallow bars at their mouths. The water entering may be either sea water or estuary water, according to the state of the tide and river flow. Dye release experiments showed that water from the inlet reached the entrance channel of Swan Lake within 4 hours (average velocity 3 cm/sec) and subsequently entered the Lake. Some dye penetrated to the east end of the Deadwater within 8-10 hours. However mixing here, and in the east end of Swan Lake, is restricted, as is shown by the fact that both become slightly hyper-saline to sea water in summer.

During the winter condition, when inlet water is fresh, the Deadwater becomes stratified and considerable wind mixing is needed for exchange to take place between surface and deep water. Water at 2 m depth was in excess of 25‰, except for about 6 weeks in July and August; even then high salinity water persisted near the bottom (Fig. 3.29).

Although Swan Lake being shallower, was fresh throughout in July, it had recovered by September with salinities of 15-17‰. There is a small direct freshwater input to the lake.

Tidal mixing is somewhat delayed in North and West Bays, exchange requiring 2 or 3 tidal cycles as compared with a single cycle in the inlet and basin.

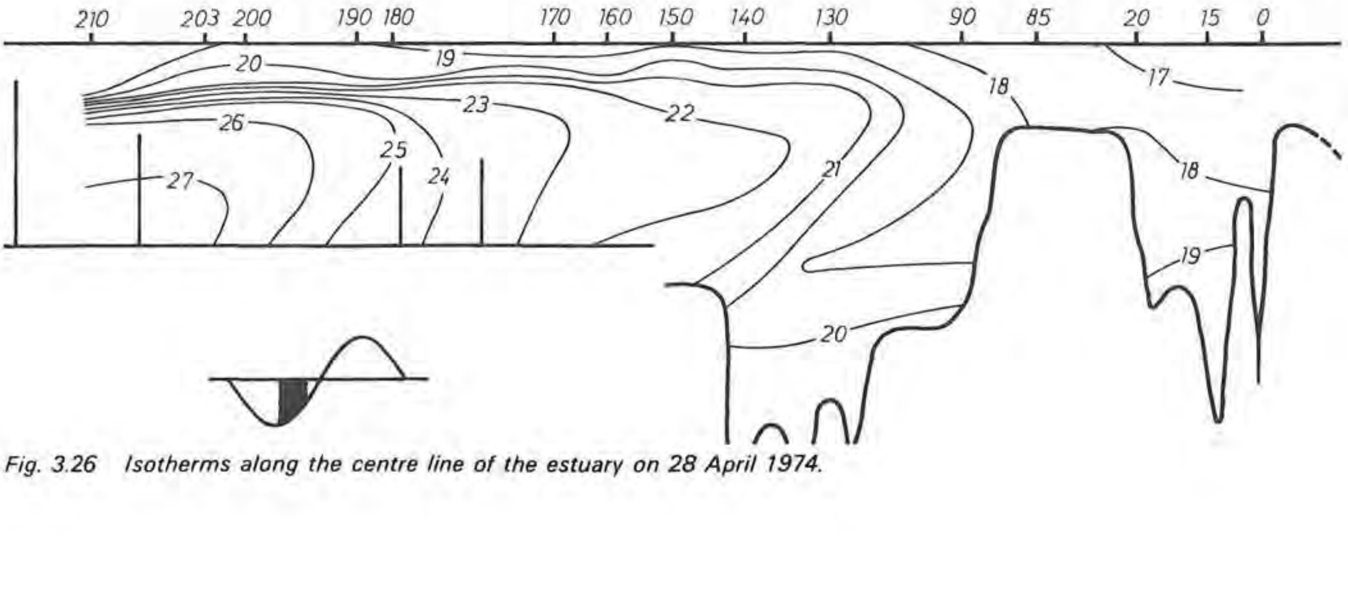


Fig. 3.26 Isotherms along the centre line of the estuary on 28 April 1974.

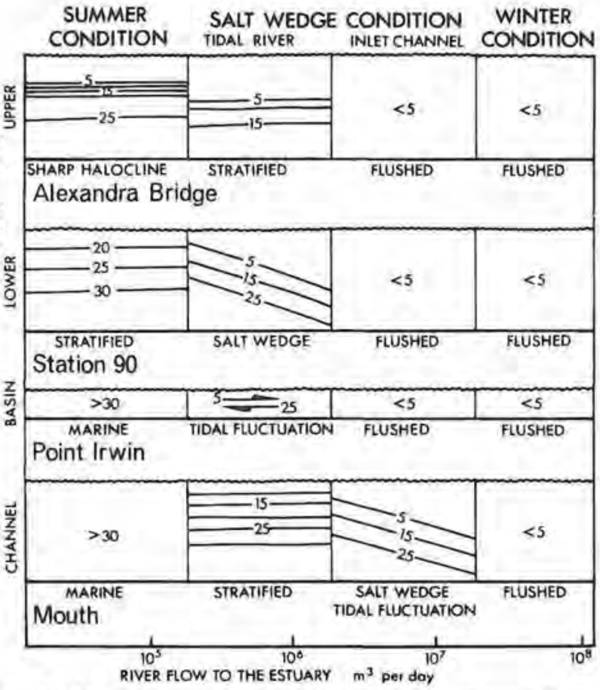


Fig. 3.27 Dynamic condition of the Blackwood River estuary in relation to river flow. Figures show salinity ‰.

However, the summer dye experiment showed a strong tidal current entering West Bay. There is an indication of a counter-clockwise circulation in the basin and the water in North Bay is probably exchanged mainly with water from the northern shore of the basin. There is clearly also some delay in exchange of water between the Molloy and Scott basins and the main river channel, and even between water of the marginal platforms of the inlet and the central water mass.

3.7 Hydrology

It will be clear from the preceding section that the hydrological picture is one of seasonal change rather than the daily or semi-daily tidal fluctuation usually experienced in estuaries.

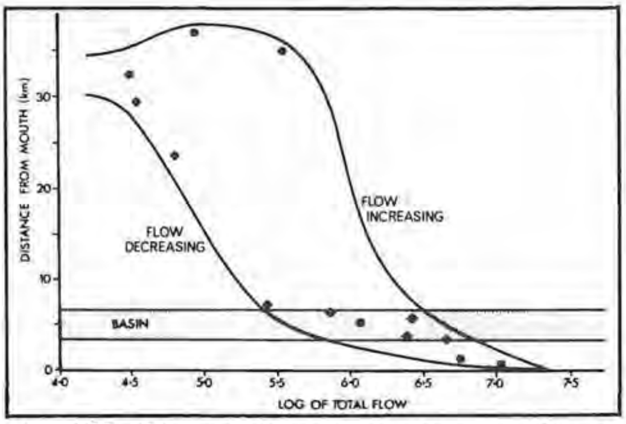


Fig. 3.28 Distance of upstream salt penetration as indicated by the 25‰ isohaline at 4m depth.

Salinity

The changing seasonal pattern of salinity in the estuary is shown in Figs. 3.16, 3.30, 3.31. Tides only induce much diurnal variation in salinity during development of the salt wedge condition. At this time, there are wide fluctuations in salinity, first in the inlet and subsequently over the basin shallows.

During the summer condition, all water in the inlet and basin is greater than 30‰ salinity. The tidal river is stratified with an abrupt halocline at about 1.5 m and the difference between surface and deep water salinities increases towards the head of the estuary. But it will be noted from the Figures that there were salinity gradients in both surface and deep water, and that the extreme penetration of the surface, 10‰ isohaline was to Alexandra Bridge (Stn. 180), for a brief time in April. In contrast, the deep water there exceeded 25‰ for about 5 months.

Increased river flow early in May depressed the halocline near the head of the estuary and forced low salinity water further downstream. Heavy rain in late May and early June resulted in all saline water being flushed from the estuary, except for a salt wedge in the inlet channel. A dry period followed and allowed

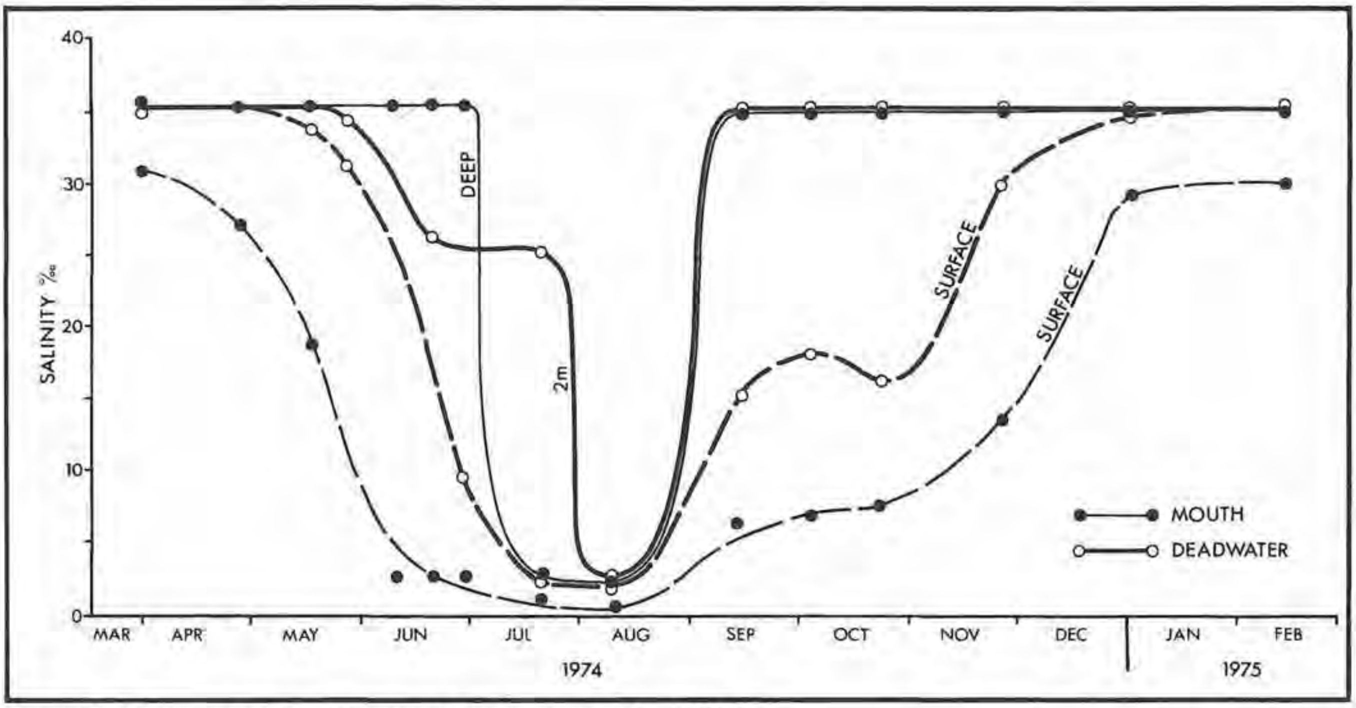


Fig. 3.29 Seasonal salinity response of the Deadwater 1974-1975.

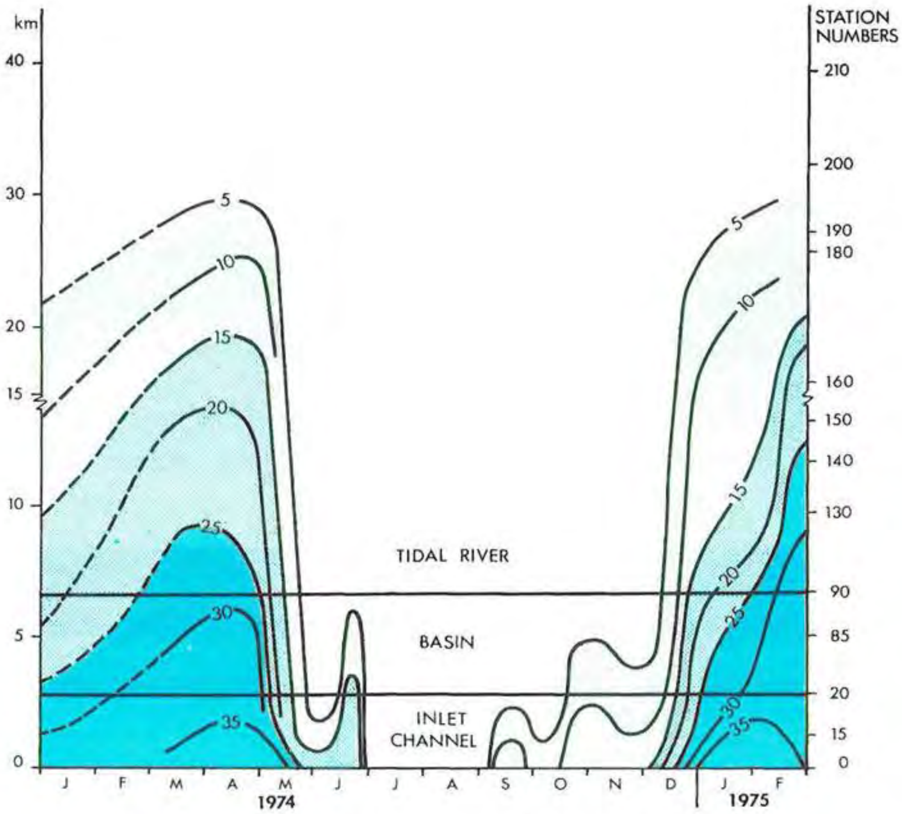


Fig. 3.30 Surface salinity in the Blackwood River estuary.

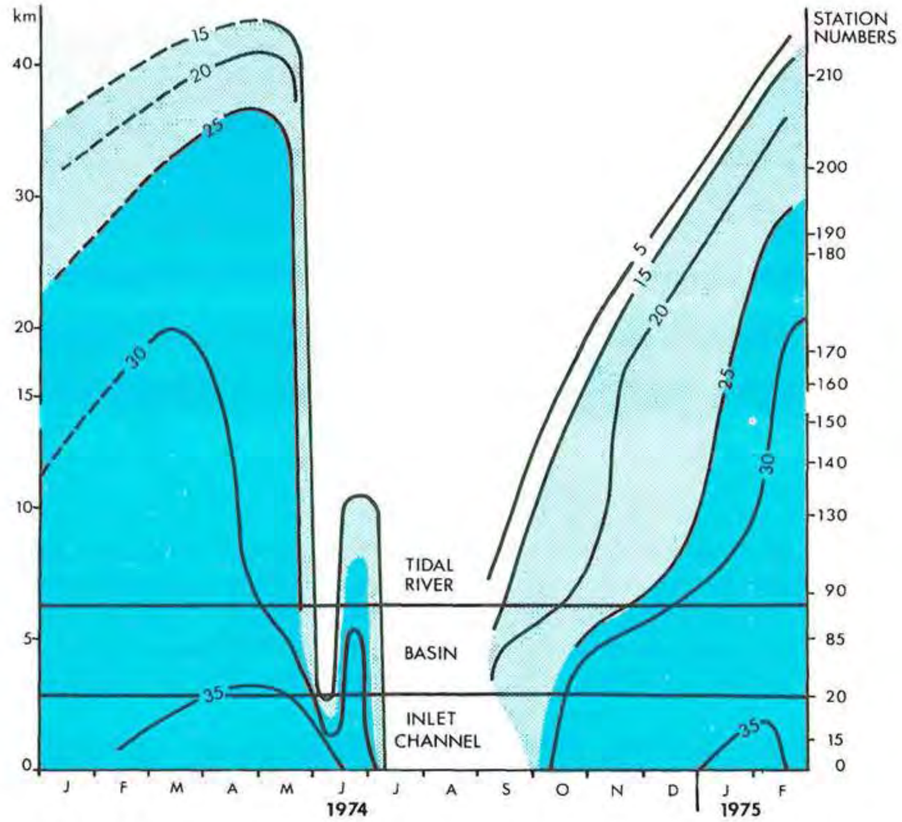


Fig. 3.31 Salinity at 4m in the Blackwood River estuary (maximum depth of basin 2m).

high salinity water to cross the basin and spill back into the bottom of the tidal river before the main flood in July made the estuary entirely fresh.

Recovery began in September with rapidly rising salinities in the deep water, but as will be seen from Fig. 3.30, there was no great increase in surface salinity until December.

The above sequence of dynamic conditions, and their associated hydrological changes, is repeated annually. However, it will be recalled that the annual volume of river discharge varies by a factor of 10 and that the 1974 winter flow was the highest on record (1965-75). It is therefore probable that in most years somewhat less extreme conditions will be experienced in the estuary and that in some years flow rates will

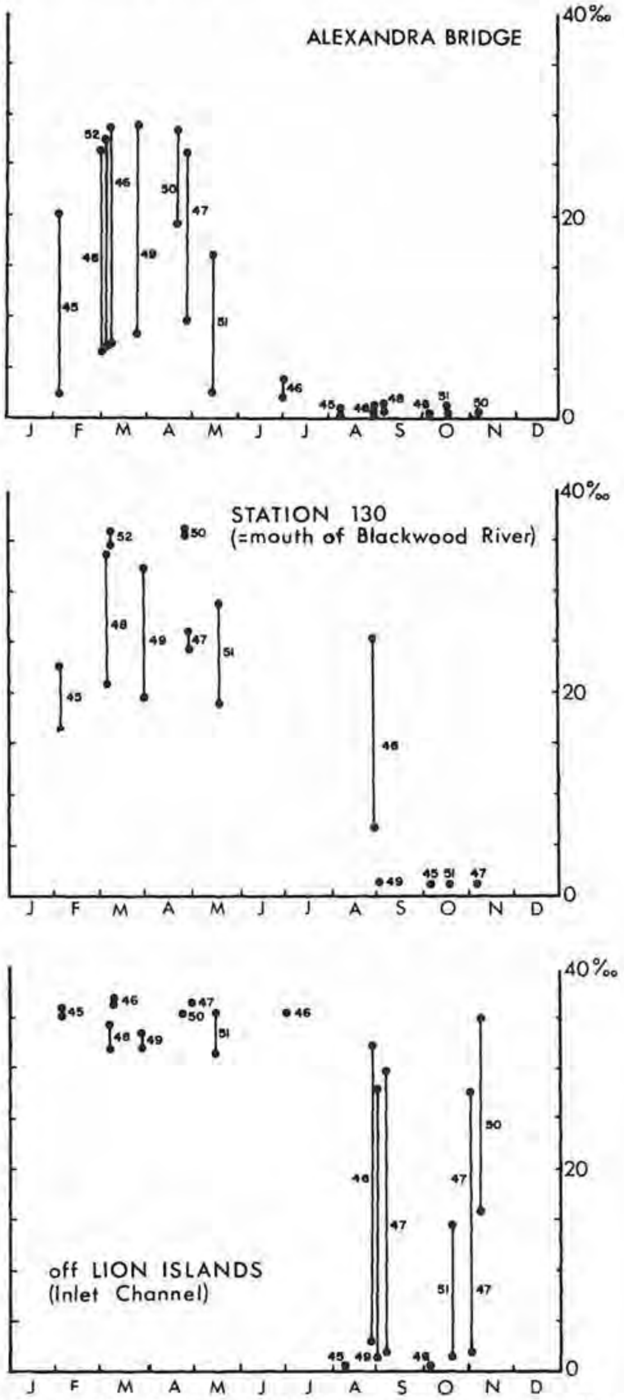


Fig. 3.32 Surface and bottom salinities in the Blackwood River estuary 1945-1952. Figures against lines show year when samples taken. Source: Rochford and Spencer, 1953, 1955, 1956.

be inadequate to exclude the salt wedge from the inlet at any time. Data for 1945-52 (Rochford and Spencer, 1953, 1955, 1956) indicate that a salt wedge condition probably persisted in the inlet in most years (Fig. 3.32). The tidal river is probably fresh throughout for several months every year, although a deep salt wedge may persist in years of very low river discharge. The shallow water of the basin will also be fresh for a period every winter, but for how long will depend on the duration of river flow in excess of about 2 x 10^6 m^3 per day, and hence may vary considerably from year to year. But it must be remembered that this figure is an order of magnitude less than that required to keep the inlet fresh throughout.

Temperature

Temperature profiles are shown in Fig. 3.33. The small seasonal range of the ocean input (about 6°C) will be noted, and the effect of solar heating in the shallow basin. Under summer conditions, the tidal river experiences a "hot house" effect which is characteristic of all south west estuaries where a halocline is formed. Water below the halocline becomes several degrees hotter than surface water and there is a sharp thermocline (Fig. 3.34). The process by which this heating takes place was discussed above (Fig. 3.25)

Oxygen

No extended study was made of dissolved oxygen and significant deoxygenation was only observed below the halocline in the tidal river in summer. Fig. 3.35 shows oxygen levels recorded at Alexandra Bridge in the 1945-52 studies by CSIRO Fisheries and Oceanography and oxygen profiles recorded under stratified conditions during the present study are shown in Fig. 3.36.

Turbidity

Secchi disc readings in the tidal river ranged from 0.1 m to 0.3 m in July 1974, during high river discharge, and 1.0 m under the lower flow conditions of July 1975. In summer the readings were 2 to 3 m and considerably greater in the marine water of the inlet channel. Scott River water is a dark peaty colour in contrast to the brown muddy water of the Blackwood River.

Blackboy, *Xanthorrhoea Preissii*

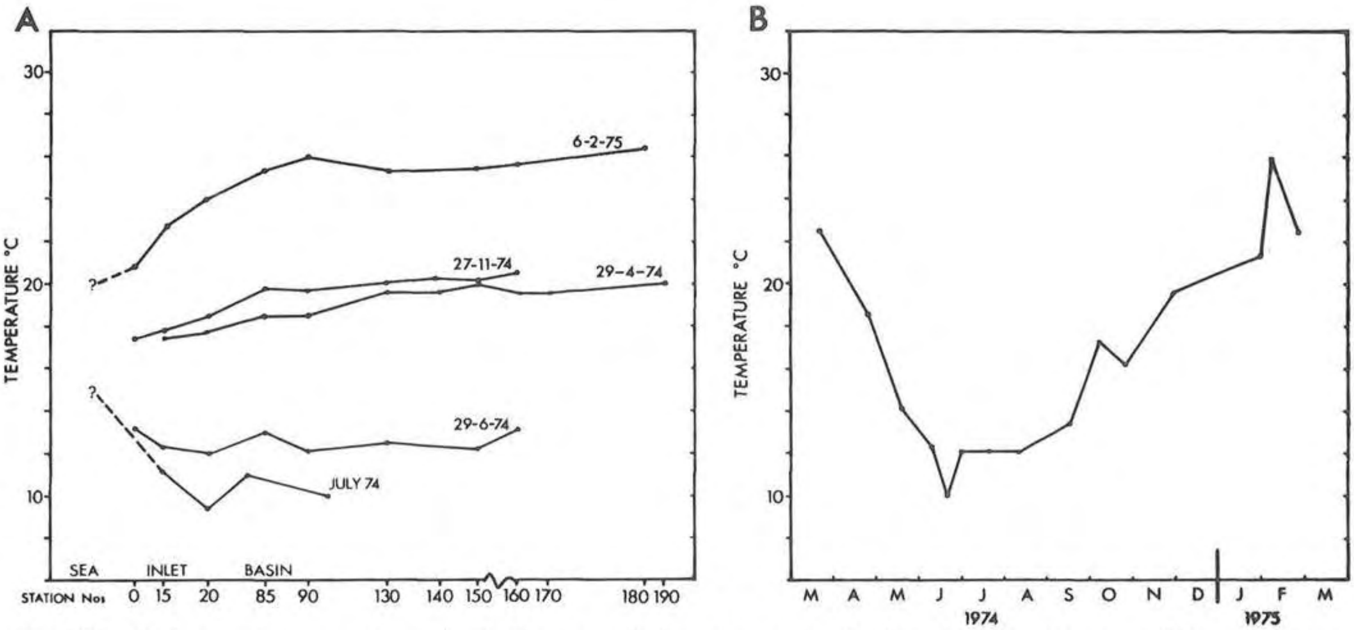


Fig. 3.33 Surface water temperatures in the Blackwood River estuary. A—Profiles along the estuary at different seasons. B—At Station 90.

The mouth of the Blackwood estuary in 1943. Official RAAF Photograph.

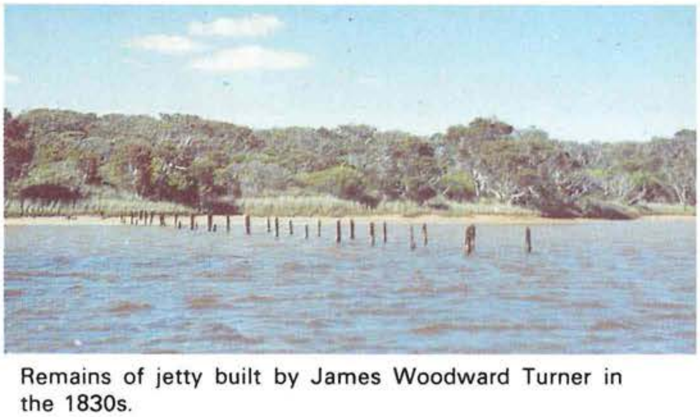
The Inlet Channel
1976

HARDY INLET

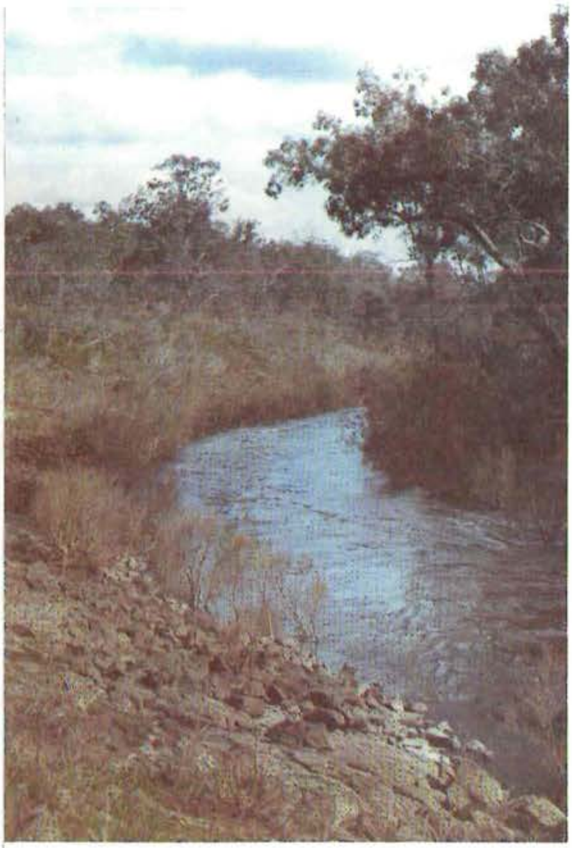
The same view in
1830

Paintings by Thomas Turner. Reproduced by kind permission of the Augusta Historical Society and the Western Australian Art Gallery.

Boles of forest trees on Molloy Island. The bark possibly stripped by Aborigines as blanks for bowls or shields.



Remains of jetty built by James Woodward Turner in the 1830s.



▲ The Blackwood River at Sues Bridge. Flood water has killed the foliage of shrubs along the banks. September 1974.

◀ Basalt outcrop in the Blackwood River at Darradup.

▼ Nannup. View south along the Darling Scarp. At right, the Sunklands forest.

The Blackwood River valley near Nannup. ▲ Farmland.

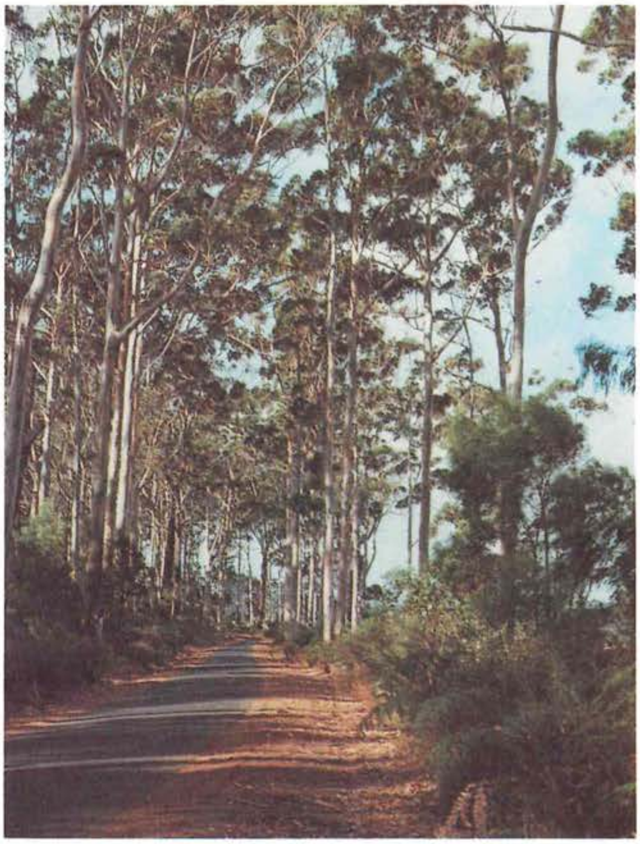
▼ Pine plantations.

▼ Norring Lake near Wagin (salt). Granite hill affords a view over the flat upper catchment.

▼ The Stirling Range, 80km south across farmlands of the plateau.

▲ Cape Leeuwin and lighthouse at the southern tip of the Naturaliste-Leeuwin ridge. Granite rocks on the shore.

▼ Hardy Inlet. View from the scenic lookout.



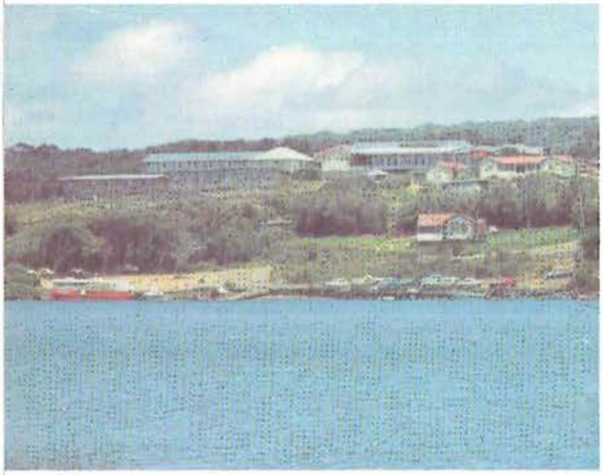
▲ Karri trees.

▲ The Scott River in summer—a chain of pools.

▼ Grazing land on the Scott River plain.

▲ Augusta, the inlet channel and woodland on the eastern shore.

▲ Swan Lakes and the Deadwater.



▲ Augusta from the eastern shore.

▼ Augusta and Hardy Inlet. Photo: Dr. M. J. Williams.

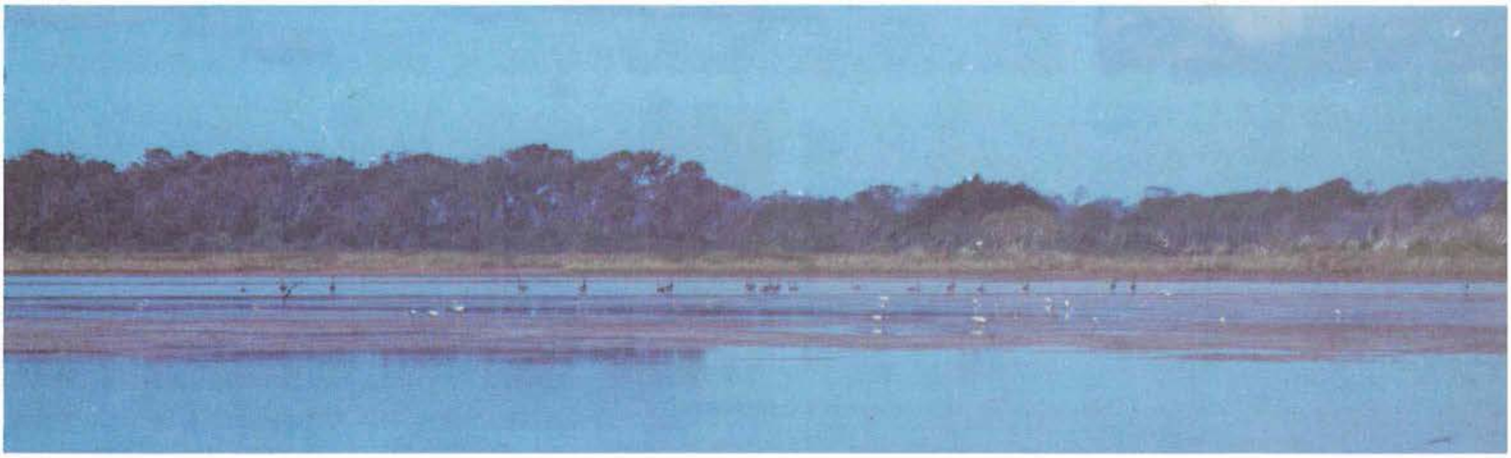
▼ Seine Bay, summer.

▼ Point Frederick. Upper: Eroded foredune April 1974. Lower: The same view February 1977.

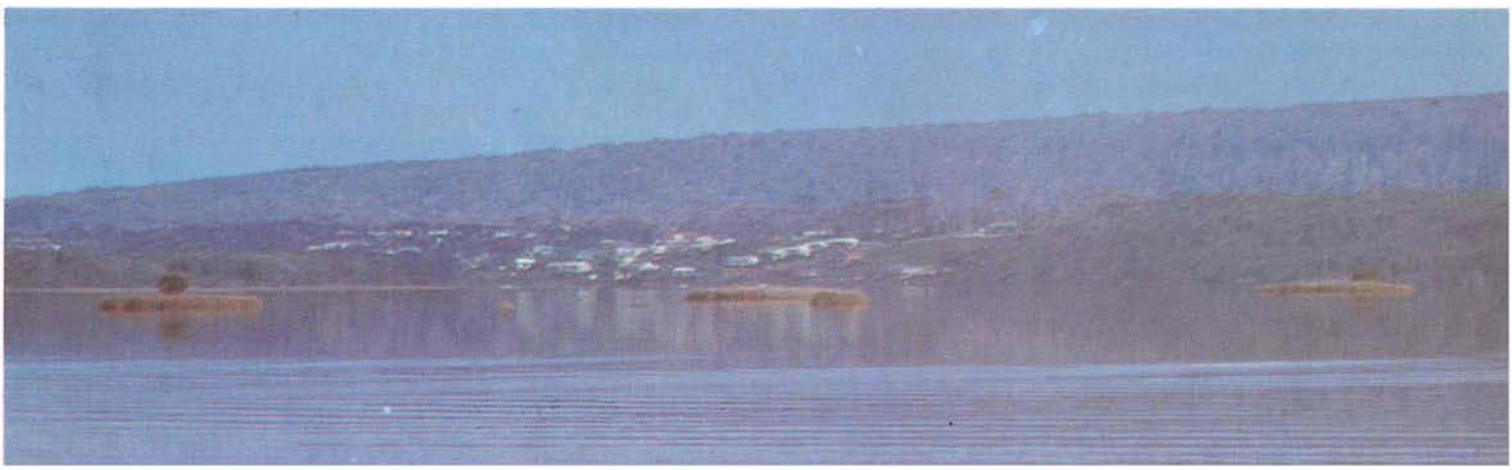
▲ Augusta. Seine Bay on the left to Lion Island on the right.

The basin. Sand flats of the delta exposed at low tide. ▶

▼ Black swans and gulls on the sand flats. The western shore of the basin.



▼ Three rush islets in the basin. Augusta in the background.



▲ The tidal river. Molloy Island on the left.

▲ Molloy Island and the Scott Basin. Photo: Ross Field.

▼ Grass trees, *Kingia australis*, on Molloy Island.

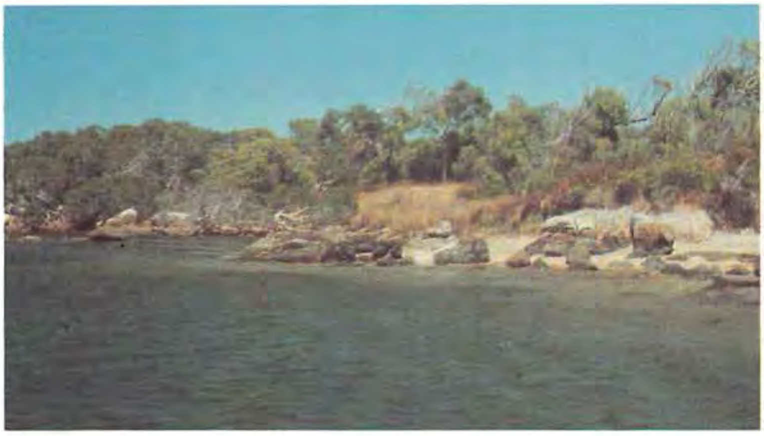
▼ The old Alexandra Bridge.

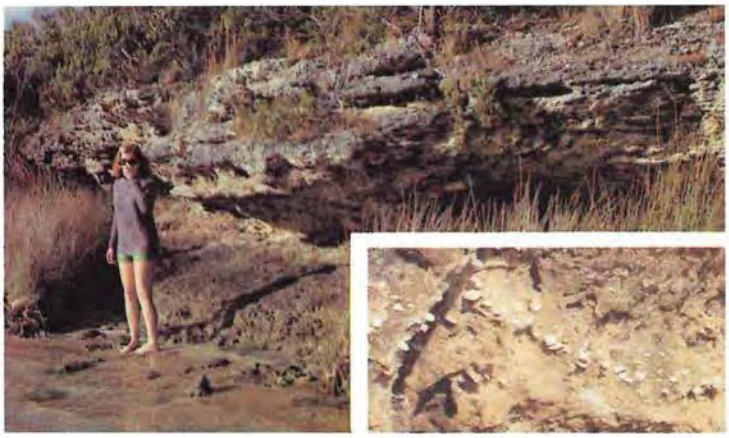
▲ Landing place, Molloy Island.

▲ Rock bar at the head of the estuary.

▼ Warner Glen Bridge.

February 1974 ▼ Views downstream from the bridge ▼ July 1974.





▲ Granite shore below Augusta.

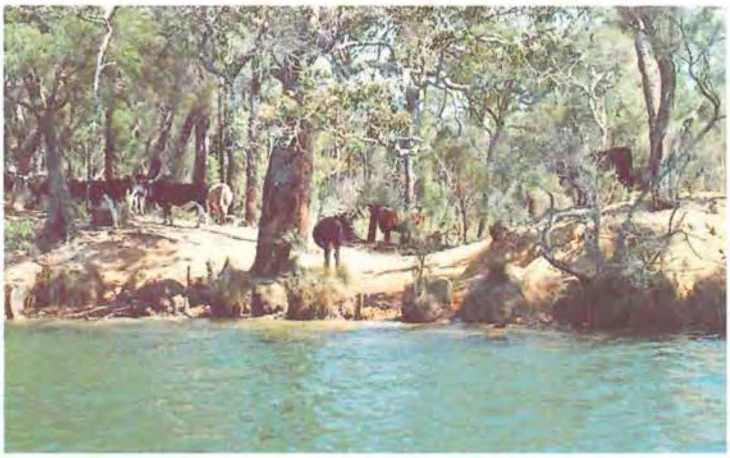
▲ Limestone on the eastern shore with (inset) embedded marine shells.

◀ Laterite cap, bank of the tidal river.

The vibro corer. ▶

▼ Heavy mineral sand on an estuary beach.

▲ Natural erosion of the river bank.



▲ Cattle have destroyed the marginal vegetation.

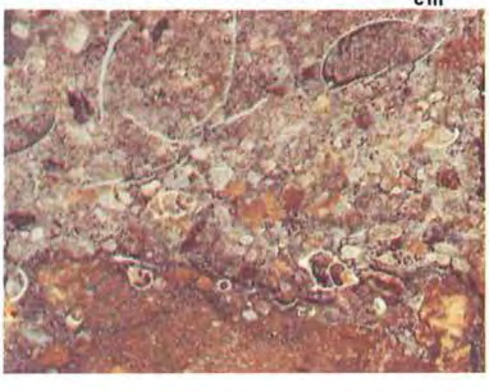
Sectioned sediment cores:

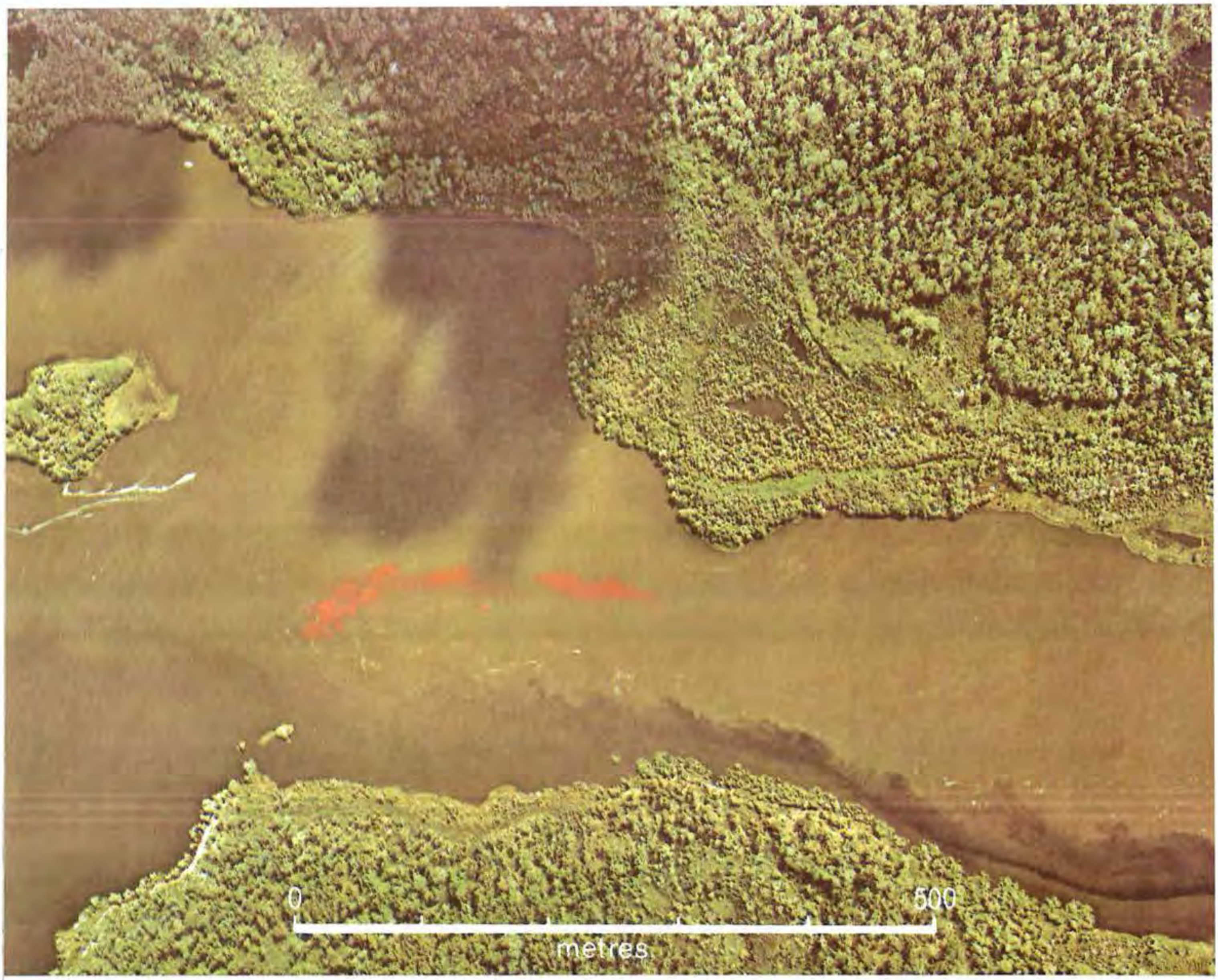
▼ Unconformity between Oyster Unit and Pleistocene soil. cm

▼ Delta sand mixed by burrowing animals.

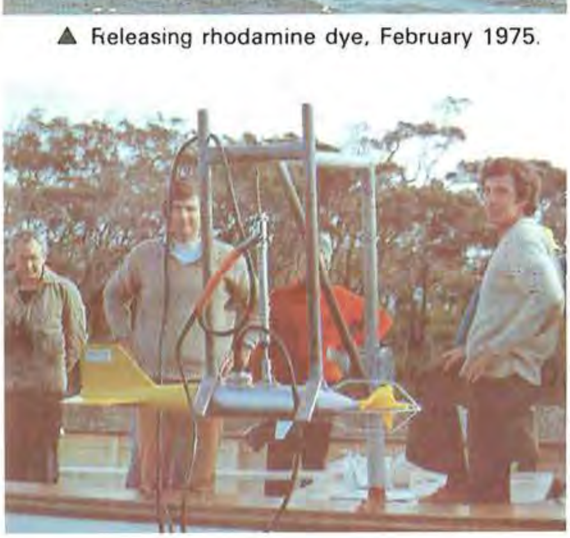
▼ Basin Unit, layered mud and shelly sand.

▼ Oyster Unit. cm



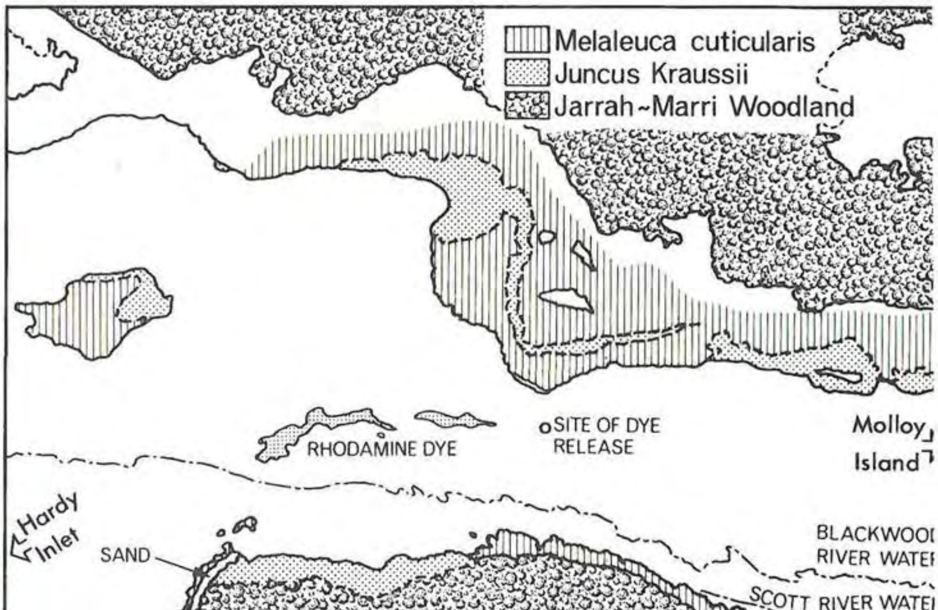


▲ Releasing rhodamine dye, February 1975.



▲ Vertical air photo at Station 90, 13 August 1974. Rhodamine dye released 1150 hrs, photograph 1157 hrs.

▼ Diagram of above



◀ Multiparameter probe in position for lowering from boat. Dr. J. Imberger centre.

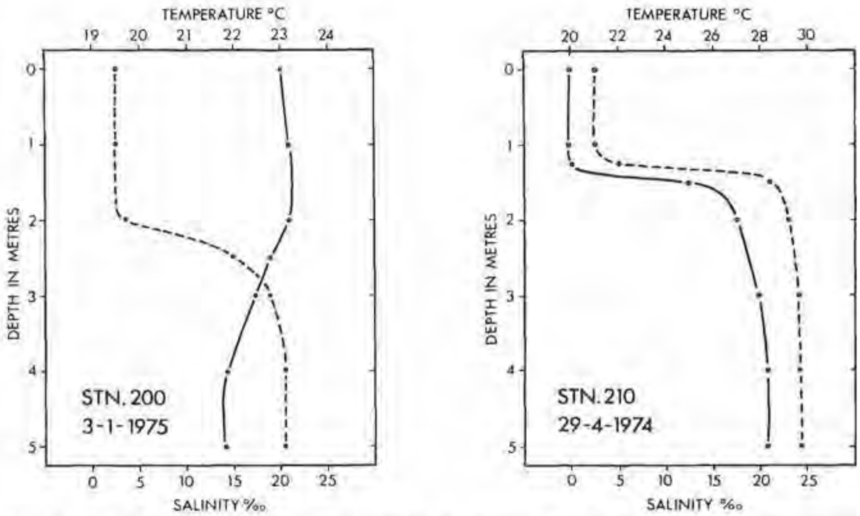


Fig. 3.34 Temperature(—) and salinity (---) profiles at stations near the head of the estuary in January and April to show development of the stratified condition.

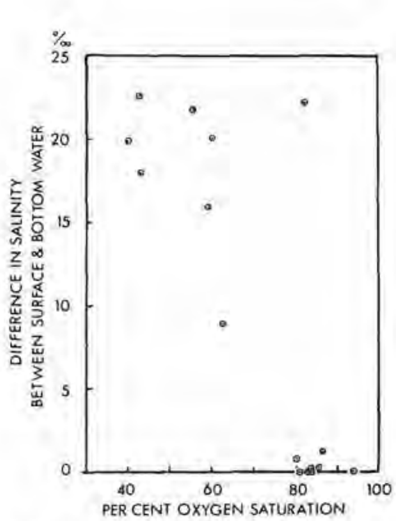


Fig. 3.35 Dissolved oxygen in bottom water at Alexandra Bridge, 1945-1952. Source: Rochford and Spencer, 1953, 1955, 1956.

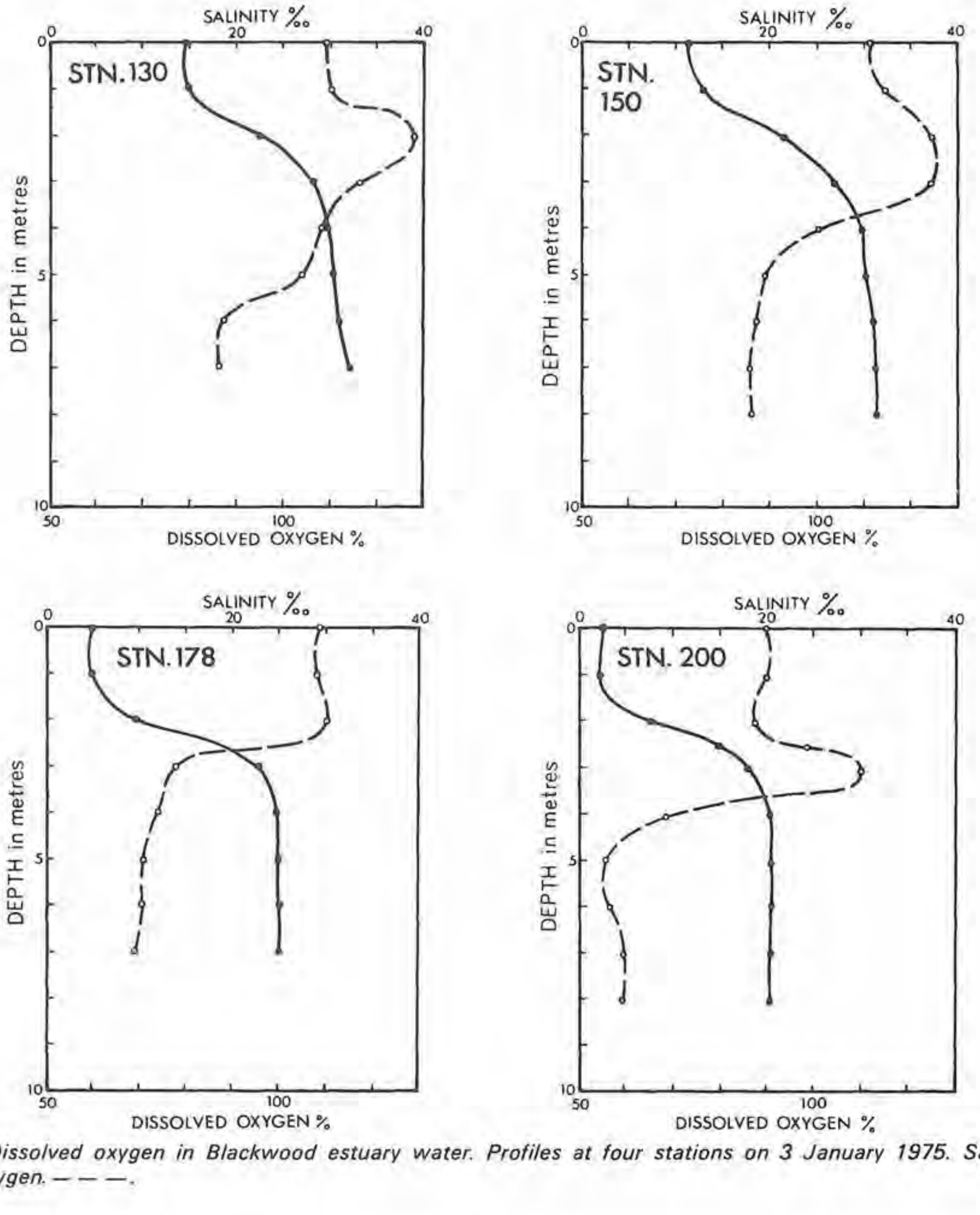


Fig. 3.36 Dissolved oxygen in Blackwood estuary water. Profiles at four stations on 3 January 1975. Salinity.———. dissolved oxygen. — — —.

CHAPTER FOUR BIOLOGICAL ASPECTS

4.1 Character of the Biotic Environment

An estuarine environment is one of constant change, both spatial and temporal, one where biologically significant environmental parameters may vary over an extreme range, both in space and time. Not only is there change on this scale in salinity, but in water flow, temperature, turbidity and light penetration, nutrient supply, predation pressure, and even in this sheltered situation in degree of wave action. They add up to a complex of environmental change, the several strands of which are difficult to disentangle; together they determine the nature of the estuarine ecosystem.

Day (1967) has pointed out that estuaries are sheltered environments and that the estuarine biota may be merely a "sheltered water biota". "Many so called estuarine species" he says "are really calm water species and the ability to survive in sheltered water is just as important as tolerance to reduced salinity in determining an estuarine population". Sheltered waters, where there is no strong wave action, have a different range of habitat types from the open sea and for that reason they favour different kinds of organisms. The estuaries of south western Australia all afford much the same range of habitat types, albeit in different proportions, so that useful comparisons can be made between them when attempting to assess the effects of other environmental factors, and especially of salinity (section 4.12).

Salinity

Reduced salinity and a gradient of this from sea water to fresh water, is probably the most important environmental characteristic determining composition of the biota and controlling distribution of organisms within estuaries. Estuarine animals may be broadly divided into (a) *osmoconformers*, animals in which the body fluids are in osmotic equilibrium with that of the environment and (b) *osmoregulators*, animals which can maintain their body fluids at a different osmotic concentration from that of the surrounding water.

Of the vast diversity of animals and plants in the sea, very few are able to survive salinities much below that of sea water (35‰). Equally, of the considerable diversity of freshwater organisms, very few can live in salinities greater than 5‰. A few, but only relatively few, organisms have specialised for life in the brackish waters of estuaries. This is true both of invertebrates, most of which are osmoconformers, and of fish which are osmoregulators, but most of which have only a limited capacity to regulate in brackish water.

The well known diagram of Remane and Schlieper (1971) emphasises the decrease in number of species in brackish waters to a minimum at 5-7‰ (Fig. 4.1). The diagram distinguishes four different types of brackish water organisms. The authors further place marine organisms which invade brackish water from the sea into five categories according to their tolerance of reduced salinity. However, for the purpose of the present discussion the five components of the estuarine fauna recognised by Day (1951) are more appropriate. These are:

1. *The freshwater component* restricted to waters of low salinity.
2. *The stenohaline marine component* at the mouth of the estuary.
3. *The euryhaline marine component* extending from the sea over the middle reaches of the estuary wherever conditions are suitable.
4. *The estuarine component* comprising the few species which are restricted to estuaries.
5. *The migratory component* which spend only part of their lives in estuaries.

[stenohaline—organisms adaptable to a narrow range of salinity; euryhaline—organisms adapted to a wide range of salinity.]

Both classifications are essentially ecological, they are based on the observed distribution of animals in relation to the environmental conditions, not on experimental evidence of ability to live in particular parts of a salinity spectrum. They do not explain this distribution, nor do they explain how physiological and behavioural characteristics or ecological interaction between the various organisms bring about this distribution. Only in a few cases, is it possible to explain with any confidence what causes particular species to be distributed in the way we observe. Some examples are discussed in section 4.13.

Without a good knowledge of the biology of individual species it is often difficult to know whether they should be assigned to component 3 or 4. There are no sharp cut off points along the "middle reaches" of an estuary. Much of the Blackwood estuary experiences the entire range of estuarine salinities at one time or another.

It is pertinent to repeat here that 1974 had the greatest river runoff on record and that less extreme hydrological conditions will be experienced in the Blackwood estuary in many years, especially in the inlet channel and Deadwater. Also, it must be remembered that for much of the year, the estuary is stratified and that even though surface water is unfavourable to all except the more euryhaline animals, sub-

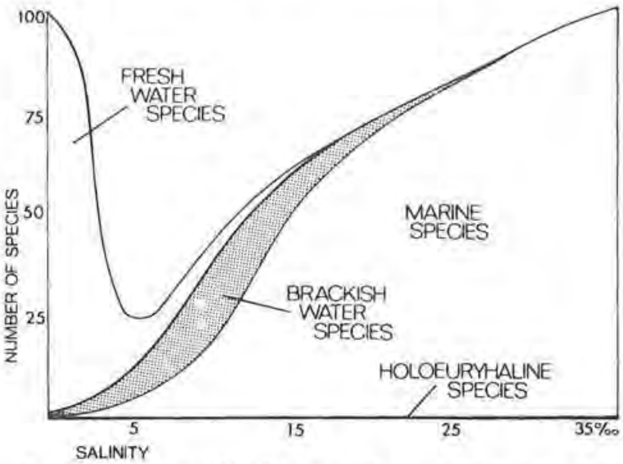


Fig. 4.1 Remane's diagram of the composition of brackish water faunas.

halocline waters provide favourable conditions for many more, including the planktonic larvae of bottom living organisms.

Other Environmental Factors

The biological characteristics of an estuarine ecosystem are of course influenced by a number of other factors which help to determine the distribution and abundance of the flora and fauna. There are great differences between estuaries, and parts of them, in respect of all these factors.

Astronomic tides have both direct and indirect effects, particularly on intertidal regions which are inundated or exposed for varying periods and through which water drains. Longer period changes of water level, annual and barometrically induced, are also important in their influence, not only on the plants and animals which live there permanently, but on the fish and birds which feed in the shallows. Tide range, with geomorphic factors, determine the volume of tidal exchange and consequent loss to and dilution from the sea. As shown above (section 3.5), tidal range is relatively large in the Blackwood estuary and tidal exchange great. Even time of tide may be significant, especially here where tides are predominantly of daily type.

Strength of currents is important to attached plants, to mobile animals, and to planktonic organisms, whether permanent or temporary. River flow is strong in winter but negligible for much of the year and the only currents then are those generated by the tides.

Turbidity, and the quantity and nature of suspended matter varies with river flow and consequently there is seasonal variation in light penetration for plant photosynthesis. The nutrient content and nature of the nutrients also varies greatly in relation to river flow.

Temperature varies seasonally, daily, and locally. Change is least at the mouth, under the modifying influence of the sea and there can be great daily changes in shallow water, with relatively high temperatures in summer. There are often considerable temperature differences associated with salinity discontinuities and these may be abrupt, as where the tidal river is stratified (Figs 3.26, 3.34).

Nature of the available substrates, rock, sand, mud, etc. to a great extent determines the composition of the fauna and flora. This is considered in section 4.3. The granulometric composition of the Blackwood sediments was described in section 3.3.

Estuarine Types; the Seasonal Estuaries of South Western Australia

There are many different classifications of estuaries, each of which is biased towards the interests of the persons concerned, be they geomorphological, hydrological, biological or other. Sanders *et al* (1965), when discussing the benthic fauna of estuaries, recognised three different types of estuary: stable, gradient, and fluctuating. Day's classification of the estuarine biota can confidently be applied to the biota of stable estuaries, estuaries in which the salinity regime is stable. It can also be applied to gradient estuaries in which there is limited tidal and seasonal movement of the isohalines up and down the estuary, with pronounced changes only in the middle reaches. However, this classification is less satisfactory when applied to fluctuating estuaries, where small volume and large tidal range result in daily change over a wide range of salinity and alternating submergence and emergence. Here, as Sanders *et al* (1965) point out, survival can be achieved by behavioural avoidance when conditions are unfavourable, by retreat into the sediments or within a closed shell, and even by tolerating unfavourable conditions for a limited period.

The estuaries of south western Australia certainly fluctuate hydrologically, however the fluctuation is on a very different time scale from that of Sanders' fluctuating estuaries: a year instead of a day. Here, organisms may be exposed to grossly different conditions for several months at a time, time periods of the order of magnitude of the life cycle of most benthic invertebrates. Under these circumstances, duration of stressful conditions is as important as the range of salinity experienced in determining survival of populations of particular animal species.

Spencer (1956) termed the Swan River estuary an "atidal climatic system". However, because of the important role of seasonal change in the environmental parameters of the estuaries of south western Australia, I prefer to term them seasonal estuaries. Moreover, despite the relatively small tidal range, tidal movements are very important to the dynamics and hydrology of the estuaries, as shown in the previous chapter, and therefore to the biota. Fig. 4.2 represents diagramatically the various environmental parameters which have a seasonal time scale of change in the estuary. Predation pressure on the benthic fauna is also likely to vary seasonally, being greater during the saline phase than during the fresh phase.

The extent to which estuarine classifications, such as those of Day and Remane, can usefully be applied to seasonal estuaries should be better understood as a result of this study, particularly that part dealing with the macrobenthos.

Seasonal type estuaries are not exclusive to south western Australia. However, the only others with such extreme hydrological changes, of which the biology appears to have been studied in any detail, are tropical estuaries with the reverse hydrological picture of summer fresh and winter saline: Lagos lagoon (Webb and Hill, 1958; Sandison, 1966) and the Cochin backwaters (Ramamirtham and Jayaraman, 1963; George, 1963).

4.2 Objectives and limitations of the Study

The various segments of the study were: vegetation and nutrients, benthos, fish, birds. Each had specific objectives governed by what could provide the most useful contribution to an understanding of the ecosystem within the time available. However, the main concern of the biological studies was to interpret the response of the biota to the changing environmental conditions, and to this end it was necessary to identify the species and determine their relative abundance.

It was possible to estimate absolute numbers of the various species of birds and determine their seasonal comings and goings. For the benthos, population density of the fauna and change in this was measured with reasonable accuracy for most species. In the case of the fish, all that was possible was a measure of relative abundance in the various parts of the estuary and at different seasons of the year. With such mobile animals, accuracy of estimates is particularly dependent on sampling technique; mesh of net, choice of sampling station, time of sampling and other factors. For the commercial species also, an estimate of their potentiality for exploitation was also required.

In the vegetational studies a measure of biomass of the various plant species was essential to understanding their response to the environment and accurate measurements of plant nutrients in water and soil were required.

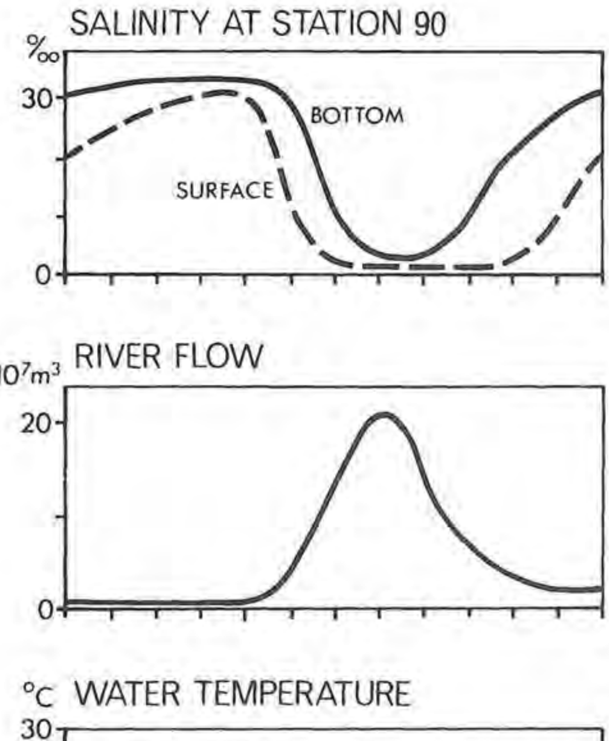


Fig. 4.2 Generalised diagram to show seasonal changes of physical characteristics of the estuary.

All this is essential information, but it is clear that it gives only a limited understanding of a complex, dynamic, biotic system. In the absence either of studies of energy flow through the system or of a precise understanding of the biology of most individual species, conclusions about the working of the ecosystem as a whole are inevitably largely subjective.

We have little data on reproduction and growth rates for most of the fauna, that is to say, data on productivity in addition to standing crop. Information on inter-specific relationships is limited to some quantative data on the kinds of food taken by fish and we know virtually nothing of the effects of predation pressure on the populations or of competition for resources. As a consequence we have little understanding of the all important matter of population dynamics. The study has afforded many useful inferences about these matters and it is to be hoped these leads will be explored by other workers. In particular, it is desirable to gain a thorough understanding of the biology of individual dominant species. It is hoped that continuing studies will do just this for two plants: the rush *Juncus krausii* and the sea grass *Ruppia maritima*. Although no part of this investigation, the biology of the shrimp *Palaemonetes australis* and of gastropods of the genus *Nassarius* have been studied in the estuary and accounts of these are included in section 4.13.

In retrospect, it is easy to see how with a better deployment of energy resources some of these gaps might have been filled and more gained from the study. Nevertheless, it would have been beyond the scope of such a purposely extensive study to have attempted to produce a balance sheet of productivity of the estuary or of energy flow and to have achieved a much deeper understanding of the ecosystem.

4.3 Estuarine Habitats

Estuaries are relatively homogeneous environments with a limited variety of habitat types and this may be an important factor in limiting the abundance of species. Nevertheless, there are a number of distinct habitats each of which favours its particular assemblage of plants and animals. They respond in different ways to seasonal changes and may be expected to be affected differently by any perturbations which may be imposed on the system. The following broad habitat types can be recognised in the Blackwood and other estuaries of south western Australia.

1. The water body. This is the most dynamic part of the system. Under high discharge conditions it is river water flowing through the estuary. At other times it is either subject to tidal exchange with the sea, in the lower estuary, or confined within the estuary for prolonged periods. Apart from flow, the main variables are salinity, temperature, turbidity and suspended matter and, in consequence, light penetration.
2. Sediments. These vary in texture from coarse well-sorted sand to fine sand and clay with organic mud and little pore space, and vertically from clean well-oxygenated material, a few centimetres thick, to black anoxic conditions producing hydrogen sulphide. There is often a surface coating of fine, mobile, largely organic material which is readily resuspended by water movement.
3. Submerged macrophytes. Principally the sea grass *Ruppia*, which of itself changes in character and abundance through the seasons.
4. Solid substrates. Rocks and logs and man-made structures such as jetty piles, are present in limited quantity only.
5. Marginal swamps. Some of these, especially the rushes, are strictly intertidal and are subject to innundation daily, others are only innundated and become part of the estuary under flood conditions.

The estuary is not a closed system and both the sea and the river are in continuity with the estuarine water mass and bring to it nutrients in dissolved and particulate form and important contributions to the flora and fauna.

4.4 Trophic Levels of the Estuarine Biota

Some generalisations about trophic relationships of the biota will form a useful introduction to sections dealing with particular elements of the flora and fauna. Without detailed studies of feeding habits of the various organisms, there is necessarily extrapolation from what is known about related organisms in other parts of the world and some informed guess-work. Nevertheless, the simplified food web Fig.4.3 does form a useful framework for assessing interrelations of the biota of the Blackwood estuary.

The direct food chain: plants—herbivores—carnivores, involves several different kinds of primary producers. Phytoplankton proved not to be abundant and the chain phytoplankton—zooplankton—fish involves only a small biomass, although it may be important for specific animals such as larval fish. The biomass of sea grass is considerable and use of this by black swans is important to the economy of the system. However, few other animals make direct use of it. Epiphytic diatoms and other algae on submerged plants are food for shrimp, other invertebrates, and probably some fish. There is no evidence as to how great a part benthic diatoms and other microscopic plant life play although it must be assumed that they are food for a variety of benthic animals.

The riparian vegetation, rushes and other marsh plants, are probably unimportant to the direct food chain, but they are essential contributors to the detrital mass through which a large part of the nutrients of the system are channelled. Much of this is cellulose and as such is inaccessible to the fauna. However, the reduction in particle size of plant detritus by such animals as amphipods makes it more accessible to the bacteria which are ultimately the main food source of a large proportion of the fauna. The importance of feedback via faecal pellets of the benthic fauna has also been stressed in a number of recent papers (e.g. Fenchel, 1970; Welsh, 1975), as has the part played by sea mullet (Odum, 1968).

It was beyond the scope of the study to unravel the complex interrelationships at these trophic levels apart from determining the immediate foods of fish and some birds. It is evident that because most of these are carnivores, there is a complex series of links in the food chain between them and primary producers.

4.5 Vegetation and Plant Nutrients

The following review derives mainly from Technical Report 3: Preliminary Report on Botanical Studies. The habitat types described in section 4.3 are not entirely suitable to discussion of the vegetation and nutrients, but are followed here with slight modification only. Macroscopic algae although attached are discussed with the phytoplankton because they obtain their nutrients from the water, unlike the vascular plants which obtain their nutrients mainly from the sediments.

Plants of the Water Body

The main plant nutrients which may limit growth in the estuary are nitrogen and phosphorus and attention has been concentrated on these. Silica, required by diatoms is at high levels in the river water (1-6 mg Si/l in July and August). It may be much lower under summer conditions but is not thought to be limiting. Data from the Swan estuary showed levels of 2.8-5.6 mg Si/l in river water with only 60-840 μg Si/l during the saline phase in summer when there were periodic diatom blooms (Hodgkin, unpublished data). Sea water contains even less silica, about 60 μg Si/l.

Nitrate nitrogen is abundant in the river water in winter; figures of about 250 mg/l were recorded both in the present study and in the earlier CSIRO data, Rochford and Spencer (1953, 1955, 1956). Summer levels are very low with no measurable quantities being recorded in many of the CSIRO samples. On the other hand, organic nitrogen levels measured in this study were fairly high and suggest that nitrogen is not likely to be limiting to algal growth, although the N:P ratio was low. However, while certain species of planktonic algae have been shown to use available organic nitrogen, higher plants and presumably benthic algae, can only use nitrogen after mineralisation (conversion to NH_3 and NO_3).

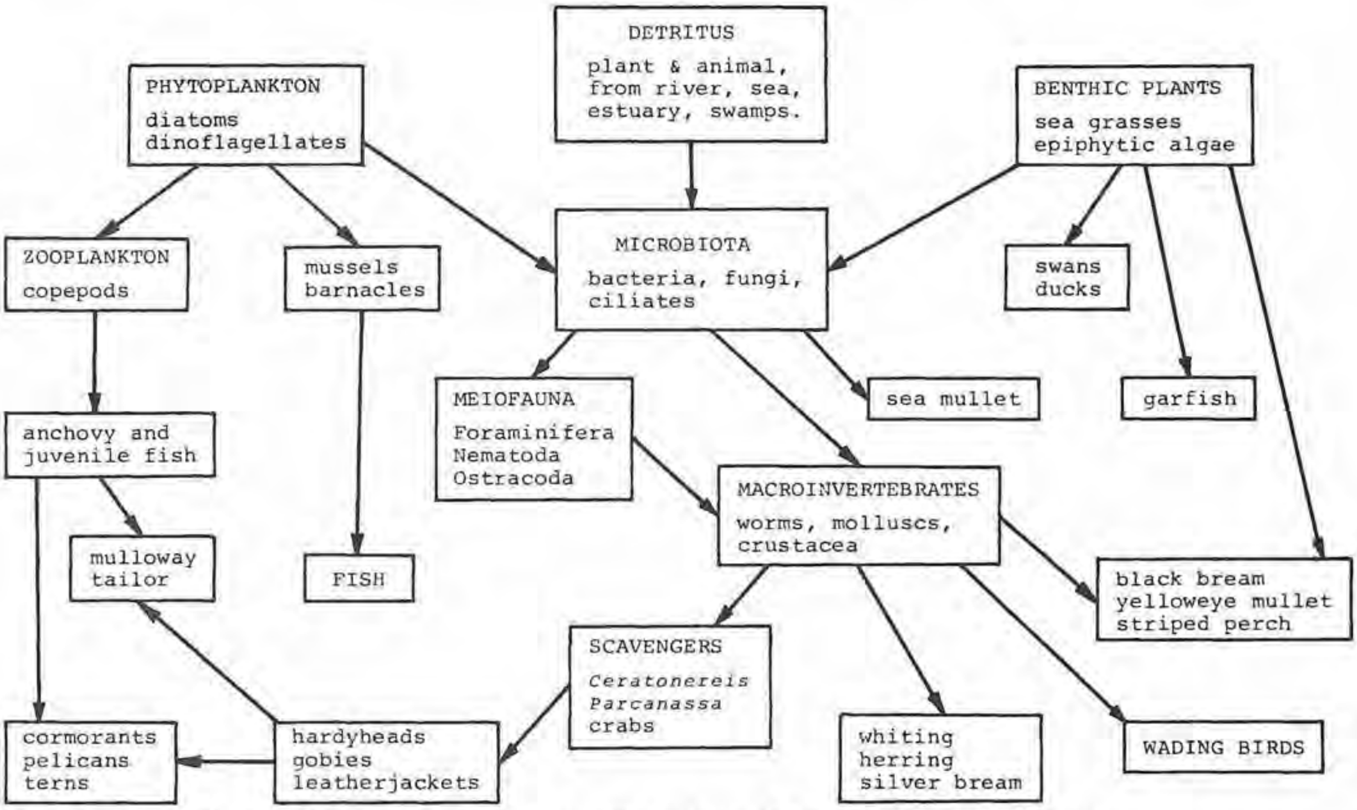


Fig. 4.3 Food web of the Blackwood estuary. A simplified scheme of the probable main pathways.

Phosphate levels recorded in river water were slightly higher than the CSIRO data of 25 years earlier: inorganic P. July 1974, 14 μg/l; August 1974, 4 μg/l; 1947-52, 5 μg/l (7 samples). It should be noted however, that while these samples were taken early in the runoff period, the CSIRO samples were taken towards the end of the fresh phase. Saline phase samples agreed with the CSIRO data in showing low total phosphate levels; both average about 10 μg/l in the lower estuary. There is of course high net loss of nutrients to the sea in winter, a loss which decreases with reduced flow in spring.

It is unlikely that under normal conditions, oxygen levels will ever be low enough in the basin and inlet for release of nutrients from the sediments. However, under stratified conditions in the tidal river summer oxygen levels approach those at which this can occur (2 mg/l).

The above data are for nutrients in the water and are therefore principally relevant to algae, both planktonic and benthic. No phytoplankton blooms were observed. Phytoplankton cell counts and chlorophyll levels were both very low in all samples examined, even in spring when a bloom might have been expected. Six common genera were identified and there were desmids and pennate diatoms (Tech. Rep. 3, Table 4).

Macroscopic algae (Tech. Rep. 3, Table 3) were not abundant, except for spring and summer blooms of *Lamprothamnium papulosum* (Charales) near Molloy Island and of filamentous green algae, especially in Swan Lake and the Deadwater where masses of *Rhizoclonium riparium* formed and were washed up on the banks of the Lower estuary in spring. Swan Lake has little tidal exchange, it is shallow (<lm) and subject to considerable heating in summer. Under these conditions, resuspension of nutrients from the sediments is to be anticipated.

The generally poor growth of macroscopic algae and low species diversity is only partly attributable to lack of solid substrates. Such algae as *Cladophora* and *Chaetomorpha*, which grow excessively in certain other estuaries (Swan, Peel, Walpole), were never abundant in the Blackwood.

In the tidal river portion of other estuaries of the south west, considerable concentrations of planktonic copepods have been found, but they were not abundant in the Blackwood estuary. This paucity of zooplankton, and the phytoplankton on which they feed, is not easy to understand. From the time the salt wedge starts to invade the tidal river, a rich growth of phytoplankton was anticipated immediately below the halocline, as has been observed in other estuaries. The two metre layer of fresh water results in great light attenuation, nevertheless Secci disc readings of 3-4m in summer suggest that there is sufficient light for photosynthesis.

Allender (unpublished data) surveyed the benthic algae in August 1966 and February 1967 and noted the predominance of green algae (9 species) and relative sparsity of brown algae (4 species) and red algae (5 species). He also found very few species upstream of the basin, particularly under winter conditions. He commented that, "compared with other estuarine floras of south western Australia the flora is very depauperate" and attributed this both "to the very short saline phase of the estuarine waters ... and to the absence of rock and other solid substrates for attachment."

Sediments

The surface sediments are colonised by a diversity of diatoms, flagellates, and blue green algae. Diatoms photosynthesise under low light intensities and are able to migrate vertically through the top few millimetres to maintain optimum light levels. They are very abundant, highly productive, and with flagellates are an important source of food for benthic fauna. No quantitative studies have been made of this part of the flora. Some species of blue green algae fix atmospheric nitrogen and thus add to the input of this plant nutrients. Table 4.1 shows nutrient levels in the sediments. Nutrients of the surface sediments are also recorded by Rochford and Spencer (1953, 1955, 1956).

Diffusion through sediments is slow, particularly through such tight-packed, poorly sorted sediments as are present in the basin. No study was made of this aspect, but salinities of 5-8‰ were found at 5-10 cm depth in sediments after they had been overlain by freshwater (about 1‰) for about three months showing that the interstitial osmotic regime can be very different from that of the overlying water.

Aquatic Vascular Plants

Unlike algae, vascular plants are not dependent on nutrients in the water and can use the richer supply present in the sediments by means of their roots, in the same way as terrestrial plants.

Four species of "sea grasses" are present in the estuary, their distribution reflecting hydrological conditions. *Zostera mucronata* is confined to the lower part of the inlet, where low salinities are only experienced for a brief period. The freshwater species *Potamogeton pectinatus* extends downstream almost to the basin in spring when it is abundant at Molloy Island (Station 95, 0.9 kg/m^2, Bray), but disappears with the advance of brackish water, being intolerant of salinities in excess of 8‰. Between these two species, and overlapping them, *Ruppia maritima* is dominant in the inlet, basin, and in marginal shallows of the tidal river in summer; it is also the dominant species in the Deadwater and Swan Lake. A fourth species, *Lepilaena cylindrocarpa*, occurs sparsely in the basin.

Table 4.1—Examples of chemical analyses of surface sediments in shallow water (August, 1974)

Locality	Interstitial phosphorus (μg/g d.wt.)	Adsorbed phosphorus (μg/g d.wt.)	Total phosphorus (μg/g d.wt.)	Organic nitrogen (mg/g d.wt.)	Loss on ignition (% d.wt.)	Description of plant Community
Swan Lake	118.3	3.3	1280.8	3.77	19.57	Dense *Ruppia*; grey coarse sediment.
North of Thomas Is.	69.1	0.5	577.5	1.96	1.86	Scattered *Ruppia*; coarse sediments—oxidized yellow over black.
Stn. 95	28.6	11.7	144.4	2.09	3.21	*Potamogeton* and *Lamprothamnium*; moderately coarse sediment.
Scott Basin	12.6	1.5	56.9	1.41	9.07	*Ruppia*; fine black gelatinous sediment.

Ruppia is a remarkably euryhaline species and has been found to grow in salinities of from 0.2 to over 70‰ in estuaries and inland saline waters. It has fine, rather delicate foliage and grows best where there is little flow. In the Blackwood, it was densest (0.3 kg/m^2) in the relatively stagnant conditions of Swan Lake and Deadwater where it was abundant throughout the year. It was less dense in the basin and, with senescence and water turbulence in summer, the foliage was broken off and washed up on the shores.

Seasonal changes in standing crop of *Ruppia,* and also of *Potamogeton,* are partly, perhaps largely, attributable to black swans which at times devastate extensive areas by eating the foliage and rooting up the rhizomes. Cattle have also been seen grazing *Ruppia* in the Deadwater. It is unlikely that fish herbivores play a significant role in the plant economy.

Although *Ruppia* flowers freely in the estuary, no seedlings have been found and regeneration is from persistent rhizomes. This regrowth took place in late winter and early spring when the river was still flowing. At this time secchi disc readings were about 1 m, indicating penetration to this level of about 5% of surface light. This is probably the minimum for survival of the plant.

Experiments were made in enclosures, covered with several grades of Sarlon cloth, to determine the long term effect of reduced light on plant growth. Even a 50% reduction in light intensity, as compared with control enclosures, was sufficient to effect a considerable reduction in standing crop when continued for a period of 164 days. The limitation of *Ruppia* to about one metre depth is thought therefore to be because of poor light penetration beyond that depth, especially during the growing period. Higginson (1966) found *Ruppia* growing to a depth of 2.4 m in Tuggerah Lakes (N.S.W.)

The rhizomes are only in the surface sediments (to 2 cm), but the roots penetrate to the black anoxic layer where nutrient levels are high (Table 4.2) and from where they draw much of their nutrient requirements. Higginson (1966) states that *Ruppia* favours soils with a high clay content (42%), similar to those of the Blackwood estuary. In the hypersaline conditions of the Coorong (South Australia), tubers develop on the rhizomes (Delroy, 1974), but no tuber formation was observed in the Blackwood estuary.

Ruppia and *Zostera* commonly acquire a covering of epiphytic diatoms and other algae which, unlike planktonic forms are not dependent solely on nutrients in the water body. There is evidence that they obtain an important part of their nutrients from the plants to which they are attached. Some also fix atmospheric nitrogen. The epiphyte load varies greatly, possibly partly in relation to grazing by the invertebrate fauna, and this is likely to have a shading effect that influences photosynthesis by the host plant. No separate study of the epiphytes has been made.

Before leaving the sea grasses it is relevant to note that, although *Ruppia* was present in the Swan estuary (Royce, 1955), it is now rare there. Also that *Halophila* which is common in Leschenault Inlet and was abundant in parts of the Swan until recently, was absent from the Blackwood in the present survey although Allender (Tech. Rep. 3) reported its presence there in 1966.

Solid Substrates

Living and dead timber and rocks in the water provide attachment for algal growth and for mussels and shelter for some mobile animals. However, they are not abundant in the lower estuary and do not contribute greatly to the ecosystem.

Table 4.2—Chemical analyses of sediments at three depths below sediment surface (Molloy Basin, May 1975).

	Depth (cm) 0-30	30-60	60-90
	(μg/g dry weight)		
Interstitial P	65	83	111
Adsorbed P	41	91	191
Total P	565	356	697
Organic N	262	268	122
Loss on ignition	2.2%	2.2%	2.4%

Marginal Swamps

The marginal vegetation plays a number of important roles in the estuarine ecosystem. It traps sediments and stabilises the shoreline.

It is an important habitat and feeding ground for some bird species, for a few semi-aquatic invertebrate species, and when flooded, for some more mobile animals such as shrimp and small fish. Although unimportant as a direct food source for the estuarine fauna, the marsh plants are probably the main contributors to the detritus and the decaying plants build up the sediment nutrient load.

In the Blackwood estuary marginal swamps, areas subject to periodic innundation, form about 10% of the area of the lower estuary and border a considerable part of it (Fig. 3.2). They are subjected to prolonged innundation in winter and may dry for long periods in summer. Although plant biomass is large, these conditions do not favour great variety and abundance of fauna.

A series of fringing plant species was identified along the length of the estuary with the less salt tolerant species only occurring upstream of Alexandra Bridge (Tech. Rep. 3, Table 6). The salt tolerant rush *Juncus krausii* and sedge *Baumea juncea* occur along the whole length of the estuary, with species such as *Lepidosperma tetraquetrum, L. effusum, Cyperus* sp., and *Anigozanthos flavidus* confined to the upper reaches.

A characteristic shore zonation is seen in many places, though the detailed composition of the flora varies (Fig. 4.4). To some extent this zonation represents a plant succession: as peat accumulates in fringing *Juncus* marsh, the salt tolerant paperbark, *Melaleuca cuticularis,* becomes established and itself builds up more peat; further from the water's edge this may be replaced by less salt tolerant species, *M. hamulosa* and *M. raphiophylla*; as ground level rises these are succeeded by flooded gums, *Eucalyptus rudis,* and finally by jarrah-marri forest on higher ground. This zonation is related not only to salinity gradient, but to soil water content, pH, and dissolved oxygen.

Juncus forms a dense intertidal margin to much of the inlet and basin, a margin that is flooded at high water and in some places reaches to the water's edge at low water. In places it is eroding, e.g. along the west side of North Bay, where the shore has been washed away and bulky rhizome masses are exposed to wave action, but in other places the *Juncus* margin is prograding into the water and sediment is being trapped. Areas of prograding marsh appear to predominate in the basin region, particularly along the northern shoreline, but there is no objective measure of the net result for the estuary as a whole. Air photos suggest that small rush islets in the delta region have about doubled in area between 1955 and 1973; an

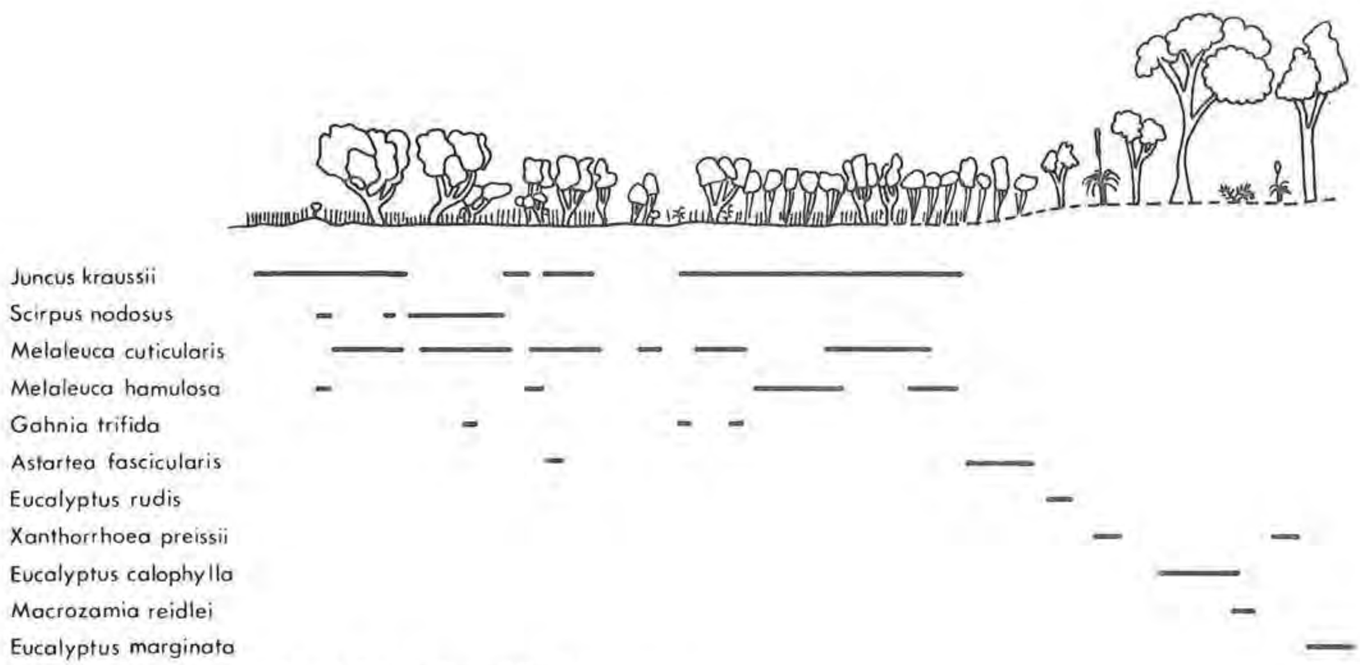


Fig. 4.4 Vegetation profile of the Blackwood River estuary.

estimated lateral advance of about 2 m. At Point Pedder the extensive *Juncus, Melaleuca,* and *Salicornia* swamps, appear to be of relatively recent development. On the other hand, the wide *Juncus* beds in the vicinity of Molloy Island may have retreated, because cores from the adjacent shallows show sediments of marsh origin. There are places in this lowest part of the tidal river where the *Juncus* fringe is replaced by paperbark trees that are falling into the water and the bank appears to be eroding. Swan Lake is entirely bounded by rushes but they are sparse in the Deadwater, except at its eatern end.

Active invasion by *Juncus* into shallow water is principally by rhizomes from which shoots grow up. Mobile sand is trapped by rushes and a ridge develops behind which a swamp can form that favours either *Salicornia* or *Melaleuca* rather than *Juncus*. In places the ridges have built up sufficiently for *Zamia, Xanthorrhoea*, and *Agonis* to be established.

Juncus seeds will develop in water of salinity up to 7‰ and seedlings have become established in sheltered situations, as at Point Pedder.

The live biomass of *Juncus* in a sand ridge was estimated to be 2.37 kg/m^2, with another 2.48 kg/m^2 dead material. This figure is considerably greater than that for the highly productive *Spartina* salt marshes of the east coast of U.S.A. (Nixon and Oviatt, 1973). With senescence of above ground parts of the plants, the nutrients released are translocated back into the rhizomes, but much of the above-ground dead material is available as a source of detritus to the estuary as well as peat to the shore. The living plants themselves do not seem to be eaten. Absolute quantities of phosphorus and nitrogen in the *Juncus* are much greater than in any other plant community (Table 4.3) but

Table 4.3—Phosphorus and nitrogen in plant material, calculated on a per area basis.

	P (g/m^2)	N (g/m^2)
Ruppia	6.1×10^{-1}	4.0
Chara	3.9	3.3
Zostera	0.2	0.2
Juncus	15.1	31.2

there is as yet no measure of turnover rates. The marshes must be regarded as the most productive part of the estuarine ecosystem.

4.6 Zooplankton

There is very little zooplankton in the fresh water of any south west estuary. However, there are often dense populations of copepod crustaceans in marine and brackish water, whether near the surface or below the halocline.

Although no regular sampling programme was undertaken as part of the present study, hauls were made from time to time with a 200 μm and 140 μm mesh net during 1971 to 1974. From these it is clear that zooplankton is sparse in the Blackwood estuary relative to that found in other estuaries of the south west, except sometimes in the Deadwater. Species diversity is similar to that in these estuaries, with four species of copepod Crustacea being dominant (Table 4.4).

Gladioferens imparipes is the commonest of these copepods. It is an extremely euryhaline estuarine species that is able to multiply over a wider range of salinity than is experienced in the estuary (Rippingale and Hodgkin, 1974). It disappears from the plankton by day and has been taken in samples of surface sediment. Although, as Rippingale showed, it readily feeds on phytoplankton it probably also feeds on benthic detrital material. Large numbers were sometimes found in fish guts (e.g. gobies, silver bream, yelloweye

Table 4.4—Fauna taken with a 140/200 μm mesh plankton net

Copepoda:	Meroplankton:
Acartia clausi	polychaete larvae
Acartia fossae	bivalve veligers
Gladioferens imparipes	gastropod veligers
Gladioferens inermis	barnacle nauplii
Halicyclops sp.	prawn larvae
Oithona nana	fish larvae
Sulcanus conflictus	
Harpacticoida indet.	chironomid larvae
Mysidacea *(Gastrosaccus* spp.)	
Sergestidae *(Lucifer* sp.)	
Amphipoda *(Melita* spp.)	
Palaemonidae *(Palaemonetes australis)*	

mullet). *Acartia clausi* and the small *Oithona nana* are cosmopolitan, euryhaline marine species which also live in sheltered marine environments such as Cockburn Sound, they are seldom common in salinities less than about 20‰ and 15‰ respectively in the Swan estuary. Both species were relatively abundant on a few occasions. *Sulcanus conflictus* is normally confined to low salinities, from 2 to 20‰, and occurs also in saline inland waters. It was abundant in pools in the middle reaches of the Blackwood River (Bridgetown to Duranillin) in salinities of 4.5 to 6.0‰. It is often abundant in other estuaries of the south west which have been studied, and may dominate the zooplankton, but it was never common in Blackwood estuary samples. Harpacticoid copepods, which are an important element in the benthic meiofauna, were also sometimes taken in considerable numbers in plankton hauls; so too were mysids, and it is clear that both are at least partly planktonic in habit, particularly at night.

In addition to the holoplanktonic fauna, the larval stages of a variety of benthic animals contribute to the meroplankton and of these polychaete larvae were probably the most abundant. Fish larvae were also taken in these hauls and in samples taken with a one mm aperture mesh net used in connection with the fish studies (4.9).

4.7 Detritus and the Smaller Benthic Fauna Detritus

Detritus, decaying organic material, is an important food source in any estuary and appears to be particularly important in the Blackwood. While initially much of the plant material is bulky, it is rapidly broken down and most detrital material has a particle size less than 100 μ.m. in diameter. Sources of detritus are: river water, bringing mainly fine particulate matter; sea water with bulky algal and sea grass material; coarse and fine detritus from the marginal swamps and vegetation; benthic plants (mainly *Ruppia*) and their epiphytes; plankton, both plant and animal. No attempt has been made to estimate the relative importance of these sources in the estuary or the considerable loss to the sea with river flow and tidal exchange.

Some of this detritus is used by the zooplankton (as seston) while in suspension in the water body, but most of it accumulates in the sediments, where the smaller particles are adsorbed onto the sand grains. Consequently, the finer the sediment the greater the organic detrital content tends to be, although some fine, poorly sorted, sediments have little porosity and little detritus. It is clear from the high levels of organic content observed at a depth of 60-90 cm (Tech. Rep. 3) that a considerable proportion of this detrital material is not used and becomes incorporated in the sediments.

Some small organisms of the microfauna, such as ciliates, are able to use plant material directly as food, but most detrital feeders rely on bacteria and fungi to convert it to a usable form. Hence the direct food value of detritus is low and turnover great. However, a number of detrital feeders such as shrimp (Welsh, 1975), amphipods (Fenchel, 1970), sea mullet (Odum, 1968) help to breakdown the detritus and increase the surface area accessible to bacteria for further decomposition. Ultimately much of it accumulates as faecal material, generally as discrete pellets, which in their turn are invaded by bacteria, nitrogen levels rise, and the pellets are reused repeatedly, as shown by Newell (1965) in the case of the small gastropod mollusc *Hydrobia ulvae* and by the shrimp *Palaemonetes pugio*, (Welsh, 1975).

Microbiota and Meiofauna

The abundant micro and meiofauna (animals which pass a 1 mm aperture sieve) include algae eaters, detritus feeders, and predators on them. However it is not clear just how important they are in the direct food chain to higher animals, because many of the macrofauna (animals retained by a 1 mm sieve) themselves use detritus as a food source.

The complex food web of estuarine sediments is still not well understood, though there have been considerable advances in recent years (e.g. Fenchel, 1970; Marshall, 1970; Odum and Cruz, 1967).

A comprehensive study of microbiota and meiofauna was beyond the scope of the present investigation. Examination of a few samples showed a great diversity of diatoms, flagellate protozoans, bacteria, spirochaetes, nematodes, harpacticoid copepods, and immature stages of macrobenthos. Ostracods (Crustacea) were found to be extremely abundant in Swan Lake, where they formed a major component of the sediment (Quilty, 1977). They were rare in basin, delta, and tidal river samples and virtually absent under the more marine conditions of Seine Bay and the Deadwater. McKenzie (1962) recorded 40 species from Oyster Harbour (Albany) but there is unlikely to be anything approaching this species diversity in the Blackwood estuary.

Fenchel (1969) found only very small numbers of micro and meiofauna in sands with median grain size less than about 95 μ.m., and only 2-4% clay and silt totally excluded the presence of interstitial animals. He found that this fauna is largely confined to the oxygenated surface layer with an abrupt cut off at the redox discontinuity layer. There was little extension downwards except in relation to large, deep-burrowing animals.

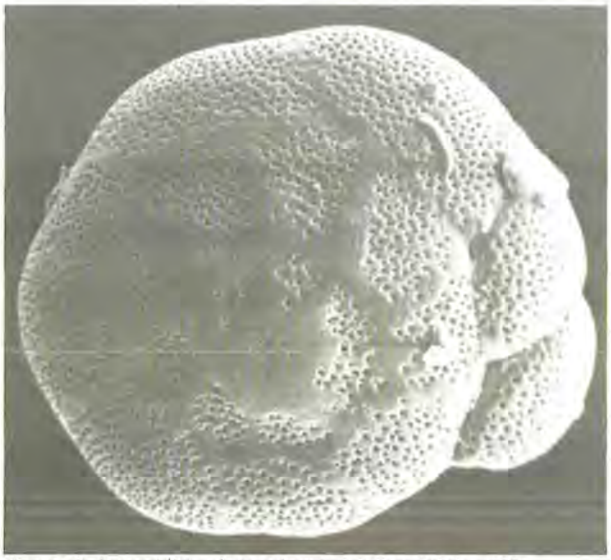
Foraminifera

These skeleton forming protozoans were studied by Dr. P. Quilty (1977) who took sediment samples from 18 sites in the lower estuary on 29 June 1974, following a brief period during which the whole estuary had been fresh, except near the mouth, in the Deadwater, and probably also Swan Lake. Foraminifera are predominantly marine and it is not surprising to find a richer, completely different, suite of species at the marine end from that where exposure to fresh water is

Elphidium macellum (from the Swan River estuary).

more prolonged. Samples taken in the inlet (5.5 m depth at Point Irwin and 1 m at Seine Bay) and in the Deadwater each had 20 or more calcareous species, many of which were also present in an ocean beach sample. Samples from the tidal river and basin only had 2 to 7 species, with a predominance of arenaceous species, the shells of which are built from fine, non-calcareous sand grains. Only a shallow water (1 m) sample from Point Irwin and one from the east end of Swan Lake showed a mixture of marine and euryhaline faunas.

Quilty lists a total of 72 species from within the estuary. McKenzie (1962) found 134 species in the more marine environment of Oyster Harbour.

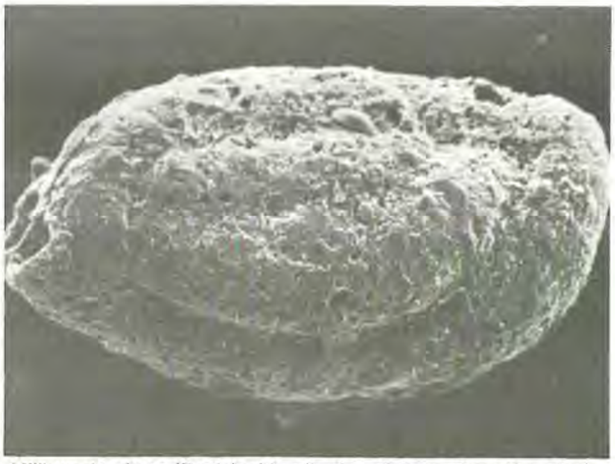


Ammonia beccari (Linne) dorsal surface. From Station 130.

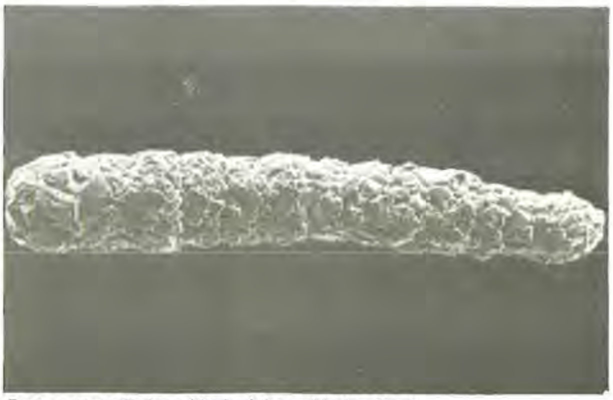
Ammobaculites agglutinans (d'Orbigny) from Island Point.

4.8 Resident Aquatic Macrofauna

It is proposed to consider here those macroscopic aquatic animals which have self-maintaining populations in the estuary; these are animals which can complete all stages of their life cycle in estuaries. In this, they differ from the migratory component of the fauna, estuarine populations of which are not self-maintaining and which, for physiological or behavioural reasons, are normally recruited from marine populations outside the estuary. They include both the euryhaline marine component and the estuarine component of Day (1951). A few of the less euryhaline marine species only establish populations in this estuary during the saline phase. However, they will be considered here with the rest of the benthic fauna. At the other end of the salinity scale there are a few representatives of a fresh-water component.



Milliammina fusca (Brady) with adhering diatoms. From Point Irwin.



Protoschista findens (Parker) from Molloy Basin.

Photographs of Foraminifera supplied by Dr. P. Quilty.

The following comments derive mainly from material presented in Technical Report 4: Macrobenthic Invertebrate Fauna of the Blackwood River Estuary, and where appropriate from Technical Report 6: Aspects of the Ecology of Fish and Commercial Crustaceans of the Blackwood River Estuary, Western Australia.

Sampling

The sampling programme aimed to identify the species present in the estuary, to identify their preferred habitats, to plot their distribution along the estuary, and to measure their abundance at different times of the year. For the sedentary fauna, it was possible to obtain reasonable estimates of their absolute abundance, but for more mobile fauna, especially the fish, estimates are only of relative abundance. The programme aimed to measure standing crop, not productivity, and to determine which are the dominant species. Also, as far as possible in a one year study, it attempted to understand how the fauna responds to the changing environmental conditions.

Sampling for both fish and benthos was undertaken every two months, from May 1974 to May 1975 inclusive, sampling sites being chosen to represent both different habitat types and distances along the length of the estuary and hence exposure to different salinity regimes (Fig. 4.5). This was a necessary compromise in order to keep the two programmes in step. In retrospect, one judges that the benthic sampling would have been more informative if it had been less extensive and more frequent, but the relative uniformity of faunal distribution was not foreseen when planning.

Sampling techniques are described in detail by Technical Reports 4 and 6. The benthic fauna was sampled with a simple coring device (surface area

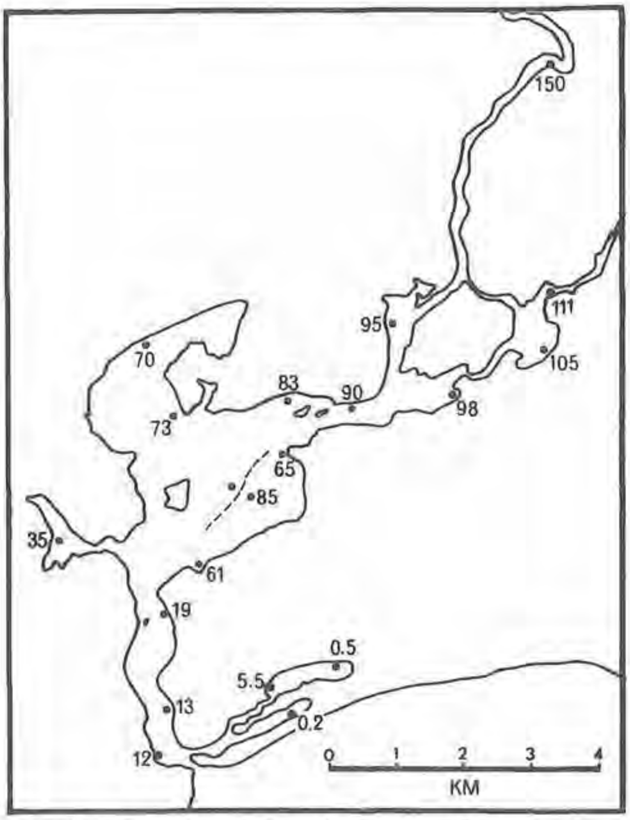


Fig. 4.5 Samping stations for the benthic fauna.

80 cm², depth 18 cm) and the sediment core was sieved through a one millimetre sieve on site. A shovel was used to sample the larger molluscs. These techniques gave reasonably accurate estimates of numbers of sediment in-fauna and of weed fauna, without distinguishing between them, but less satisfactory data for more mobile animals, such as shrimp, and for animals attached to solid substrates. A few common species, such as chironomids and corophid amphipods, often occur in dense localised patches and are absent or rare in adjacent areas, thus making sampling unreliable. A similar, but less extreme, non-random distribution is true of many species and adds to the difficulty of interpreting population data; the worm *Capitella* is one such species. Repetitive sampling at a single site still showed great variation. Examination of the contents of fish guts served the dual purpose of giving information about the kind of food eaten by the various species of fish and also as a check on the benthic sampling.

Fish sampling was by means of seine nets, set nets, and occasionally with trawls. The sampling methods are described more fully in section 4.9.

Composition of the fauna

In the benthic sampling programme 55 species of invertebrates were taken (Tech. Rep. 4, Appendix I). They were distributed among the following taxa as shown:

	Species found	Resident species
Nemertea	1	0
Polychaeta	13	8
Mollusca, Bivalvia	8	8
Mollusca, Gastropoda	12	10
Crustacea	17	12
Insecta	4	4
	55	42

The "resident species" are those which are believed to have self-maintaining populations in the estuary. Of them, seven species compose over 90 per cent. of the estuarine population: three worms—*Capitella, Scoloplos, Ceratonereis*; two bivalves—*Arthritica, Anticorbula*; two snails—*Potamopyrgus, Hydrococcus*. A further six species are common and form an important part of the benthic fauna: the large bivalves *Katelysia, Sanguinolaria*; the amphipods *Melita, Paracorophium*; the shrimp *Palaemonetes;* and larvae of the midge *Pontomyia*.

Table 4.5 shows the results of quantitative sampling for a number of species at six sites in the estuary, in summer and winter. Of these sites, Station 02 (Deadwater) had the longest saline phase and highest salinities and Stations 150 and 111 (Scott River) had the longest fresh phase and lowest salinities. As was to be expected, the greatest number of species was found at the marine end and decreased upstream. Also it will be noted that in the upstream parts the number of species was less during the fresh phase than during the marine phase.

On the basis of this data the 21 commoner species may be grouped according to their distribution in the estuary, as shown in Table 4.6. This represents an ecological grouping which shows population response to this estuarine situation. However, as discussed above, this does not necessarily represent the physiological potential of the species, or for that matter the expected distribution in other estuaries.

Species belonging to Group 3 were confined to the marine end of the estuary in winter, but some were able to extend their range into the basin during the saline phase. The response of these to the hydrological conditions is exemplified by *Sanguinolaria* (Tech. Rep. 4, Fig. 12) and *Katelysia*. Growth rings on the shell of *Katelysia* record its age; most large shells show three years' growth (the oldest found was 5 years) and these were common in the inlet at Stns 12 and 13 and in the Deadwater. Juvenile *Katelysia* appeared in the delta sands (Station 73) in March 1975 and by May had grown to about 10 mm. They survived some weeks of exposure to freshwater, but eventually died. Thus, although larvae settling from the plankton colonised the basin sediments and grew during the saline phase, they did not survive prolonged exposure to freshwater. No 1⁺ shells have been found here. It would be valuable to know just what are the physiological limits of the species. Both species are subject to heavy predation by amateur fishermen collecting bait, especially in Seine Bay, and it is impossible to know how far the observed population represents their environmental potential. This also explains the anomalous presence of these bivalves in stomachs of black bream taken at Alexandra Bridge.

The bulk of the benthic fauna belong to Group 2: animals which were present throughout the area surveyed (downstream of Stn. 150). Most of them were abundant as far as Molloy Island, but were less so in the tidal river which in any case has restricted suitable habitats. It is also noticeable that they were less abundant during the fresh phase than during the saline phase and this may be related to the fact that all (with the exception of *Palaemonetes*) are small animals with several generations during the year.

The nature of the response of these animals to prolonged exposure to freshwater requires investigation, but some surmises are warranted and relevant here. The worms burrow deep into the sediments and may thus isolate themselves from the overlying fresh water. Sediment samples taken in the basin at the end of September 1975, after at least three months of fresh

TABLE 4.5—Relative abundance of common species of benthic animals at six sampling stations under "winter" (W) low salinity (July, September, November 1974) and "summer" (S) high salinity (January, March, May 1975) conditions. Numbers per square metre.

Station No.	02		13		61		85		90		111		150	
Season Salinity: approx range	W	S	W	S	W	S	W	S	W	S	W	S	W	S
POLYCHAETA														
Capitella capitata	4 619	7 595	351	1 262	196	2 113	114	576	1 227	2 782	188	2 325	76	300
Scoloplos simplex	300	560	214	1 357	500	1 595	511	566	261	886	83	125	80	204
Armandia sp.	0	508	0	309	0	351	0	200	0	47	0	2	0	0
Prionospio sp. A.	0	0	0	12	0	19	0	648	1	232	0	3	0	0
Ceratonereis erythraeensis	1 719	3 613	625	839	970	3 750	1 867	3 531	1 324	5 304	278	583	378	818
MOLLUSCA: BIVALVIA														
Anticorbula amara	0	0	0	0	42	12	146	212	222	527	271	125	725	176
Arthritica helmsii	2 106	2 293	554	1 262	3 274	4 905	3 515	4 667	534	891	958	1 150	203	138
Katelysia scalarina	42	26	21	104	0	3	0	12	0	0	0	0	0	0
Sanguinolaria biradiata	172	247	25	21	0	49	0	0	0	0	0	0	0	0
MOLLUSCA: GASTROPODA														
Potamopyrgus sp. (est.)	83	0	0	0	280	155	197	219	580	418	1 465	608	76	196
Hydrococcus graniformis	2 244	2 672	2 446	2 863	428	1 268	0	0	0	0	0	0	0	0
CRUSTACEA														
Paracorophium sp.	6	57	36	577	13	65	0	74	6	49	35	12	56	118
Melita zeylanica	8	187	30	589	1	12	0	7	6	43	24	2	+	+
INSECTA: CHIRONOMIDAE														
Pontomyia natans	470	2 400	738	393	60	171	26	65	102	0	108	18	508	5
Chironomus australis	0	0	0	0	0	0	0	0					850	10

water, showed salinities of 5-8 per cent. at 5-10 cm in the sediment, probably adequate for survival of the worms; this is of course an anoxic situation, but like other animals in such places they have haemoglobin in the blood.

It would be valuable to know just how the remarkable little bivalve *Arthritica* manages to perform so successfully. Of the arthropods the Chironomid *Pontomyia* and the amphipods and isopods can be assumed to osmoregulate and *Palaemonetes* certainly does so (Section 4.13).

Group 1 includes three molluscs, the two mussels *Xenostrobus* and *Anticorbula* and the hydrobiid gastropod *Potamopyrgus*. It is unlikely that their exclusion from the more marine part of the estuary can be explained in terms of salinity tolerance, both bivalves are known to tolerate sea water salinity. The response of *Xenostrobus* to a salinity of less than 4‰ is to close the valves and to remain thus until higher salinities return (Wilson, 1969). *Anticorbula* remains active at even lower salinities.

No surveys were made in the uppermost part of the estuary, above Alexandra Bridge, where surface water is fresh for most of the year. Consequently the small freshwater component of the fauna was not well represented in the sampling. Some species, such as *Chironomus* (midge) larvae, are residents while others such as the cladocerans taken in fish guts probably only enter with river runoff. The catfish, *Tandanus bostocki*, is also a freshwater species which entered with river runoff.

Seven species of fish appear to be resident in the estuary: *Gambusia affinis, Mylio butcheri, Atherinosoma* (2 spp.), and three gobies *F. tamarensis, A. bifrenatus, L. olorum*. With the exception of the introduced *Gambusia*, these can be regarded as true estuarine species even though, as shown by Mutton (1973), the goby *L. olorum* and a hardyhead also occur in inland brackish waters. They are clearly all very euryhaline species with the ability to live for prolonged periods in salinities ranging from 1 to 40‰ at least. In addition, the goby *F. lateralis* and the catfish *C. macrocepahalus* may be resident, although they also live in marine embayments but it is uncertain whether they live continuously and breed in this estuary. The catfish at least probably breeds in other estuaries of the south west and completes its development there (Kowarsky, 1975).

TABLE 4.6—Ecological grouping of the principal benthic invertebrate fauna.

Group 1. Species confined to the tidal river and basin:	
Xenostrobus securis	(Mollusca, Pelcypoda)
Anticorbula amara	(Mollusca, Pelcypoda)
Potamopyrgus sp. (estuarine)*	(Mollusca, Gastropoda)
2. Species found throughout the estuary:	
Capitella capitata	(Polychaeta)
Scoloplos simplex	(Polychaeta)
Ceratonereis erythraeensis	(Polychaeta)
Arthritica helmsii	(Mollusca, Pelecypoda)
Melita zeylanica kauerti	(Crustacea, Amphipoda)
Corophium sp.	(Crustacea, Amphipoda)
Paracorophium sp.	(Crustacea Amphipoda)
Palaemonetes australis	(Crustacea, Palaemonidae)
Pontomyia natans	(Insecta, Chironomidae)
3. Species not found upstream of the lower basin (Stn. 61)	
Hydrococcus graniformis	(Mollusca, Gastropoda)
Tellina deltoidalis	(Mollusca, Pelecypoda)
Sanguinolaria biradiata	(Mollusca, Pelecypoda)
Katelysia scalarina	(Mollusca, Pelecypoda)
Rush fauna	
Tatea preissi	(Mollusca, Gastropoda)
Potamopyrgus sp. (fluviatile)	(Mollusca, Gastropoda)
Orchestia sp.	(Crustacea, Amphipoda)
Cyclograpsus audouinii	(Crustacea, Grapsidae)
Leptograpsodes octodentatus	(Crustacea, Grapsidae)

*and in Swan Lake

Food and Feeding Habits

There is little direct evidence as to the nature of the food eaten. However it is clear that a large proportion of the invertebrate fauna feed directly on protophytes (diatoms etc) and bacteria, even though there is selection for particle size, location of the food particles, their source, and the method of obtaining them. The two mussels, *Xenostrobus* and *Anticorbula*, the cockle *Katelysia* and the barnacle *Balanus* are suspension feeders which filter phytoplankton from the water. However, they probably also consume other small-particle organic matter thrown into suspension by water movement. Other bivalves are probably using mainly similar material, on or within the immediate surface of the sediment, and should be regarded as deposit feeders. The only bivalve which burrows to any depth is *Sanguinolaria* and it extends a long siphon to the surface.

Most of the worms must be assumed to be deposit feeders, deriving their nourishment from the bacteria and protophytes present in small particulate matter and from the meiofauna. The gastropods also, with the exception of *Nassarius*, are probably deposit feeders or browse on epiphytic algae. Of the smaller Crustacea, *Corophium* and *Paracorophium* are deposit feeders, while *Melita* and isopods feed on larger particles and break these down to obtain their nutrients from bacteria and Protophyta. The shrimp, *Palaemonetes*, is omnivorous and feeds on both animal and plant matter (Bray, 1978) and the same is probably true of prawns and crabs.

There are no true predators among the macroinvertebrate fauna; *Nassarius* is a scavenger and perhaps sometimes predatory and the same is probably true too of the polychaete *Ceratonereis*. On the other hand, it is clear that the resident fish, black bream, hardyheads, and gobies, are all predators and feed on a diversity of invertebrates depending on their availability (Tech. Rep. 5).

Habitat preferences

Five habitat types were described in section 4.3, and it was noted that these respond differently to changes in environmental conditions. The preferred habitats of all individual species are shown in Tech. Rep. 4, Appendix I. Each habitat has its characteristic faunal association, though some species are not confined exclusively to one habitat type. It is proposed here to discuss the faunal assemblages of the various habitats in relation to their structure and environmental effects on them.

The water body favours only the more mobile animals, fish and to a lesser extent shrimp. There is no evidence from gut content data that adult fish make any great use of the zooplankton as food, though it is possible that juveniles of these, as well as other fish, eat zooplankton. Sea mullet of less than 30 mm are known to do so (Odum, 1970). Blue spot goby were found to have eaten freshwater Cladocera in winter.

These mobile animals are able to select favourable habitats actively as adults. However, for most of the benthic fauna site selection is by larvae settling from the plankton with little subsequent movement.

The sediments have both the greatest biomass and greatest diversity of resident macrofauna. They range in composition from gravel in the tidal river, through relatively coarse, well-oxygenated sands, as in the shallows of the Deadwater, to the fine black mud of the bottom of the inlet and lower tidal river, or the highly organic mud of Swan Lake. However, the bulk of the sediments are a poorly sorted sand-mud mixture with relatively little pore space. These various sediments favour different faunal assemblages.

No attempt was made to sample the coarse mobile sand and gravel of the upper part of the tidal river but the macroinvertebrate fauna of this may be expected to be sparse. Higher parts of the delta, which are regularly exposed at high tide, and the bank of mobile sand opposite Seine Bay in the inlet, are almost devoid of life; they do not attract feeding birds. The black mud of deeper parts has a restricted fauna dominated by the polychaetes *Capitella* and *Ceratonereis*, other species being sparse in this situation. The organic mud of Swan Lake has, as noted above, a particularly rich meiofauna, especially Ostracoda.

Deadwater sands are well-oxygenated to a depth of 10-15 cm above the black layer; *Sanguinolaria* and *Katelysia* are particularly abundant here and in Seine Bay and it may be that the great depth of clean sand is as important as high salinity in favouring these species. *Sanguinolaria* does burrow into the anoxic layer, extending the siphon to the surface, but *Katelysia* is confined to the top 5 cm. The lugworm, *Arenicola* sp., was taken in the Deadwater, principally in the deeper parts. This deep burrowing species would not be adequately sampled by the techniques used and may have been more abundant than shown by the sampling.

Most of the sediments of the marginal platforms and delta are a muddy sand that grades to more muddy material with increasing depth of water. There is only 1-3 cm of yellow, oxygenated material above the black layer (redox potential discontinuity, RPD). The fauna of these sediments consists predominantly of the polychaetes, *Capitella, Scoloplos, Ceratonereis*) the bivalves *Arthritica, Anticorbula*; the two hydrobiid gastropods, *Hydrococcus* and *Potamopyrgus*. The arthropods *Corophium*, isopods, and *Pontomyia* are patchily abundant and because of their small size were probably underestimated. Of these animals, *Capitella* and *Scoloplos* burrow deeply below the RPD, to a depth of about 10 cm. *Ceratonereis* does so too, but is more often in the surface sediment and emerges into the water, where it is eaten by hardyhead fishes. Other species are confined to the oxygenated surface sediment and they become less abundant as the sediments become more muddy (Tech. Rep. 4, Figs. 4-8).

The bottom sediments are also inhabited by the goby *Arenigobius bifrenatus*, which constructs burrows in it and emerges to feed on the invertebrate fauna.

The submerged macrophytes, principally *Ruppia, Potamogeton*, and *Lamprothamnium*, provide shelter for shrimp (*Palaemonetes*) whose abundance seems to be directly related to the density of such plants available to them (section 4.13). They also afford shelter for large numbers of hardyheads and juvenile fish. *Ruppia*, particularly the dense beds in Swan Lake and the Deadwater, also provide attachment for great numbers of hydrobiid gastropods, which probably browse on epiphytes, and for the amphipod *Melita* and chironomid *Pontomyia*. *Potamogeton* does not seem to afford such a good habitat, perhaps because of the generally sparse growth of epiphytes.

Solid substrates, rocks, logs, and jetty piles, provide attachment for the mussels *Xenostrobus* and *Anticorbula* and the barnacle *Balanus*. The abundance of these animals in the estuary is clearly related to the limited availability of such sites. *Balanus*, for example, was only abundant on rocks of the inlet and on the piles of Alexandra Bridge, below the halocline (though they probably do not survive the fresh phase there). A variety of other animals, isopods especially, find shelter among the mussels and under small rocks, etc.

The marginal swamps were not sampled beyond the rush margin, which is flooded at high water. The small hydrobid gastropod *Tatea* is often abundant on the surface of the mud and the small crabs *Cyclograpsus* and *Leptograpsodes* are sometimes abundant under logs, etc. or burrowing in the mud. These animals are semi-terrestrial; they require continuous moisture but are out of the water most of the time. *Tatea* is seldom found in fish guts, but crabs (species undetermined) are more often eaten. Probably all provide food for wading birds. When the rushes are submerged *Palaemonetes* and hardyheads and other small fish feed among them.

Reproduction and Recruitment

As stated above, the study aimed primarily to determine standing stocks. To make an accurate assessment of recruitment from breeding within the estuary or migration from outside, it would be necessary to have a great deal more knowledge about the biology of individual species than we have now. However, some generalisations can usefully be attempted on the basis of what we know. The species under consideration are, by definition, ones which breed successfully in the estuary. Those belonging to Group 3 may also be recruited from populations outside the estuary, but we do not know which species maintain populations in the adjacent marine embayment; they have not been found in dredge sampling there.

Given favourable salinities, some species are likely to breed throughout the year and have a number of generations, even though breeding slows under winter conditions; this is probably true of the polychaetes.

The population data indicates that effective recruitment is principally during the saline phase. The bivalve *Arthritica* may be more successful in this respect because the large eggs hatch to veliger larvae which are retained in the mantle cavity until they are miniature, shelled juveniles. Such juveniles were found in July, but again population data indicates that recruitment is mainly during spring and summer.

Other species are known to breed at particular periods of the year and have only one or two generations. This applies to *Xenostrobus* and it is likely that the prolonged fresh phase results in it taking two years to reach maturity in most of the Blackwood estuary, with recruitment in early summer. *Nassarius* also takes a minimum of one year to reach maturity, and more commonly two years because of the prolonged fresh phase (Smith, 1975). On the other hand, *Palaemonetes* with its ability to osmoregulate efficiently, is able to breed successfully through spring and summer; nevertheless there is only one effective generation a year (Bray, 1978). Observed settlement of the three large bivalves *Katelysia, Sanguinolaria,* and *Tellina* suggests that they also have a restricted breeding period in summer, with settlement taking place in January or February. Marine populations may mature earlier, but there is no evidence that they contribute signigicantly to the estuarine population.

The gobies and hardyheads are well adapted to breeding in estuaries. They produce relatively few, large eggs which are attached to plants by stalks (hardyheads) or under rocks, etc. on the bottom or perhaps in nests (gobies). It is not known when *A. bifrenatus* breeds, but the other three species of goby all had developed eggs from September and gobiid eggs and larvae were collected during the period September to December. Hardyheads were found in spawning condition in September and larvae were taken both in summer (December to March) and in September (in a salinity of about 10‰).

Barnacles, *Balanus* sp., on post of Turner's jetty.

No juveniles of black bream (*Mylio butcheri*) were caught during the survey and it is not known where breeding takes place, but this is thought to be in the tidal river.

Population Density and Biomass

Population density data is shown in Table 4.5 and in more detail in Tables and Figures in Technical Report 4.

With the exception of a few species, such as *Hydrococcus,* population densities proved to be more uniform both along the length of the traverses and in different parts of the lower estuary than had been anticipated. Densities were considerably lower in the upper estuary.

No attempt was made to estimate biomass. Allowing for size, it is obvious that the bivalves *Katelysia, Sanguinolaria* and *Tellina,* and the shrimp *Palaemonetes* form a much greater part of the estuarine biomass than is indicated by population figures.

Conclusions

It is evident that despite the extreme hydrological conditions in the Blackwood estuary, there is a successful fauna of resident species. Such species form the majority of the invertebrate macrofauna, with only a small contribution of stenohaline marine animals, animals which are a negligible part of the biomass. The reverse is of course true of the fishes. There are only five or six resident species, which is a relatively small component of the estuarine fish fauna, but they are nevertheless abundant and are an important part of the estuarine biomass.

As noted above, 42 invertebrate species are regarded as being 'resident', in that they are believed to have self-maintaining populations in the estuary. Some 13 are considered to be 'common' and only 7 make up over 90% of the biomass.

It is clear that the small number of species present in the estuary is primarily attributable to hydrological conditions which prevent all but the more euryhaline species from maintaining populations there.

The lower estuary is the richest both in population density and number of species. This again is partly due to the more restricted availability of suitable shallow water habitats in the upper estuary, but also to less favourable hydrological conditions there. This is evidenced by the decrease in number of species away from the mouth and Deadwater, even within the lower estuary, and by seasonal mortalities among less euryhaline species towards their upstream limits.

A number of species which are common in the estuaries of the south west were notably absent from the Blackwood or present only in small numbers. The tube worm *Mercierella enigmatica*, is common on rocks and piles in most estuaries but is sparse in the Blackwood. The small bivalve *Spisula trigonella* is abundant in several estuaries, but only two live specimens were taken in the Blackwood. The small crab *Halicarcinus australis* is abundant in other estuaries, even in the tidal rivers, but was not found here either in the samples or in fish guts although another less euryhaline species, *H. ovatus*, was found in the inlet region. Winter salinities are clearly unfavourable to *Mytilus edulis planulatus*, the edible mussel, which is present in several other estuaries. The common estuarine jellyfishes *Aurelia aurita* and *Phyllorhiza punctata* were not recorded here. Only small numbers of the cobbler fish, *Cnidoglanis macrocephalus*, were caught. It is a common species in other estuaries and probably breeds in them (Kowarsky, 1975).

The quantitative surveys represent standing crops only, the net result of environmentally caused mortality, predation pressure, and recruitment. Mortality resulting from exposure to low salinity in winter was only observed in the case of *Katelysia*, at its upstream limit. Other species may be affected in the same way, but there are no data. Predation pressure is likely to be greatest on all species during the saline phase, but this is more than compensated for by recruitment which also takes place mainly under saline conditions. Hence the greater "summer" populations shown in Table 4.5. The very euryhaline *Palaemonetes* breeds through spring and summer, irrespective of the salinity of the water, but none of the other estuarine species are known to do so.

It is evident therefore, that estuarine production will vary considerably according to the relative duration of fresh and saline phases. There will be both spatial and temporal differences, along the length of the estuary and between years of greater and lesser river runoff. The year of the study, 1974, had an above average runoff, but it is not clear whether the freshwater phase was more prolonged than usual in shallow water.

Finally, it should be stressed that the resident invertebrate fauna are predominantly suspension-feeders and deposit-feeders. The former feed on seston, suspended organic (living and non-living) particles and inorganic detritus, and the latter on detritus and a diversity of small organisms within the sediment, including the bacterial flora involved in decomposition of the detrital material. The important part played by some species in the physical breakdown of detrital plant material has been noted, as has the fact that their faecal pellets are an important component of the organic mud of the sediments. Deposit feeders rework many times their own volume of sediment in a year and in doing so change grain size and interstitial space, produce a deeply oxidised surface layer, and help to maintain surface stability (Rhoads, 1974).

4.9 Non-resident Aquatic Macrofauna

The distinction made here between resident, or true estuarine, and non-resident species of fish, is somewhat subjective in the present state of knowledge. However, it is used in order to emphasise the ecological approach adopted in this report to distinguish between species which are recruited from breeding populations within the estuary and those recruited from outside. Where appropriate, resident as well as non-resident species are discussed in this section. The large commercial crustaceans, two species of crab and a prawn, are also considered here. The crab populations are recruited from the sea, but it is not known whether the prawn breeds in the estuary.

These non-resident species are all animals which also live in marine embayments and may migrate considerable distances along the coast. Although they are able to osmoregulate and maintain a more or less constant internal environment, equivalent to a salinity of about 10 to 15‰, this does not mean that they are necessarily able to live successfully at salinities much below that of sea water.

There are specific differences in their ability to do so, some species being much better able to live at low salinities than are others. The mechanisms by which fish osmoregulate are complex and still not well understood and there is no experimental evidence as to the response of most of our local species to reduced salinity. Hence the basis on which they have been grouped here according to ability to tolerate reduced salinity, is almost entirely observational. In any case this may be the most useful criterion because, even though a fish may not be able to withstand prolonged exposure to a particular salinity, it may well be able to make successful excursions into it for feeding or other purposes. We are concerned here with the use made by fish of the estuarine environment rather than with their physiological potential.

Other physical environmental factors which affect the way in which fish use estuaries are temperature, oxygen concentration, velocity of current flow, and turbidity, although there is little precise data as to how individual species respond. There are strong temperature gradients at times both between the sea and the estuary (Fig. 3.33) and within the estuary itself. While these may be barriers to the passage of fish, they may also be zones at which fish tend to concentrate because of the concentration of plankton in such places or for other reasons.

Most fish are intolerant of low oxygen tensions. Levels between 3 and 5 mg/l may reduce fish activity and below 2 mg/l may be fatal. The only situations in which this is likely to be limiting in the Blackwood estuary are the bottom of the tidal river during the summer stratified condition and perhaps in the winter in the Deadwater when it too is stratified (Figs. 3.35, 3.36). Considerable fish mortalities occur from time to time in the Swan estuary under stratified conditions and these have been attributed to deoxygenation (Middleton, 1955).

Fish species vary greatly in their tolerance of suspended solids. Some, especially those which feed at the mud-water interface, tolerate relatively high concentrations while others are adversely affected. The latter include species which feed on plankton, also juveniles of some species which are more tolerant as adults. Again there is little precise knowledge in respect of local species, but studies are being made by Lenanton.

Other factors influencing the use made of the estuary by the various species are food availability, in relation to the type of feeding adopted, shelter, especially in the case of juveniles, the presence of other fish, especially predators, and specific behaviour patterns. It is well to remember too that larvae, juveniles, and adults may respond differently to environmental conditions and that they have important behavioural differences. For example, the sea mullet sifts mud through the gills in order to extract bacteria but its larvae capture zooplankton (Odum, 1968).

A useful discussion of the ways in which fish use our estuaries will be found in Lenanton (1974a).

The objectives of the study were stated in section 4.2, and it need only be re-emphasised that in respect of fish and commercial Crustacea, the aim was to obtain measures of relative abundance, at different times and in different parts of the estuary, rather than to attempt to estimate absolute abundance.

The discussion which follows is derived from material reported in full in Technical Report 6: Aspects of the Ecology of Fish and Commercial Crustaceans of the Blackwood River Estuary, Western Australia.

Sampling Methods

A sampling programme was repeated every two months from March 1974 until March 1975 and again in July 1975, each field trip lasted about two weeks. On each occasion, samples were taken at the same fixed stations under as near as possible the same environmental conditions. The stations are shown in Figure 4.6. With such mobile animals it is necessary to use a variety of different sampling methods, to standardise these and evaluate the nature of the information obtained by them.

The gear used were:

Beach seine net. This is run out from the beach to enclose an area and hauled to the beach.

Set, or gill, net. Nets are paid out across a shallow area and left overnight to catch fish which become entangled in the meshes of the net.

Trawl net. A net towed from a boat over the bottom for a specific distance or time.

Plankton net. A fine mesh net towed through the water, also for a specific time.

Each gear type is necessarily selective to some extent and they complement one another. Seine nets proved the most generally useful, but they give unreliable results both for the the smallest fish which pass the mesh and the largest and most active, which are able to escape while the net is being hauled. It was principally for this reason that the seine netting was supplemented by plankton nets and set nets. Another source of loss from the net is when there is much weed in the area enclosed by the net, the foot rope rolls over the weed in which small fish are able to hide. The results of a trial to test the efficiency of the net under these conditions are recorded in Appendix 3 of Technical Report 6. While the net sampled large fish quite efficiently, it did not give an accurate measure of the number of small fish present where there was much weed. Most fish are not randomly distributed and tend to school, so that individual catches are greatly affected by the chance enclosure or exclusion of schools in hauling the seine net. The set net, on the other hand, is thought to take a reasonably balanced sample of fish moving in the area at the time, within the limitations imposed by mesh size. Some species, especially yellowfin whiting, are known to move in and out of the estuary over short periods, thus again influencing the sampling efficiency of the nets. In July 1974, one catch took a large school of this fish in the inlet while none of the other hauls took any.

In view of these sampling difficulties, the catch (numbers) per haul at the 30 sampling stations have been averaged for each of six areas of the estuary at each field trip and an 'index of relative abundance' calculated for each species. The areas are shown in Figure 4.6, they were:

1. Swan Lake.
2. Deadwater.
3. Inlet (channel), lower basin, and West Bay.
4. Basin (lagoon), a region mainly of shallow banks.
5. Molloy and Scott Basins and Scott River.
6. Tidal river.

Each of these areas appears to be reasonably homogenous and the figures calculated provide a useful basis for comparison with regard to the relative abundance of individual species in the various parts of the estuary and seasonal changes in this.

Composition of the fauna

Fifty-seven species of fish were taken in the estuary during the survey and a complete list of these will be found in Table 3 of Technical Report 6 with notes on individual species in Appendix 1 of that report. The common species are included here in Table 4.7. Lenanton (1974b) records 30 species from Hardy Inlet, some of which were not caught during 1974-75. There is thus a considerable diversity of fish species using the Blackwood estuary, probably as rich as in any south coast estuary. Although many of the species are found throughout the south west, the fauna has more in common with other estuaries of the south coast than with those of the west coast.

The fish were placed in four groups according to their ability to penetrate into estuarine waters, to use water of reduced salinity, on the evidence of their presence or absence in seine and set net catches from water of known salinity (Table 4.7):

S-M Stenohaline marine, confined to water of 30‰ to 40‰.

EI Euryhaline I, found in water from seawater to 15‰.

EII Euryhaline II, seawater to 3‰.

EIII Euryhaline III, seawater to <3‰.

This grouping is similar to that of Remane and Schlieper (1971), though with somewhat different salinity limits.

From the Table, 4.7, it will be seen that most of the 18 more abundant species which form the great bulk of the fish biomass, are assigned to the more euryhaline groups (EII and III), even though salinities in the lower estuary were within the observed range of EI and even S-M species during the saline phase. Only one stenohaline marine species, the garfish, was common. Thus it is evident that at all times the estuary is used predominantly by species with a considerable tolerance of reduced salinity; they are euryhaline marine species which can live in water of half sea water salinity.

The 23 more stenohaline species (S-M and EI) should probably be regarded as essentially marine species, which use the estuary as they would any other sheltered marine situation when salinity is favourable.

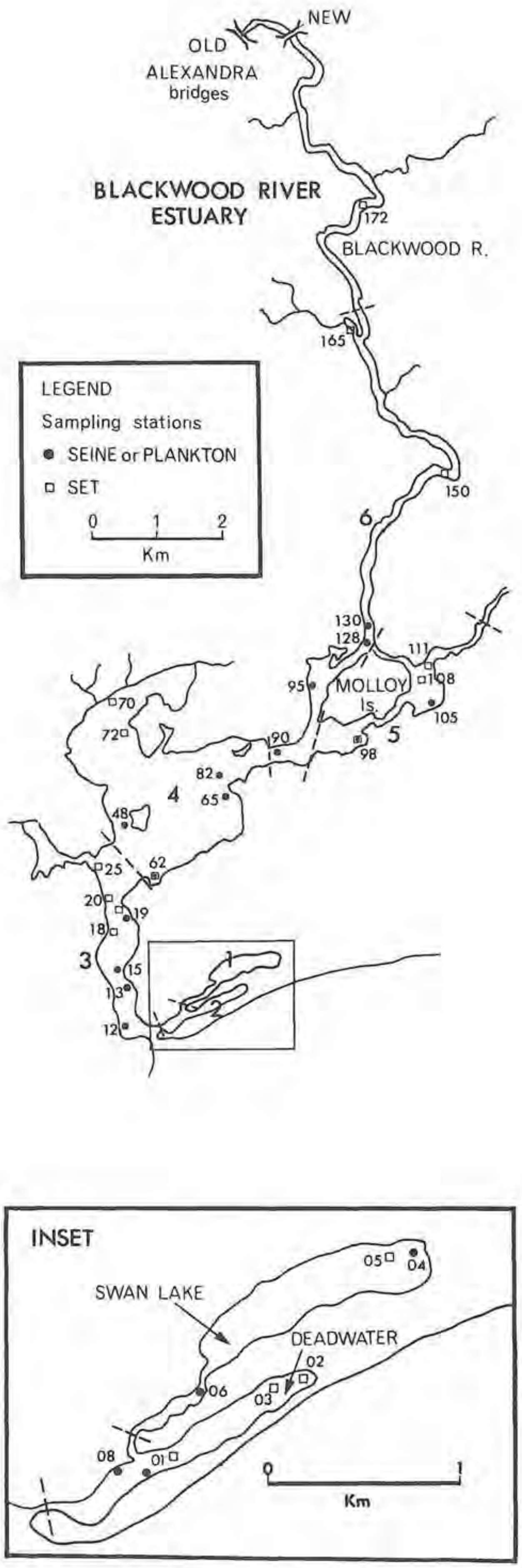


Fig. 4.6 The locations of fish sampling stations in the Blackwood River estuary.

Species taken by professional fishermen in the estuary all belong to groups EII and III although several S-M and EI species are included in catches by amateur fishermen (Tech. Rep. 8). These fish were probably caught close to the mouth.

The two crab species and the prawn were not common in catches during the survey. Blue manna crabs are reported to have been much more abundant in some previous years, and again in 1976-77. Recruitment to estuarine populations is known to vary greatly from year to year in all estuaries.

Distribution and abundance

Figure 4.7 summarises information about seasonal distribution of fish in the estuary, showing the response of the four groups of fish to changing environmental conditions. This shows only presence or absence data and must be read in conjunction with Technical Report 6, Appendix 1 which shows seasonal distribution and abundance individually for the common species.

Table 4.7—**Species of Fish Grouped According to Tolerance of Reduced Salinity**

For explanation see text. Only species with a relative abundance greater than ten in seine and set net samples are named.

RESIDENT	
Euryhaline III (EIII)	
Black bream	*Mylio butcheri*
South west goby	*Favonigobius tamerensis*
Brindled goby	*Arenigobius bifrenatus*
Blue spot goby	*Lizagobius olorum*
Hardyheads	*Atherinosoma* 2 spp.
NON-RESIDENT	
Euryhaline III (EIII)	
Yelloweye mullet	*Aldrichetta forsteri*
Sea mullet,	*Mugil cephalus*
Yellow fin whiting	*Sillago schomburgkii*
King George whiting	*Sillago punctata*
Silver bream	*Rhabdosargus sarba*
Striped perch	*Helotes sexlineatus*
Long finned goby	*Favonigobius lateralis*
Euryhaline II (EII)	
Australian herring	*Arripus georgianus*
Trevally	*Caranx georgianus*
Tailor	*Pomatomus saltator*
Banded toadfish	*Sphoeroides pleurogramma*
Australian salmon	*Arripus trutta esper.*
Cobbler	*Cnidoglanis macrocephalus*
Long snouted flounder	*Ammotretis rostratus*
Small toothed flounder	*Pseudorhombus jenynsii*
Prickly toadfish	*Contusus richei*
+ 2 other species	
Euryhaline I (EI)	
Southern sea garfish	*Hyporamphus melanochir*
Sandy sprat	*Hyperlophus vittatus*
Blue sprat	*Spratelloides robustus*
Old wife	*Enoplosus armatus*
+ 2 other species	
Stenohaline-marine (S-M)	
Flathead	*Platycephalus* sp.
Mulloway	*Sciaena antarctica*
Blue rock whiting	*Haletta semifasciata*
+ 14 other species	
EI & II	
Leatherjackets (4 species)	Balistidae

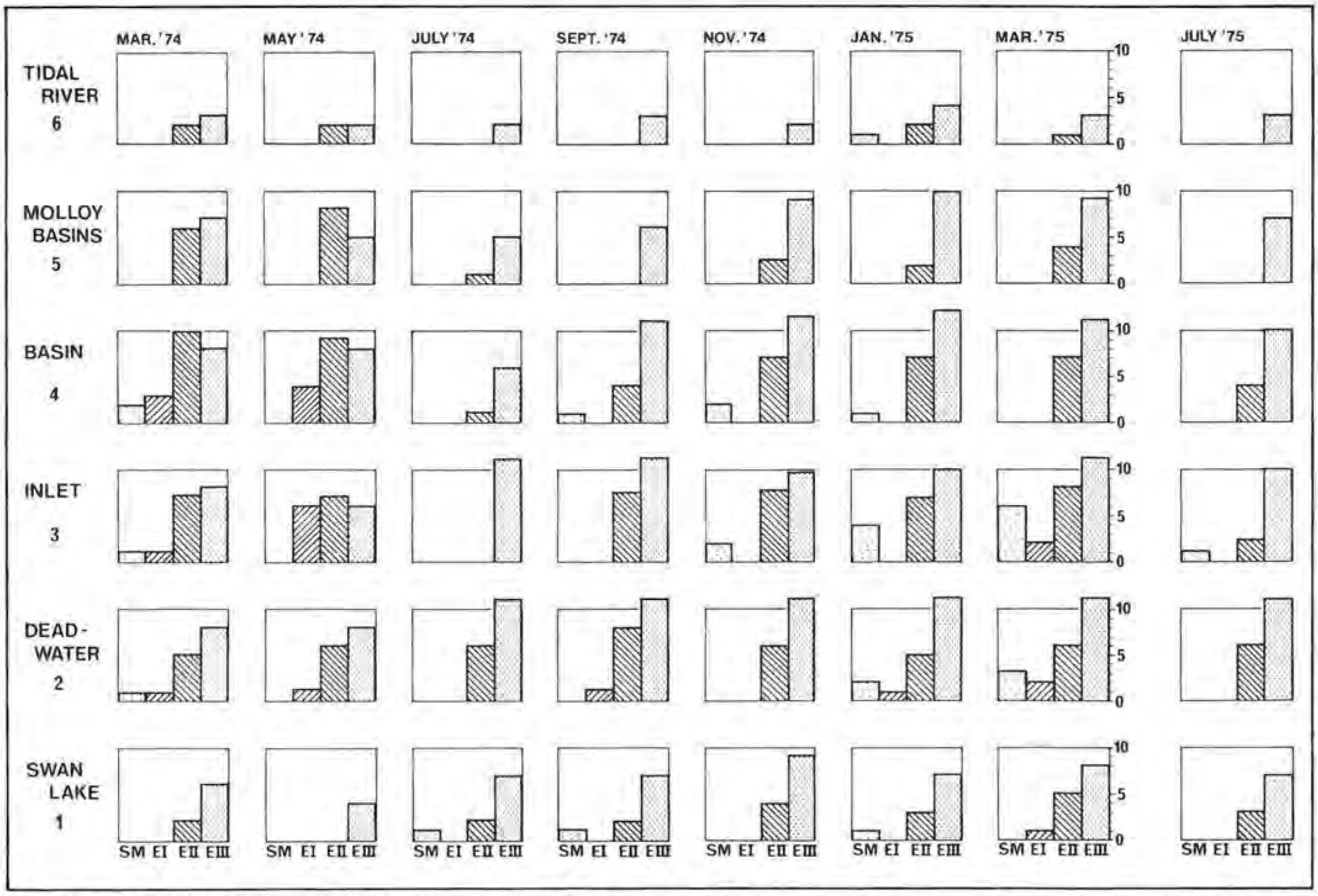


Fig. 4.7 Seasonal and topographic distribution of fish belonging to the groups: stenohaline marine and euryhaline I, II and III. For explanation see text and Table 4.7.

Black bream, a true estuarine fish, is the only species which was more abundant in the upper reaches of the estuary (tidal river and Molloy basins) than in the lower estuary. During the fresh phase, perhaps in response to high flow rates in the river, it moved down to the lower estuary and was abundant in Swan Lake. Although fish numbers increased again upstream with the returning saline water, a population with a high proportion of larger fish (>25 cm) persisted in Swan Lake and the Deadwater in summer.

The two most common gobies show a contrasting distribution. The true estuarine *F. tamarensis* was more abundant in the tidal river and Molloy basins and *F. lateralis* most abundant in the inlet, Deadwater, and Swan Lake. The data is not adequate to show whether there were significant seasonal movements of gobies. Hardyheads were most abundant in the lower estuary at all times, particularly in the basin and Deadwater.

Of the other six non-resident EIII species, the two mullets continued to be abundant in the estuary throughout the year, even though numbers in the tidal river decreased during the fresh phase. The two whiting species showed a more marked downstream movement at this time, as also did silver bream and striped perch. However with the exception of perch, all continued to be abundant in the lower estuary throughout the year.

The four common species in group EII all left the estuary during the fresh phase or persisted in small numbers only in the Deadwater in July. They started to reappear in the inlet and lagoon in September. During the saline phase, small numbers of both herring and tailor penetrated upstream into the tidal river.

Species of groups EI and S-M were absent from the estuary during the fresh phase and only reappeared in any numbers in January samples with the return of more marine water. All stenohaline marine (S-M) species had left the estuary in May after the first flush and reduced salinity. Following the major flush all EI species had left the estuary.

The follow up survey in July 1975 produced data of considerable interest because of the milder conditions then as compared with the previous July. River flow was less strong and saline water (>20‰) persisted in deeper parts of the inlet channel, even though surface water there and in the basin was fresh (2‰ or less). In Swan Lake and the Deadwater the salinity was about 7‰, with over 30‰ below the halocline in the Deadwater. In consequence, a number of species, including cobbler, were more abundant and some less euryhaline species which had not been present in the estuary in July 1974 persisted there in 1975. The smaller catches of black bream may also be attributable to the lower flow rate of the river; bream are thought to have remained in the upper reaches. Also in marked contrast to the previous year, was the relatively large number of juvenile crabs (*P. pelagicus*) taken in trawls in the inlet. Some were also caught in seine net hauls in the shallows.

Both seine and set net sampling was confined mainly to shallow water because this proved more reliable and more rewarding than was the trawling in deep water. However, it is clear that although fish retreat to deeper water at times, the shallows are the main feeding grounds; they contain the most abundant and diverse benthic fauna.

Food and feeding

The problems associated with determining the food preferences and feeding habits of fish are well known and it is difficult to present useful generalisations when dealing both with a considerable number of fish species and of food types. Gut contents are not readily quantifiable and presence of a particular item in the stomach is not necessarily evidence that it is being digested as food; it may simply indicate the method of feeding employed. A crude example is the sea mullet; a large proportion of stomachs contain sand which has been ingested with the detritus and micro-organisms on which the fish feed. Animals without hard parts are much more difficult to recognise than those with some skeletal material. The worms *Capitella* and *Scoloplos* are probably a more important part of fish diet than appears from the data.

Contents of fish stomachs were examined as part of the study of the macrobenthic fauna. The results are presented and analysed in Technical Report 5: The Food of the Fish of the Blackwood River Estuary. Most of the common species are included in the much simplified food web shown in Fig. 4.3. Generalisations in what follows are made in the context of that diagram, thus contributing to an understanding of the ecology of the estuary rather than of the biology of fish species.

The only species which can be regarded as a herbivore is the garfish, which were found to eat *Ruppia*, though whether they digest this or only the associated organisms is not known. Both large algae and sea grasses were commonly found in stomachs of a number of species, including black bream, silver bream, and trevally, and they can be regarded as omnivores. However, it is again questionable whether sea grass itself is an important part of their diet because it appeared little changed in the intestines. Blaber (1974) showed that *Rhabdosargus holubi* was digesting epiphytic diatoms, but not the *Ruppia* on which they were growing. Talbot (1955) found that *R. globiceps* in the Klein River estuary (South Africa) feed largely on filamentous algae, but also eat a diversity of benthic invertebrates, and groups of fish specialise on one particular type of food. Like many species of fish they will take the commonest foods available to them in their particular habitats.

Detritus was present in stomachs of many species, but the only species known to use the contained microbiota as food, is sea mullet. Other species ingest both detritus and sand in the process of eating small benthic animals, but have no mechanism for filtering out the microbiota.

Tailor, mulloway, small toothed flounder, and flathead were found to be feeding predominantly on other fish, and on shrimp. The more omnivorous trevally was also an important fish eater. Of these, only tailor and trevally are common species. All belong to groups EII and S-M, hence they do not occur in low salinities and are rare in or absent from the estuary during the fresh phase and predation by them would then be low.

The remaining species, the majority, appear to feed mainly on the invertebrate benthic fauna, any specialisation is probably more with respect to size of prey, depth to which they probe the sediments, and method of feeding, rather than selection of food type. Many also had plant material in the gut, but it seems better to regard them as opportunistic carnivores rather than as omnivores; they feed on whatever is abundant at the time and in the place of feeding. Black bream is perhaps the most varied in its feeding and food found in stomachs of bream represented the most abundant prey available in the area from which they were taken. This is not altogether surprising for the species which has the low salinity part of the estuary almost to itself. Mollusca are not an important part of the diet of a number of these opportunistic species. The smaller species, *Arthritica, Hydrococcus,* and *Potamopyrgus,* are those most frequently eaten, partly because they are also the most abundant, but also because of the larger species have heavy shells or burrow deeper into the sediments. It is relevant to note that small and large yelloweye mullet and silver bream select much the same kind of food, but the big fish select bigger prey and hence to some extent different species also.

It is clear from examination of fish stomachs that fish caught in the estuary are feeding there, none of the gut samples showed any specifically marine fauna. It is also significant that a large proportion of yellow fin whiting and yelloweye mullet caught in the Deadwater had empty stomachs, despite the abundance of suitable food there. They were taken on a rising or high tide and are thought to have newly entered the estuary from the sea.

The results of this study also support the findings of Thomson (1957), who investigated the food of estuarine fish caught principally in Leschenault and Wilson Inlets.

Reproduction and recruitment

Time of spawning of the common species and their first appearance as juveniles in the estuary are shown in Table 4.8. Only the two mullet species and King George whiting were found to be spawning in winter, herring spawned in autumn, but all other fish spawned in spring or early summer.

Goby eggs were found in the estuary and the long finned goby (as well as the south west and blue spot gobies) was caught with well developed ovaries and probably breeds here. Both yelloweye mullet and yellow fin whiting were caught with gonads in an advanced stage of development and it is possible that they too may sometimes spawn in the estuary. The cobbler is thought to breed in the Swan and other estuaries (Kowarsky, 1975) but there is no evidence that it can do so under the more extreme conditions of the Blackwood. It is unlikely that any other non-resident species spawn in the estuary, even though eggs may sometimes be carried in by tidal currents and appear in the plankton hauls. It should be noted that although the time and place of breeding of black bream is not known with certainty and no juveniles of this true estuarine species were caught, it almost certainly breeds in the estuary, probably in the upper reaches where young fish live among snags along the margins of the tidal river and are inaccessible to the sampling techniques used.

The estuary is favoured as a nursery ground by many common species, even though few actually spawn in it. Juvenile fish, those less than one year old (0^+ fish), actively swim into it and they formed a large proportion of seine net catches, as shown in Table 4.8. Some entered as very small fry, as for example sea mullet at 1-2 cm, and others apparently not until further developed, e.g. King George whiting at about 7 cm.

A number of less common species also use the estuary mainly or exclusively as a nursery area and these include some of the more stenohaline species. In some cases it was only juveniles which were caught in the estuary.

Table 4.8—Spawning and First Appearance of Juvenile Fish in the Estuary

S—estimated spawning time.
J—first record of 0+ year old fish.

	MONTH												Percentage of juvenile fish in seine net catches
	J	F	M	A	M	J	J	A	S	O	N	D	
Black bream												S	
Gobies	S	S	S						{S J}	S	S	S	
Hardyheads					J				S				
Yelloweye mullet								S	J				46
Sea mullet						S	J						87
Yellow fin whiting			J				(J)					S	4
King George whiting						S					J		69
Silver bream			J							S			68
Striped perch			S				J						1
Australian herring					S				J				17
Trevally									S		J		66
Tailor			J									S	47
Banded toadfish		S	J										0
Garfish			J									S	34

The estuary provides relatively rich feeding as compared with the open sea and a greater measure of protection from large active predators which, as shown above, tend not to frequent low salinity water in the estuary. Juveniles seek the shelter of plants and they are taken in greatest abundance in the shallow, sea grass covered banks of the Deadwater where 98% of the sea mullet, King George whiting, and silver bream caught were less than one year old.

It has been suggested that juveniles of some species are better able to contend with the osmotic stress of low, and high, salinities than are adults. There is, however, no evidence to show that they can long survive the very low salinities of the fresh phase of the Blackwood estuary.

Conclusions

The fish fauna of the estuary consists on the one hand of true estuarine species, species which are confined to estuarine and other brackish waters, and on the other of marine species which show varying degrees of ability to contend with lower salinities. Of the true estuarine species only one, black bream is caught by fishermen. The others, gobies and hardyheads, are smaller species which nevertheless are an important component of the estuarine eco-system.

All the common, non-resident species can be described as 'euryhaline marine' because, although they are also common in the sea, they can live in water of less than 30‰ S. 'Stenohaline marine' fish, species unable to tolerate salinities less than 30‰, enter the estuary but were never common there even when salinity exceeded that figure. All fish taken in the estuary by professional fishermen are among the more euryhaline species, they belong to groups EII and EIII. They are thus well adapted to estuarine conditions. Estuarine populations are thus restocked from the sea and, from the management point of view, there is little risk of overfishing, because the estuarine population is only a small part of a large south west Australian coastal and estuarine population. Most of these fish enter the estuary as juveniles and all age classes may be taken there. However, fish less than one year old form a large proportion of the estuarine population of most species and it is evident that the estuary is an important nursery ground, one where there is abundant food, good shelter among weed, and probably a lower predation rate than in the open sea. Juveniles of King George whiting and silver bream especially, are present in the estuary all year round. The extent to which these estuarine marine species are dependent on the nursery areas afforded by this and other estuaries is not known. Some protected marine embayments, such as parts of Geographe Bay, also provide favourable nursery grounds for some species.

TABLE 4.9—Percentages of Commercial Fish caught by Amateur and Professional Fishermen and during the Fish Survey.

Species	Amateur Fishermen (numbers)		Professional Fishermen (-kg-)		Survey (numbers)	
	line	log books	seine nets	set nets	seine nets*	set nets
Yelloweye mullet	—	3.5	20.6	—	17.5	24.6
Sea mullet	—	—	27.8	79.6	4.7	15.2
Yellow fin whiting (Western sand whiting)	42.0	20.3	33.2	—	22.6	4.6
King George whiting	3.3	4.4	0.3	—	13.0	0
Silver bream	4.0	8.7	12.4	10.2	15.1	9.4
Black bream	15.6	23.7	1.9	4.1	5.1	17.6
Australian herring	23.6	12.7	1.9	5.1	0.2	21.5
Trevally (Skipjack)	6.4	16.1	—	—	1.7	0.2
Tailor	2.7	5.6	1.2	1.0	0.6	4.7
Striped perch	—	—	—	—	7.4	2.1

*includes 0+ year old fish, many of which would be under size.

Yellow fin whiting was the most abundant species, as estimated in the survey and in both professional and amateur fishermen's catches. As noted above, this species may sometimes spawn in the estuary. Other species are listed in Table 4.9, which shows the relative abundance of common commercial species in amateur and professional catches, as compared with catches by the survey team. Reliable data on net fishing by amatuer fishermen could not be obtained because much of it is done illegally. Sea mullet, yelloweye mullet, Australian herring, tailor, yellow fin whiting, and King George whiting were the most important species taken (Tech. Rep. 8).

Although some of the more euryhaline fish were present in the estuary throughout the year, it is not known whether any, except the true estuarine species, can live continuously in freshwater, or whether under the unfavourable conditions of the fresh phase, they must return periodically to the sea. They may well continue to congregate in the brackish water, which extends for some distance outside the mouth, and return to the estuary when conditions ameliorate. Under less extreme hydrological conditions than those of 1974, some fish stay in the saline bottom water of the inlet channel and in the Deadwater, as in July 1975 & 1976.

Most marine fish can tolerate dilutions of sea water down to salinities isosmotic with the blood (10‰-15‰) without much change in concentration of the body fluids, but no lower (Potts and Parry, 1964). "Euryhaline osmoregulators can regulate sufficiently in waters of fluctuating, reduced, or increased salinities, but over longer periods require more salt than is available in pure fresh water ... Holoeuryhaline osmoregulators are able to regulate sufficiently in media ranging from pure fresh water to full-strengh sea water or higher" (Kinne, 1967). The true-estuarine species are clearly holoeuryhaline osmoregulators but it is not known whether any non-resident species, except sea mullet, also are. Sea mullet will live in water of less than 1‰ for at least eight days and in this salinity the metabolic rate is not significantly different from that of fish in water isosmotic with the blood (Nordlie and Leffler, 1975).

Lenanton (pers. comm.) observed that King George whiting, which had been trapped in Wilson Inlet when the bar closed in summer, secreted a thick layer of mucus over their bodies. They appear to have been stressed by prolonged exposure to low salinity (about 10‰ for some six months). This was not seen in fish caught in the Blackwood estuary even when salinity was much lower. They are thought to have only recently entered the estuary from the sea. Kowarsky (1975) found no mortality among cobbler kept at 3‰ for 30 days, but there was a high mortality at 1‰. As with the invertebrate fauna, success in using the estuary during the fresh phase may depend as much on how long fish can tolerate low salinity, as on the precise level of salinity to which they are exposed.

The Scott River. Rock bar at head of the estuary.

Use of the various parts of the estuary by fish populations is related, on the one hand, to salinity and, on the other, to availability of suitable shallow feeding grounds. Catches in the tidal river (area 6, Figure 4.6) were low at all times (except for black bream) and a maximum of seven species was taken there in any survey. Mullet were noticeably less abundant in this part of the estuary than in the corresponding part of the Murray River estuary, perhaps because there are extensive shallows there and almost tideless (daily) conditions.

The shallows of the Molloy and Scott basins (area 5) provide good feeding grounds and 12 or 13 species were taken there each survey during the saline phase. The basin (area 4) and shallows of the inlet (area 3) both provide good feeding grounds with about 20 species caught in surveys during the saline phase, but only seven in July 1974 in the basin. Deeper parts, with a muddy bottom, are less favoured. The very shallow water of Swan Lake, with its abundant weed, is a good feeding ground especially for small fish, in spite of high temperatures in summer and hypersaline (to 40‰) conditions at times. However, the number of species of fish was similar to that of the Molloy and Scott basins, a maximum of 14 species.

The importance of the Deadwater has been noted in several connections. It has a rich growth of ***Ruppia,*** has negligible flow, although there is good tidal ventilation, and saline water persists in it when the rest of the estuary is fresh. In consequence, it is both a good nursery ground with a high proportion of juveniles in all catches, and also a refuge during the fresh phase, especially for less euryhaline species. The Deadwater did not of course exist before 1945, but it is evidently now an important part of the estuarine ecosystem.

Emphasis has been laid on salinity throughout. This is because it is seen to be the overriding factor in determining species distribution; also because it is difficult to separate temperature effects, and those of other environmental parameters, from salinity and little is known about the responses of local fish to temperature. Moreover the response of fish to salinity stress is linked to temperature (Kinne, 1964). Observed temperature range in the estuary was 9°C-29°C. Adjacent sea temperature was not measured, but the range is unlikely to have been more than about 6°C (Hodgkin and Phillips, 1969). Whether the temperature difference between sea and estuary is ever sufficient to bar the passage of fish, as has been suggested in the case of some Atlantic coast South African estuaries (Day, 1974) is not known, but the differences are much less here than there.

Just how representative 1974-75 was it is not possible to say. Professional catch records from other estuaries of the south west, show great variation in annual catches of individual species. Such variations cannot be explained solely in terms of the prevailing estuarine conditions. They are determined also by the availability of marine stocks for recruitment at the appropriate time. There are no previous separate catch records for the Blackwood estuary so that it is not known what long term changes there may have been. The flathead (*Platycephalus* sp.) is known to have been common about 40 years ago, but very few were taken during the survey and it is not recorded by Lenanton (1974 a).

Differences between the July 1974 and 1975 catches noted above are probably related to the lesser flow and higher salinities of 1975. The March catches for the two years were similar, except in respect of whiting, of which King George whiting was the more abundant in 1974 and yellow fin whiting in 1975. It is to be expected that in years of high river flow few if any estuarine marine (non-resident) species will remain in the estuary during the period of high discharge. However, it is evident that it will be rapidly restocked from the sea when saline conditions are re-established, though species composition may well be different. On the other hand in dry years, with low river flow, euryhaline marine species will make greater use of the estuary in winter.

Blue manna crabs were not abundant at any time during the survey and formed only an insignificant part of the estuarine fauna. However, they are reported to have been abundant for about 3 years to 1974 and were caught commercially. It is unlikely that crabs will survive in the estuary when there is a fully developed winter condition, as in 1974. However when salt wedge conditions persist in the inlet channel and Deadwater, crabs may be expected to survive there over the winter months, buried in the sediment as they normally do in Leschenault Inlet (Meagher, 1971). This probably explains the large numbers of crabs again present in the estuary in the summer of 1976-77. Crab abundance is likely to be greatest in years when the recovery phase begins early, but recruitment to estuarine stocks is also dependent on planktonic larval and juvenile populations at sea and their return to the vicinity of the estuary mouth in early summer.

4.10 Waterbirds

One reason for studying the birds of the estuary is because of their aesthetic appeal. People enjoy seeing them and relate to them emotively more than to any other animal, except perhaps dolphins. A reduction in the number of pelicans is an easily identifiable "threat to the natural environment" in a way that the disappearance of some fish or invertebrate species can never be.

However, waterbirds are an important part of the estuarine ecosystem, even though they are not aquatic animals and it is primarily in this context that they are considered here. There are considerable numbers of some species and because of their high metabolic rate, they consume a great deal of food. Black swans are estimated to have consumed 230 tonnes of sea grass during the year, a significant part of an estimated standing crop of some 650 tonnes growing in Swan Lake. Waterbirds too have been shown to consume a large part of the production of estuarine molluscs, and doubtless of worms also (Milne and Dunnet, 1971). Moreover, as these authors claim, a great deal can be learnt about estuarine food chains and predator-prey interrelations by a study of birds, because they are more easily observed and quantified than fish, the other main predators. It was beyond the scope of the present study to attempt a quantitative assessment of the part played by birds in these relationships; nevertheless a great deal has been learnt from the bird study.

This aimed to identify the species of birds using the estuary, to get an accurate estimate of their numbers and seasonal changes in abundance, and to obtain an understanding of the way they use the estuary and the various parts of it. The study was part of a long term investigation of the birds of WA estuaries. The bird fauna of Leschenault Inlet was studied in the previous year and that of Peel and Harvey Inlets started in 1975.

Technical Report 7: The Birdlife of the Blackwood River Estuary, is the basis for the present account and should be referred to, especially for information on individual species.

Methods

Monthly visits were made to the estuary, each visit lasting 3-6 days. On the first day of each visit three survey flights were made over the estuary at 0730, 1200 and 1630 hours at a height of about 150 m. During these flights, large birds, pelicans and egrets, were counted and plotted onto an orthophoto map and black swan flocks were photographed and subsequently counted in the laboratory. Other species were counted or populations estimated in surveys made by boat or on foot. Some small species were too shy and too dispersed for it to be possible to make accurate estimates of their populations.

Composition of the Fauna and seasonal changes

A total of 57 species of waterbirds were seen during the course of the survey (Table 4.10) and this figure compares favourably with the bird fauna of other estuaries which have been studied. The composition of the fauna is very similar to that of Leschenault Inlet. (Tech. Rep. 7, Appendix 2.) The most noticeable absentee was the Avocet, which occurs in hundreds on west-coast estuaries, but does not seem to extend its range to the extreme south west.

Table 4.10—Maximum Populations of Waterbirds July 1974-June 1975

Non-Migratory Species		Migratory Species	
	10 000—1 001:	1 SPECIES	
Black Duck est 1 100			
	1 000—101:	10 SPECIES	
Little Black Cormorant		Red-capped Dotterel	220
Little Pied Cormorant		Red-necked Stint	700
White-faced Heron		Curlew Sandpiper	110
Black Swan	700		
Musk Duck	est. 250		
Crested Tern			
Silver Gull			
	100—11:	22 SPECIES	
Australian Pelican	60	Large Sand-dotterel	50
Black Cormorant		Eastern Golden Plover	46
Darter		Greenshank	
Nankeen Night Heron		Common Sandpiper	
White Egret	12	Knot	23
Mountain Duck	14	Great Knot	31
Grey Teal		Sharp-tailed Sandpiper	23
Whistling Eagle		Sanderling	60
Swamphen		Bar-tailed Godwit	39
Caspian Tern			
Fairy Tern			
Rock Parrot	50		
Little Grassbird			
	10—1:	24 SPECIES	
Hoary-headed Grebe	2	Double-banded Dotterel	2
Pied Cormorant	10	Grey Plover	4
Brown Bittern	1	Turnstone	1
Reef Heron	2	Whimbrel	6
White Ibis	2	Eastern Curlew	1
Chestnut Teal	3	Grey-tailed Tattler	2
Blue-winged Shoveller	4	Terek Sandpiper	1
White-breasted Sea Eagle	1	Pectoral Sandpiper	1
Swamp Harrier			
Osprey	2		
Coot	8		
Pied Oystercatcher	10		
Pied Stilt	1		
Pacific Gull	1		
Kelp Gull	1		
Sacred Kingfisher			

Birds using the estuary fall into four categories:

(i) summer migrants from overseas,

(ii) summer immigrants from elsewhere in W.A.,

(iii) a few winter visitors,

(iv) species resident throughout the year.

Eighteen migrant species breed in the northern hemisphere and fly south to feed here during the northern winter. The double-banded dotterel, is a migrant from New Zealnd and birds visited the Blackwood in March and April of both years. Numbers of the more abundant species were considerably less than on Leschenault Inlet and the Swan estuary. Suitable shallow water feeding grounds are less extensive in the Blackwood than in those estuaries. Three species were commoner on the Blackwood and one, the sanderling, was only seen here, with a flock of 60 birds feeding on the basin sandflats from December to March (Fig. 4.8A).

Migrant species started to arrive in September, remained on the estuary from October to March, and most left abruptly in March-April. Of them only red-necked stint and curlew sandpiper were seen in flocks greater than 100 and the rapid build up and abrupt disappearance of their populations can be seen from Fig. 4.8A and B. There were also substantial numbers of 9 other species, so that at times in summer, over 1,000 of these wading birds were feeding on the tidal flats and samphire marshes of the estuary.

Waterfowl only started to build up to large numbers after inland waters dried up in summer, later than migrants. Black duck arrived in December and black swans in January (Fig. 4.8D). The season of abundance was a short one with many ducks leaving in February and Swans in May. Large flocks of Musk Duck were present only from February to May, 1975 (much earlier on Leschenault Inlet). To what extent these are static populations or moving between the estuary and other feeding grounds, is not known. Elsewhere a big turnover of swans has been observed but there do not appear to be exensive alternative feeding grounds in the Augusta area. White-faced heron showed a similar seasonal abundance from December to May. Pelican return to the Blackwood earlier (Fig. 4.8C) after nesting from March to August, mainly at Shark Bay and further north.

The white egret was a regular autumn-winter visitor and up to 12 birds fed among rushes and on samphire flats from March to July. Some other less common species only visited the estuary briefly at this time of year.

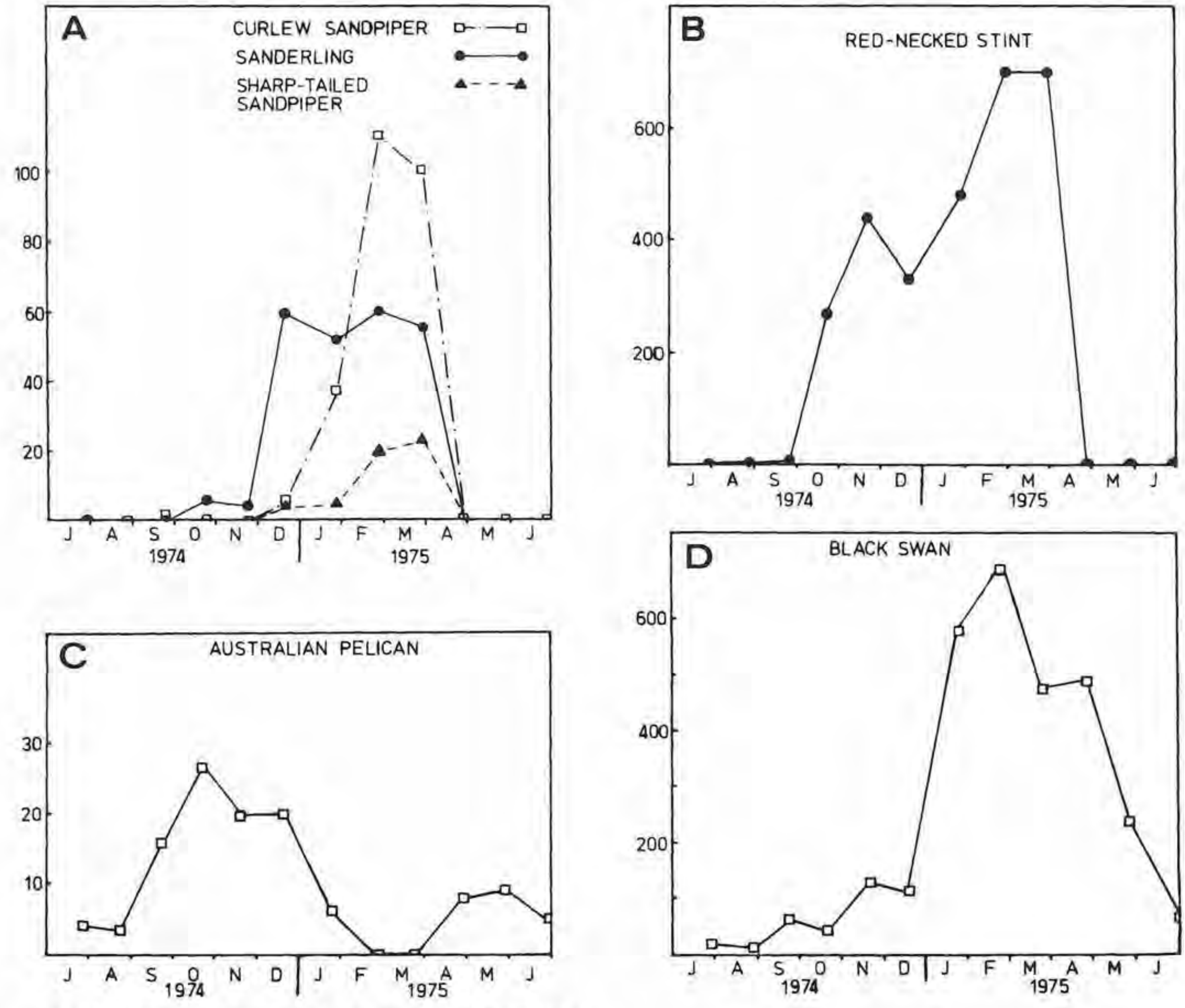


Fig. 4.8 Seasonal abundance of six species of waterbirds.

Other common birds such as little black cormorant, little pied cormorant, and silver gull, showed a more uniform abundance through the year without marked peaks. They are mainly fish eaters.

Subsequent observations (Lane, pers. comm.), show much the same seasonal trends. However, during the summer of 1975-76 the number of black swans on the estuary was nearly double that of 1974-75, and during the dry winter of 1976 populations approached the summer levels of 1974-75. Pelican numbers were also much greater in 1976.

Feeding and habitat preferences

No study was made of the food of the waterbirds. Any attempt to do so would almost certainly bring the investigator into conflict with bird lovers. In any case, the general type of food consumed is known in most cases and much can be deduced from observation of the feeding habits. Most species show marked habitat preferences in relation to the type of food consumed and the commoner speciès observed in the Blackwood estuary are listed in Table 4.11. Five sequential feeding habitats were recognised:

(i) rush beds,

(ii) samphire marsh,
both of these are above water most of the time in summer,

(iii) tidal flats,

(iv) shallow water,

(v) open water, including shallow water.

Rush beds, with the good cover they give, were the favoured feeding grounds of five species of which the white egret, swamphen, and little grassbirds are the commonest, though with a maximum of only 12 white egrets. These birds feed mainly on the restricted invertebrate fauna and perhaps also on reptiles and on small fish at high water. Swamphen also eat plant material.

Samphire marsh is not as extensive here as in many estuaries, but there are areas near the mouth of the Deadwater, at Point Pedder, on Thomas Island and more restricted marginal areas elsewhere. This habitat is favoured by a variety of small semi-aquatic invertebrates which form the principal food for six waders and four other species including white egret and white ibis. Both white-faced heron and silver gulls are abundant though they also feed in the more productive shallow water and tidal flats respectively. Tidal flats cover over half the area of the basin and more restricted areas along the margins of the inlet, Molloy basins, Deadwater, and Swan Lake. They are uncovered at low tide, or covered only with a few centimetres of water, and are completely covered by normal summer high tides. The 19 species that use this habitat are principally migrant waders which are opportunistic feeders taking the most abundant and accessible small invertebrates of the sediments, so that there is heavy predation through the summer months. The polychaete worm *Ceratonereis* appears to be an important part of the diet of these birds.

Shallows include both the tidal flats when submerged at high tide and areas permanently submerged to less than one metre, the length of a black swan's neck, and consequently they offer diverse feeding. Black duck, musk duck, and grey teal feed on water plants. On the Coorong of South Australia, Delroy (1974) found that over 90 per cent of the food of these birds consisted of the tubers and seeds of *Ruppia* and

TABLE 4.11 Feeding-habitat Preferences of the Commoner Waterbirds.

Species with maximum populations of 10 or more. Birds are grouped according to natural Orders, for which common names have been used.

Species	Feeding Habitats				
	Rush beds	Samphire marsh	Tidal flats	Shallows (< 1 m)	Open waters (including shallows)
PELICANS CORMORANTS					
Australian Pelican				x	
Black Cormorant					x
Little Black Cormorant					x
Little Pied Cormorant					x
Darter					x
HERONS					
Nankeen Night Heron				x?	
White Egret	x	x			
White-faced Heron		x		x	
SWANS AND DUCKS					
Black Swan				x	
Mountain Duck				x	
Black Duck				x	
Grey Teal				x	
Musk Duck					x
EAGLES					
Whistling Eagle					x
WATERHENS					
Swamphen	x				
WADING BIRDS					
Red-capped Dotterel			x		
Large Sand-dotterel			x		
Eastern Golden Plover			x		
Greenshank		x	x		
Common Sandpiper			margins		
Knot			x		
Great Knot			x		
Sharp-tailed Sandpiper		x	x		
Red-necked Stint			x		
Curlew Sandpiper			x		
Sanderling			x		
Bar-tailed Godwit			x		
GULLS					
Silver Gull		x	x		x
Caspian Tern					x
Fairy Tern					x
PARROTS					
Rock Parrot		x			
PASSERINES					
Little Grassbird	x				

Lamprothamnium, but tubers have not been found in the Blackwood, probably because of the lower salinities, and it is not known what the birds eat here. Swan eat large quantities of *Ruppia* and *Potamogeton*.

Deeper water, "open water" is favoured principally by fish eaters, cormorants, eagles, gulls and their relatives, birds which swim or dive for their prey. These include some of the most abundant birds of the estuary, though cormorants are not as abundant as on Leschenault Inlet and some other estuaries.

Nesting

The estuary is only an important nesting area for some of the less common species. The overseas migrants all nest in the northern hemisphere (double-banded dotterel in New Zealand) and most waterfowl disperse to inland swamps and lakes to nest in spring. Only four pairs of swans nested on the estuary and raised eight cygnets to the downy stage. No ducklings of black duck were seen. Two whistling eagle and one osprey nests were found. One or two pairs of pied oystercatcher nested and two nests of little grassbird were found, in September. Juvenile caspian tern and fairy tern were seen, in September, and these species nest on the nearby Seal Island.

Puddling by silver gull on the delta flats.

The role of waterbirds in the ecosystem

Waterbirds play a number of important roles in the economy of the estuarine ecosystem, these relate principally to their feeding habits and we are therefore concerned primarily with energetics. For a quantitative assessment of estuarine productivity used by birds, we need to know how many bird days are spent feeding on the estuary, at least for the commoner species, the metabolic requirements of the birds, the nature of the food consumed, its calorific value, and a measure of the amount eaten. Three main food types are indicated above: aquatic plants, fish and shrimp, and benthic invertebrates. Fish are shared as a resource with man, benthic invertebrates are shared with fish, but the black swan is the principal herbivore consuming macroscopic aquatic plants and a reasonable estimate can be made of swan utilisation of the estuarine productivity.

The number of swan days on the estuary was estimated at 94,727. Each bird requires 574 Kcal or 2.48 kg wet weight of *Ruppia* a day (Tech. Rep. 7, Appendix 3). The calorific value of *Ruppia* is 3.24 Kcal/g dry weight (Congdon, pers. comm.). This gives a total consumption of 230 tonnes wet weight in the year which must be a substantial part of the *Ruppia* production of the estuary, estimated at about 1 000 tonnes per year. Swans have two methods of feeding, one a lawn mower technique in which the foliage is chopped into short lengths of 2 to 10 mm and another more like a rotary hoe in which the birds dig circular pits. In the latter process, they consume the plant rhizomes which are rich food stores. However they dig to a greater depth than is necessary to get access to the rhizomes and they have also been observed to use the same technique where there are no rooted plants. In both feeding methods there is considerable wastage, much of the foliage is undigested in passage through the gut despite the large muscular stomach and contained sand, and not all that is pulled up is consumed.

Swans were seen to destroy almost the entire crop of *Potamogeton* in the Blackwood basin in spring, but rhizomes persisted and the plants regenerated when salinity was again low in the following fresh phase. It is interesting to speculate whether this cultivation of the sediments plays a significant part in making buried nutrients available at the surface, and worms to fish predation.

Swans were always present in Swan Lake where *Ruppia* is densest at all times, but they feed throughout the estuary wherever there is sea grass and swan numbers seem to reflect sea grass abundance.

No estimates were made of food consumed by fish eaters or by waders eating benthic invertebrates, but it is evident from the literature that, in both cases, birds consume a considerable part of the production. Milne and Dunnet (1971) found that Eider were the principal predators on *Mytilus* (mussel) and consumed some 39% of production in the Ythan estuary of Scotland.

Some idea of the quantity of fish consumed can be gained from Serventy (1938) in which he found 593 fish in the guts of 74 Little Pied Cormorants shot on the Swan estuary and 87 fish in 13 Little Black Cormorants. Most of the fish were gobies and other non-commercial species (but included cobbler). Shrimp (*Palaemonetes*) formed the other main item of diet of these birds. Food consumed by them is equivalent to some 17% of their body weight each day, so that on a rough estimate these two cormorants consume some 1 to 1.5×10^6 small fish each year, weighing 15-25 tonnes.

Without some measure of the absolute numbers of fish present in the estuary, it is not possible to estimate what part of the fish production is consumed by birds.

Two other aspects of the ecological role of waterbirds require consideration: seasonality of pressure on food resources and the significance of the different parts of the system. Fig. 4.9 represents seasonal changes in bird pressure on the various food resources by the principal bird feeding types. It emphasises the extreme seasonality of pressure on aquatic plants and the benthic fauna and probably more uniform pressure on the fish resource by waterbirds.

Usage of the different parts of the estuary is of course related to availability of the various feeding habitats (Table 4.11), but also to the need for suitable nesting places. Thus, although the main feeding grounds of black and musk duck are in the basin, these birds are commonly encountered on the tidal river, a part of the system that is otherwise little used

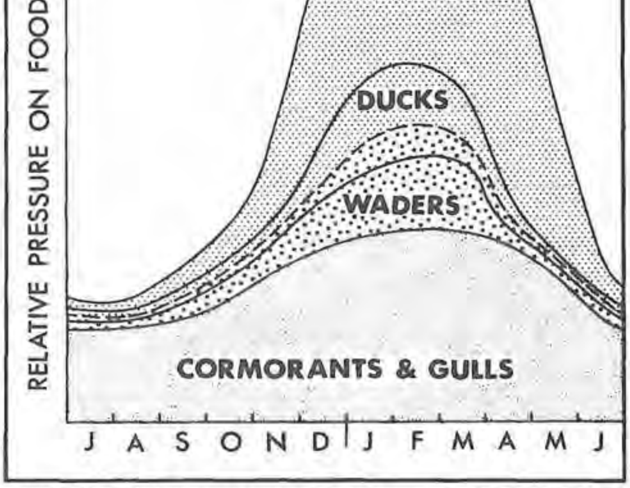


Fig. 4.9 Relative seasonal pressure on the estuarine food resources by the main bird types.

except by some fish-eating birds. The basin is the only part of the system greatly altered by changing tide levels. At low tide about half is exposed while at high tide little is left uncovered. Thus when they are exposed, the tidal flats of the basin are the principal feeding grounds for waders and when covered they are important for ducks and swans.

The higher parts, which are out of the water most of the time in summer, are a favourtie resting place for these and other species of birds. The marginal rush beds attract the few species which favour them and similarly the samphire marshes afford feeding grounds for a number of species. The basin, with its two bays, is the most heavily used part of the estuary.

The shallows of the three Molloy Island basins are seldom exposed and never have more than about one metre of water and afford good feeding for ducks and swans when there is *Potamogeton* or *Ruppia*, or *Lamprothamnium*.

The inlet with its deep water and marginal shallows provides good feeding for cormorants and gulls, ducks and swans. The samphire and sand bar at the west end of the Deadwater, are used both for feeding and as a resting area for a considerable variety of birds. This is also a place where birds can be easily seen and enjoyed by humans. Shallow water at the east end of the Deadwater is also favoured by waders at times.

Swan Lake is especially important for flocks of black swans, which use it heavily throughout their stay on the estuary, both for feeding and resting. The shallow water and marginal rush beds are a favourite feeding ground for white egret and swamp harrier.

Pelican relate to man more than any other bird, and man to them, and small flocks are often seen perched on jetties waiting for handouts of fish, though they also parade on the various sandflats.

Finally, although we are concerned here only with waterbirds, it is pertinent to note that a considerable number of other bird species inhabit the area. Mr. Michael Ellis has kindly supplied a list of 35 species of terrestrial birds recorded over a period of 18 months (Table 4.12). These were all seen in a small area on the east bank of the inlet, where the vegetation is mainly Peppermint thicket behind marginal rush beds.

TABLE 4.12—Birds observed at Augusta, 1971-72 by Mr. M. Ellis, other than waterbirds.

Bronzewing Pigeon	Magpie Lark
Wedge-tailed Eagle	Blackfaced Cuckoo Shrike
Brown Hawk	White Crowned Babbler
Boobook Owl	Western Warbler
Purple Crowned Lorikeet	Broad-tailed Thornbill
White-tailed Black Cockatoo	Yellow-rumped Thornbill
Western Rosella	Spotted Scrub-wren
Twenty Eight Parrot	Splendid Wren
Kookaburra	Pardalote
Pallid Cuckoo	Western Silvereye
Fantail Cuckoo	Brown Honeyeater
Golden Bronze Cuckoo	New Holland Honeyeater
Tree Martin	Red Wattle Bird
Grey Fantail	Raven
Willie Wagtail	Grey Currawong
Scarlet Robin	Grey Butcher-bird
White-breasted Robin	Western Magpie
Golden Whistler	

4.11 Man

The human impact on the physical features of the estuary has been discussed elsewhere (Section 5.4); here only man's role as a predator will be considered.

Technical Report 8: The Estimation of Catches by Amateur and Professional Fishermen of the Blackwood River Estuary during 1974-75, records the results of studies of amateur and professional fishing in the estuary. The fishery is predominantly an amateur one and the problems involved in obtaining a reasonable estimate were formidable. A creel census involved periodic (10 days per month) interview sampling of boat and shore fishermen, both local residents and visitors. Log books were issued to a few local amateur line fishermen. The amateur net fishery was largely illegal, being done in closed waters and by unlicensed fishermen, and in consequence estimates of fishing success could only be obtained by interview with selected fishermen. The few, part time, professional fishermen co-operated by keeping log books.

Composition of the catches as thus estimated are shown in Table 4.9 and compared with catches made by the survey team. The latter are biassed by the large number of juveniles of certain species taken in set net hauls, while undersize fish are not included in amateur and professional data; otherwise, there is good agreement between them. The amateur catches also reflect the seasonal data obtained by the survey team, in that catches by both boat and shore fishermen increased in September and thereafter, as the summer hydrological regime was re-established.

Yelloweye mullet and sea mullet are caught mainly by net, and black bream, Australian herring, and yellow fin whiting mainly by line. Black bream form a large part of the catch in the tidal river and are only a small item in the net fishery, because nets are set mainly in the basin (it is illegal to net in the inlet, Deadwater, and Swan Lake). Pressure on the fishery, both by amateurs and professionals is strongly seasonal and reflects, on the one hand the salinity status of the estuary and on the other, the numbers of visitors who flock to Augusta mainly during the December January holiday period and at Easter.

An estimated 430 000 fish were taken from the Blackwood River estuary during the one year period from May 1974 to April 1975, by amateurs and professionals (Table 4.13). It will be seen that the greatest numbers were taken by line fishermen and that catches by professionals formed only a small part of the total catch. If it is assumed that there are 9 fish per kg then the fish taken from the estuary during the year weighed a total of about 45 tonnes. The research team took an additional 27 670 fish in the course of their work, about half of which were non-commercial species.

Table 4.13—Distribution of catches by amateur and professional fishermen. Numbers of fish caught.

Area	Amateur line fishermen	Amateur net fishermen	Professional
LAKE (Swan Lakes and Deadwater)	24,900		
INLET (1) (Mouth to northern extremity of Molloy Island)	192.000		
INLET (2) (Point Irwin to northern extremity of Molloy Island)		100.000	19,000
RIVER (northern extremity of Molloy Island to Alexandra Bridge)	70,400		
TOTAL	287,300	100,000	19,000
Period covered in Survey	MAY 1974 to APRIL 1975	MAY 1974 to APRIL 1975	SEPT 1974 to JAN 1975

Both the estimated catch by amateur net fishermen and the rates of success for both boat and shore fishermen during September, reflect the increase in the numbers of fish moving into the estuary as the summer hydrological regime becomes established. Virtually no crustaceans were taken from the Blackwood River estuary by either professional or amateur fishermen.

4.12 An ecological assessment

In geological time, and in respect of the evolution of the flora and fauna, the Blackwood estuarine ecosystem is of very recent origin. It cannot have existed in anything like its present form for more than about 4000 years. Nevertheless, on the human time scale, it appears to be a stable system, with the various elements of the biota in dynamic balance with one another and with the changing physical environment. Aspects of this eco-system have been discussed in this chapter and in this concluding section it is proposed to review these and examine the nature of this balance.

The physical environment

In the introduction to this chapter emphasis was laid on the seasonal character and extreme range of environmental change with respect especially to river flow and salinity. This is illustrated in Figure 4.2. There can be little doubt that in the Blackwood estuary, as in other estuaries of south western Australia, salinity "represents the dominating limiting entity—the ecological master factor—for all or at least the majority of the species present" (Kinne, 1964). Here there is a "special or extreme condition." Kinne goes on to say that under these conditions "the biological effects of a given master factor may depend more on the extremes and the pattern of fluctuation than on average values." The salinity extremes experienced and duration of these are certainly the overriding factors in respect of diversity and composition of the biota and its distribution within the estuary. This is borne out by observations on the mollusc fauna, by changes in the composition of the biota along the length of the estuary, and by gross changes in number and abundance of the estuarine-marine species of fish between the fresh and saline phases of the estuary.

The overall range of salinity, 1‰ to 35‰, is not unusual in estuaries. What is unusual is that the change from fresh to marine is experienced throughout the lower estuary and that the organisms living there are exposed to one or other extreme for months at a time.

Although salinity is of overriding importance, other environmental factors do greatly influence the composition of the biota and the success of the various elements. Volume of river flow, temperature, nature of the substrates, strength of currents, and tides are all important modifying factors, and the effects of these are not readily seperable from those of salinity.

Temperature range is greater than that in the open sea (Fig. 3.33). However there is no evidence that either range or the differential between sea and estuary greatly affects species abundance or distribution of the fauna and flora within the estuary. The thermocline associated with the halocline in the tidal river in summer may affect fish movements, but how is not known.

Nature of the substrate to a considerable extent determines composition of the benthic flora and fauna occupying the different habitats. Current strength may influence composition and distribution of the mobile fauna (shrimp and fish) during the period of major discharge. The nature and volume of flow greatly affects supply of nutrients and loss of them and suspended matter to the sea. Tides are particularly important even here, where they are of small range. They influence both composition and abundance of the benthic fauna of particular parts and the area of feeding grounds available to fish and birds. All have to be taken into account when considering the composition and abundance of the flora and fauna, as has been done in the foregoing sections.

Number of species and trophic relations

Various elements of the estuarine biota have been recognised and the composition of these and the nature of their contribution to the economy of the ecosystem is summarised here. A food web was proposed in Fig. 4.3 and this indicates the main pathways of the system. The following are the principal elements of which it is composed.

1. Plankton of the water body. It is clear that phytoplankton makes only a small contribution to primary production in the Blackwood; cell densities were very low and chlorophyll was scarcely measureable. It is thought that this is attributable principally to the relatively low nutrient levels and the large tidal volume of the lower estuary.

   Zooplankton, the principal herbivores on phytoplankton were also sparse in the estuary. The only species at all common here *(Gladioferens imparipes)* is thought to feed on benthic detritus as well as algal plankton. The large numbers found in stomachs of a few fish may result from benthic rather than planktonic feeding. Planktonic and bentho-planktonic animals (mysids and harpacticoid copepods) were most abundant in hauls in the Deadwater.

2. Benthic algae. The number of species of macroscopic algae occurring in the estuary was small. Table 4.14 shows the composition of the algal flora and the response to environmental conditions.

Table 4.14—Numbers of species of macroscopic algae recorded from the lower Blackwood estuary.

	Fresh phase July-Sept	Saline phase Feb-May	Salinity group			Total
			S	E	O	
Chlorophyceae (green algae)	8	7	1	6	3	10
Phaeophyceae (brown algae)	1	5	4	1	0	5
Rhodophyceae (red algae)	4	5	2	3	1	6
Cyanophyceae (blue-green algae)	1	1	1	0	2	3
Charophyta	1	0	0	0	1	1

S—Stenohaline-marine species
E—Euryhaline species
O—Oligohaline, freshwater species

Only two species were abundant: the filamentous green alga *Rhizoclonium* and the charophyte *Lamprothamnium*, both of which belong to predominantly freshwater groups. They, and other, algae were present in fish gut samples and may be an important part of the diet of omnivorous species. The high proportion of green algae is characteristic of such a stressful estuarine environment.

Diatoms and other microscopic algae of the surface sediments, are important primary producers in shallow water and are eaten both by benthic invertebrates and some species of fish. No quantitative study was made of them or of the epiphytic algae, principally diatoms, which are abundant on sea grasses and other vegetation. These are also important food for both invertebrates and fish.

3. Aquatic vascular plants. In the Blackwood, the very euryhaline species *Ruppia maritima* dominates the lower estuary, but it is replaced by the less salt tolerant *Potamogeton pectinatus* in the upper estuary and around Molloy Island during the fresh phase. They are an important part of the primary production and great quantities are eaten by herbivores, particularly swans. The plants are confined to shallow water and the best growth is in situations of relatively restricted flow such as Swan Lake, the Deadwater, and embayments along the tidal river.

4. Marginal vegetation. Rush beds form a large part of the margin of the lower estuary, dominated by *Juncus krausii* but with the sedge *Baumea juncea* also present near the water's edge. Both occur throughout the estuary but tend to be replaced by freshwater plants above Alexandra Bridge. Behind the rushes are swamps with paperbark trees *(Melaleuca spp.)* and samphire *(Salicornia)*. The rushes and salt marsh plants are not eaten to any extent by the estuarine fauna, but they make a major contribution to the detritus. The salt marsh is less extensive than in many estuaries elsewhere in Australia and overseas; nevertheless it covers about 10% of the total area of the lower estuary.

5. Microbiota. Study of this important part of the estuarine eco-system was beyond the scope of the present investigation. Bacteria, fungi, spirochaetes, flagellates, diatoms, ciliates, and other Protista are present in vast numbers. They have been shown elsewhere to be the essential element in making detrital material available to the benthic animals and recycling nutrients present in the abundant faeces. Because many of the invertebrate fauna are deposit feeders, a large part of the estuarine production is channelled through the microbiota to the top predators.

   The Foraminifera reflect dramatically the effect of salinity on species diversity and faunal composition. There were about forty species of these predominantly marine Protozoa in the inlet region, but only three species in the tidal river at station 130.

6. True estuarine macrofauna. The resident aquatic fauna are animals which have self-maintaining populations in the estuary and can be regarded as 'true-estuarine' animals. These are animals which, by one of the response patterns discussed by Kinne (1964, 1967) contrive to contend successfully with the salinity extremes of the estuary. Most are species which favour shallow water environments and they are unlikely to occur along the open, exposed coast outside our estuaries. None of them have been present in hauls made in Flinders Bay subsequent to this study. Indeed, many are not found in such sheltered, fully marine, environments as Cockburn Sound and it can be said with reasonable certainty that they are confined to estuaries. Of 55 benthic invertebrate species found living in the estuary, some 40 are probably confined mainly to estuarine environments. Only 13 species formed the great bulk of the invertebrate fauna: 3 polychaete worms, 4 bivalve and 3 gastropod molluscs, 2 crustaceans, and one insect. These are the main food of most fish species and many of the birds.

   There are six species of true-estuarine fish. They are species which are adapted physiologically and reproductively to contend with the stresses imposed by this environment and which, despite their mobility, are confined to estuarine waters. Although only one is caught by fishermen, they are quantitatively an important element in the estuarine ecosystem. On the one hand, they are in competition for food resources with the non-resident fauna and on the other, most are in turn food for the top predators.

7. Non-resident macrofauna. The great majority of the fish that use the estuary spawn in the sea, and they enter the estuary as juveniles or adults. Moreover, their estuarine populations are only part of large marine populations. About half of the non-resident fish species are believed to be stenohaline-marine species which do not tolerate salinities less than 30‰. They are not an important part of the estuarine biomass, even though some are caught regularly by amateur fishermen, near the mouth of the estuary. The rest (24 species) can be regarded as euryhaline marine species, in that they are observed to tolerate lower salinities, at least to 15‰, and 18 species down to 3‰.

   Little is yet known about the extent to which these species are dependent on estuaries. For some of the more euryhaline species (groups E II and E III), estuaries may be the preferred habitat, providing abundant food and sheltered feeding grounds, where predation is low. They are certainly the favoured nursery grounds for some species, e.g. silver bream, and probably also for young adults.

   Further research on two aspects is very desirable. First on the physiological capacity of these species to accommodate to salinities below that with which they are in osmotic balance (about 10‰), and second population partition between the marine and estuarine habitiats.

   Very much the same sort of questions apply to the commercial Crustacea. However, in the case of the blue manna crab, it is clear that while spawning and larval development take place at sea, estuaries are favoured by juveniles and adults in south western Australian waters. This is because they are sheltered, rich in food, and have higher water temperatures than the sea through much of the year. The very low fresh phase salinities experienced in the Blackwood estuary in 1974 are fatal to crabs. Recruitment to estuarine crab populations varies greatly from year to year.

   Most of the fish are omnivores or predators; the majority feed on the invertebrate fauna, a few on other fish. Sea mullet feed directly on detritus and several species eat aquatic plants, though it is unlikely that any, except garfish, are solely dependent on plant material for their nutrition. Crabs are omnivorous and both they and prawns eat detrital material.

8. Waterbirds. Because they are not aquatic and are hightly mobile, the birds are minimally affected by physiological problems associated with an estuarine environment. Pelicans, cormorants, ducks, waders, and gulls, the majority of the waterbird fauna, all have salt glands, though little is known about how effective these are. Other birds require access to fresh water to drink, but there is probably ample available in nearby swamps and in the upper estuary itself.

The extreme seasonality of waterbird usage of the estuary (Fig. 4.9) relates more to the availability of other suitable aquatic habitats than to conditions in the estuary itself. Most waterfowl come to the estuary when inland waters dry up. The Blackwood and other estuaries are summer refuges and as such they are very important to maintenance of waterfowl populations. For most of the northern migrant waders, estuaries are the principal feeding ground in Australia and the Blackwood estuary receives a considerable share of these birds. The more permanent bird population, cormorants, gulls, and a number of less abundant waterbirds, are to a large extent dependent on the estuary throughout the year.

Pressure on various food resources of the estuary is illustrated by Fig. 4.9. The role of swans, and to a smaller extent ducks, as the principal consumers of sea grasses has been stressed more than once; they eat a large part of the sea grass production (Section 4.10). Much of this returns to the nutrient bank in the form of only partially digested faecal matter and is recycled by the detrital flora and fauna.

The large flocks of waders, with their high metabolic rate, consume vast numbers of the small benthic invertebrates. How this compares in biomass with that consumed by fish cannot be estimated from the data available.Finally the fish eaters, top predators in the estuarine ecosystem, consume a considerable quantity of fish. Fish consumed by two common cormorant species was estimated at 15 to 25 tonnes per annum, not greatly different from the estimated 45 tonnes taken by amateur and professional fishermen.

Birds and man prey on different species of fish, commercial species only being a minor part of the diet of cormorants which feed mainly on gobies, hardyheads and other small fish.

9. Man. Man's principal role in the aquatic ecosystem is still as a predator on the fish. We have no estimate of the fish biomass of the estuary, however it is unlikely that human predation makes a serious impact on this. Except for black bream, the species caught are all recruited from the sea and are probably only a small part of a much larger population that moves freely along the coastline of south western Australia. The estimated 45 tonnes taken during the year was probably only a small part of the estuarine population. Other aspects of man's influence on the estuarine ecosystem are discussed in Section 5.4.

The food web (Fig. 4.3) represents the principal pathways by which nutrients travel through the estuarine ecosystem. It would be difficult to represent the system more accurately without access to a lot more information on productivity, feeding habits, and parts of the web which were not examined. However, one important omission from the Figure (made for simplicity) should be stressed. Faecal material, the faecal pellets of worms, molluscs, and crustaceans, as well as the more bulky faeces of fish and birds, the herbivores especially, return a considerable quantity of nutrients into the detrital system. Dissolved nitrogen and phosphorus compounds are also released to the photosynthetic plants.

Phytoplankton makes only a small contribution to primary production. Sea grasses are quantitatively the most important macroscopic plants, although only a small variety of fauna is directly dependent on them. Benthic and epiphytic diatoms must represent a considerable part of primary production, but we have no measure of this.

Probably the principal input is from detritus derived from a variety of sources the relative importance of which can only be guessed at this stage. Much of the detritus is undoubtedly derived from marginal vegetation, the productivity of which has been shown to be high. However as Teal (1962) points out, there is considerable energy loss in the decay process and a time delay is involved in making nutrients available to the fauna. This is in contrast to the direct primary producer to herbivore route. If, as appears to be the case, much of the detritus derives from within the system, variation in supply may be expected to be small and this to be a well-buffered system where deposit feeders predominate and where recycling of organic matter is extremely important (Levinton, 1972).

There is an excess of energy in the estuarine system and much of this is exploited by the non-resident fauna, but the estuarine detrital system is not fully exploited. Much of the available resources of energy and nutrients become incorporated into the sediments and there is probably a net accumulation during the saline phase. On the other hand, there is a big seasonal loss to the sea with river flow during the fresh phase.

Table 4.15 summarises the composition of the fauna of the various taxonomic groups of the estuary and gives an indication of the nature of their dependence on it. It will be seen that almost identical numbers of benthic invertebrates, fish, and waterbirds were found. As noted by Milne and Dunnet (1972) in the Ythan estuary a few highly productive invertebrates (here only 13 species) support a considerable diversity of predatory fish and birds, most of which are not permanent residents of the estuary. Also as Bayly (1975) has noted in respect of Australian estuaries generally, the proportion of true estuarine species appears to be much lower for fish than for benthos.

In this as in any other estuary, there is change in composition of the biota along the length of the estuary, a gradient in relation to salinity. Here, this is due to duration of favourable or unfavourable salinity as much as to absolute salinity levels. This has been documented above (sections 4.5 to 4.9) and in every case there is decreasing diversity of the aquatic biota from the mouth to the upper reaches of the estuary, with only a very small contribution made by freshwater (oligohaline) organisms. It is clear that the small number of species present in the tidal river is largely attributable to the unfavourable hydrological conditions.

The basin with its marginal marshes, rush beds, extensive sand flats and shallows, and some deeper water, is probably quantitatively the most important

Table 4.15—Numbers of animal species in taxonomic and faunal groups.

	FAUNAL GROUP				total
	Fresh-water	True-estuarine	Estuarine-marine	Stenohaline marine	
Nemertea	0	0	1	0	1
Polychaeta	0	7	6	0	13
Pelecypoda	0	8	0	0	8
Gastropoda	0	10	2	0	12
Crustacea	0	14	5	0	19
Insecta	3	1	0	0	4
Fish	1	6	28	20	55
Waterbirds	—	—	—	—	57

part of the system. However, even here the number of species is less than close to the mouth. During the fresh phase there are fatalities among benthic animals and algae which are able to persist throughout the year, nearer the mouth.

The lower part of the inlet, near the mouth, and the Deadwater are the most marine part of the estuary, where duration of the fresh phase is least. Indeed, the deeper water probably remains marine throughout in many winters. These parts have the greatest variety of benthic fauna at all times and greatest number of fish species during the fresh phase. It is clear that the Deadwater, especially, is a refuge for some species which would be unlikely to survive in other parts of the estuary. The thick *Ruppia* growth is also an important habitat for juvenile fish.

Swan Lake is a unique situation within the estuary having negligible flow through it, reduced tidal exchange and very shallow throughout. Moreover, it was a freshwater lake until some 50 years ago. It now has a thick growth of *Ruppia* and a bottom organic mud with an abundant ostracod fauna, quite unlike that of the rest of the estuary. It supports a large population of waterfowl and provides a protected habitat for juvenile fish.

Stability of the system

Sir Frederick Russell, in his introductory remarks at the Royal Society discussion on Freshwater and estuarine studies of the effects of industry (1972), says: "The finely woven pattern of life in fresh waters and estuaries is most difficult to unravel, and subtle changes in floral and faunal population composition, hardly noticeable at first, may eventually have far reaching results on the whole pattern. Often long-term observations are necessary before man-made effects can be distinguished from the natural changes that may occur".

This study has examined the various elements of the biota, the significance of the various habitat types to these, the importance of the several geomorphic units of the estuary, and the impact of changing environmental conditions. This has been done on the basis of one year of investigation, a year which had a greater than average river runoff. How far, then, are our findings of 1974-75 representative of the long term status of the system, and what stability has the system within the human time scale of a few decades?

There is almost no historical basis on which to judge how the ecosystem may have changed in the recent past and on which to gauge the stability of the system at the present time. It was a healthy system in 1830 and fish formed a considerable part of the diet of the early settlers. Physical changes produced by human activities have been small since then (section 5.4). Even formation of the Deadwater and inclusion of Swan Lake can have had only a small impact on the extreme seasonal hydrologic and dynamic fluctuation and its effect on the life of the estuary.

It seems probable too that over the much longer time scale of the sedimentary record since the sea bar formed, there has been no great change in composition of the biota.

The great majority of the aquatic flora and true estuarine fauna are species well adapted physiologically and behaviourally to the environmental extremes, though at times this is at the cost of heavy mortality. Variation in annual volume of discharge and consequent duration of the fresh phase may be expected to influence distribution and abundance of these organisms within the esturay, but is unlikely to result in any great change in species composition. It is unlikely even that a series of low discharge years would result in any significant influx of marine elements. There is no evidence, from subfossil material, that this has happened in the recent past. It seems unlikely too that a series of high discharge years would greatly change the composition of the fauna. Some less euryhaline species may disappear temporarily, to be recruited again from the sea when conditions again ameliorate.

Granite outcrop at Point Irwin.

In the next section, comparison has been made with other estuaries of south western Australia, all of them seasonal estuaries, but with their individual characteristics. On the one hand, Nornalup Inlet is shown to be a more marine environment than the Blackwood and with a greater range of species and on the other, Peel Inlet has a more impoverished fauna. It is unlikely that the Blackwood estuary will ever approximate either of these extremes under the present climatic regime. Also the sort of cyclical variation, which is observed in the Swan estuary, is not expected in the Blackwood because of the much greater river run-off here, even in a dry year.

Ecosystems with few species are considered to be more vulnerable than those with many species. The elimination of even a single species or the introduction of a new one may upset the balance when, as here, much of the energy of the system is channelled through only a dozen invertebrate species. Such changes may well have taken place in the past and there have been such introductions and disappearances in the Swan estuary in recent years.

Dynamic changes in distribution and abundance of the estuarine biota, with disturbance of the pattern of biotic relations, are to be expected but it is concluded that there is long term stability of the ecosystem—under the present physical environmental conditions.

The Blackwood estuary and the estuaries of the south west

No two estuaries are alike, either in their physical or biological character. The many physical parameters can be quantified and the estuaries can be grouped into categories. However, even where we have adequate data, we are not able with any confidence to predict from the physical features alone, the biological characteristics of a particular system.

One of the principal objectives of the study was to gain an understanding of the working of the ecosystem as the basis for making judgments about its management and the management of other estuaries of the south west. For this purpose, it is valuable to have some biological criteria by which the "health" or "welfare" of an estuary can be judged, even though this must necessarily be a somewhat subjective concept. It is conceived here as a measure of the extent to which the potential of the physical environment is achieved, of the long-term stability the ecosystem displays, and of its vulnerability to perturbations of the environment, however caused.

The recent history of the Thames estuary affords what is perhaps an extreme example of change in the welfare of an estuary. In the early 1960's, the Thames estuary was clearly unhealthy, it was a dying, almost dead, estuary. Today it is in good health, even if maybe it has not yet achieved its full potential.

Absolute abundance, biomass, is indicative only of the energy available to the biota and shows nothing of how this is being used; a eutrophic situation with abundant energy may be highly unstable. Composition of the biota is of course an essential guide to quality, when there is the necessary understanding of the biology of the component species. For example, there are indicator species of pollution and others which are known to be intolerant of pollution. Fortunately, we have as yet little evidence of industrial pollution of our estuaries, although there is evidence of eutrophication of some. Where, as here, salinity is the "dominating limiting entity" for the estuarine biota, the number of species present may be expected to reflect the measure of stress to which the system is exposed (Fig. 4.1) This is not to say that a system with few species is necessarily less viable than one with many, they may both be healthy ecosystems. Nevertheless, the one with many is likely to be the more resilient in the event of environmental change, beyond the range to which it is normally exposed.

Although differences in number of species and composition of the estuarine biota are attributable to a large extent to salinity pattern, the effects of this are modified by a variety of environmental characteristics: geography (latitude and water temperature), tidal exchange, habitat types, and no doubt others, and the effects of these are not easily separable. In south western Australia we are dealing with a single geographic unit, although there are significant minor differences in composition of the fauna between west and south coast estuaries. Similar habitat types are available in all the open estuaries of the south west. Most are shallow and only the Swan has water more than about 10 m deep. Even though we have little data on tidal exchange, it is clear that there are considerable differences between the estuaries in this respect.

Until we have a better understanding of the biology of our estuarine organisms, number of species must be the single most useful criterion on which the quality of an estuary can be judged. On this criterion, the various estuaries of the south west can be ranked in order from Oyster Harbour to estuaries east of Albany where mouth bars remain closed, except immediately following heavy rain in the catchment.

Only fish and molluscs have been studied in any detail. The fish fauna of south coast estuaries are compared by Lenanton (1974) and it will be seen from this, that the Blackwood compares favourably with other estuaries. This paper is valuable, particularly with respect to Lenanton's different categories of estuaries, ranging from permanently open to permanently closed. Here, only the permanently open estuaries are compared; those where fish and other organisms can move in and out at all times. However, because of their mobility, fish are not likely to be good indicators of the welfare of the ecosystems, at least not of these relatively healthy, permanently open estuaries.

Molluscs, with their limited mobility, are likely to be better indicators of the welfare of these estuaries. No estuarine or marine molluscs are known to osmoregulate, their blood remains in osmotic balance with the environment, although some are able to tolerate considerably reduced environmental salinities for prolonged periods. Identification presents few difficulties, and the mollusc fauna of the estuaries is well enough known to give a good measure of species abundance, even though little has yet been published. Moreover they have the added advantage of leaving a fossil record of their presence. The number of mollusc species is therefore used here as the basis for comparison between the open estuaries of south western Australia.

1. Oyster Harbour. This has an area of 16 km^2. The mouth is narrow but there is no sill and tidal range is virtually undamped. There is no strong flow through it in winter from the two tidal rivers, the King and the Kalgan, which discharge into it. Surface salinity probably seldom drops below 27‰ and then for only a short time (McKenzie, 1964). The centre is relatively deep, over 7 m, but there are extensive marginal shallows which provide a sheltered, virtually marine, habitat for molluscs and other benthic animals. Oyster harbour and the two rivers thus provide a valuable basis for comparison with other estaries of the south west, with their greater seasonal extremes.

   G. W. Kendrick (pers. comm.) has listed 43 species of bivalve and 69 gastropod molluscs from Oyster Harbour. Because these were identified from shell material, it is possible that some do not live there now, but more would undoubtedly be found in an intensive survey. The list includes almost all the species found in the Blackwood and other estuaries of the south west.

2. Nornalup Inlet. This is rather smaller than Oyster Harbour and again has two tidal rivers discharging into it, but with a considerably greater flow of water in winter. The mouth is narrow, but the tidal range is little damped and sea water continues to be pumped back into the Inlet even in winter, so that bottom water in the centre of the Inlet is seldom less than about 30‰ and surface water about 10‰. Walpole Inlet opens off Nornalup Inlet, this is very shallow and hydrological conditions are much more extreme with the water being fresh for some months in winter and becoming slightly hypersaline at times in summer.

   Collections were made by Kendrick and by a group of students under winter conditions (Chalmer, pers. comm.). They listed 17 species of bivalves and 12 of gastropods and it is likely that the real number will be considerably greater than this. Species diversity is considerably less in Walpole Inlet; 6 bivalves and 4 gastropods (Lenanton, pers. comm.).

3. Estuary of the Swan River. The estuary has a large (24 km), deep (to 22 m) basin with two tidal rivers discharging through it, but with only half the discharge of the Blackwood River, despite the large catchment. Tidal range at Perth is about

80% of that at the mouth, but effective tidal exchange with the basin is reduced by the long (8 km) inlet channel. Surface salinity in the basin varies from 5‰ in a wet winter, to about 20‰ in a dry winter and is marine through summer. Deep water in the basin and inlet never deviates greatly from sea water salinity, but may be deoxygenated under winter, stratified conditions (Spencer, 1956). Chalmer, Hodgkin, and Kendrick (1976) found 96 species of Mollusca in the estuary, but they believe that not more than 33 of these (18 bivalves and 15 gastropods) are continuously represented in the estuarine fauna, the others being recruited from marine populations. Of these 33 only 3 bivalves and 4 gastropods are thought to be exclusively estuarine and one is a freshwater species. Only 6 bivalves and 7 gastropods were thought to live permanently in the basin and tidal rivers, the remainder (20 species) being confined to the inlet region.

The less extreme hydrological conditions experienced during dry winters, with salinity remaining greater than 15 to 20‰, permits invasion of the basin region by a few species not found there following wet winters, or which are represented only by juveniles recruited from populations in the inlet region. The most notable of these is the edible mussel *Mytilus edulis planulatus*.

4. Leschenault Inlet is a coastal lagoon of 28 km^2, into which two rivers, one of them tidal, discharge. The Inlet becomes somewhat hypersaline in summer (about 45‰) and much of it probably seldom drops below 10‰ in winter, since the new cut was made (1951). Tidal exchange is good near the mouth, but is much reduced along the long, narrow, shallow lagoon. Chalmer and Scott (unpublished data) found 6 bivalve species and 3 gastropods in a survey made in December 1974. This survey did not include the immediate vicinity of the mouth, the most marine part.

5. Peel and Harvey Inlets with the Murray and Serpentine Rivers, form the largest estuarine system of the south west (115 km^2). They have a very small daily tidal range, a maximum of only 5 per cent of the ocean tide, although longer period "tides" are little damped. River flow is relatively small and salinity seldom drops below 10‰ for more than a brief period and may become slightly hypersaline in summer. Only 5 species of bivalve and 6 gastropods have been found in surveys in Peel and Harvey Inlets. However some species, such as *Arthritica helmsii*, were present in great abundance.

6. The Blackwood estuary. During the course of the present survey of this estuary, 8 bivalve species were found and 10 gastropods, a total of 18 mollusc species. Collecting has of course been more thorough and prolonged than in the other estuaries, except the Swan, nevertheless in a brief preliminary survey made in December 1973 all but three (gastropods) were found.

It is possible that if some taxon, other than Mollusca, had been selected the estuaries would rank differently. Indeed it should be noted that Allender (unpublished data) found that the Blackwood estuary had a very depauperate macroscopic algal flora, compared with other estuaries he visited in the south west. He attributed this both to the relatively short saline phase and lack of solid substrates for attachment.

The Blackwood receives the greatest volume of river flow and has probably the most prolonged freshwater phase of any of our estuaries. It is therefore surprising to find that even looking at the fauna of the basin region, the Blackwood does not rank last on the criterion of number of mollusc species. The explanation for this would seem to be that there is a core of "true estuarine" species, which have the physiological capacity to flourish under these extreme hydrological conditions, but that there are other factors which are unfavourable to them in the Peel-Harvey system especially. What these factors are is not known, but it is suggested that they may be related to the poor tidal ventilation of that system.

If number of mollusc species is an acceptable guide to quality of an estuary, then the Blackwood compares favourably with the other estuaries of south western Australia. With the evidence adduced above of long term stability, there is then every reason to believe that this is a healthy, resilient, ecosystem in balance with the extreme hydrological conditions, despite the relatively few species when compared with more marine estuaries elsewhere.

4.13 Single species studies

It will be evident from the foregoing that the benthic fauna of the Blackwood and other seasonal estuaries can be categorised as a "physically controlled community", rather than a "biologically accommodated community" (Sanders, 1968). The environment is one in which "the physical conditions fluctuate widely and the animals are exposed to severe physiological stress". If we are to understand how the community is maintained in such an environment, it is important to understand how individual species respond.

It was no part of the present study to investigate the biology of individual species. However, a few Western Australian estuarine species have now been sufficiently thoroughly studied for us to interpret the devices by which they are enabled to maintain populations in this stressful environment. The mussel *Xenostrobus securis* was studied by Wilson (1969) and the small crab *Halicarcinus australis* by Lucas and Hodgkin (1970). Planktonic copepods have been studied: *Sulcanus conflictus* by Bhuiyan (1966) and *Gladioferens imparipes* by Rippingale and Hodgkin (1974b), and the interaction between these two species by Rippingale and Hodgkin (1974a).

Three other benthic animals have since been studied in some detail and the, as yet unpublished, results are summarised below as further "case studies", without any attempt at a synthesis here.

An estuarine-freshwater shrimp, *Palaemonetes australis*.

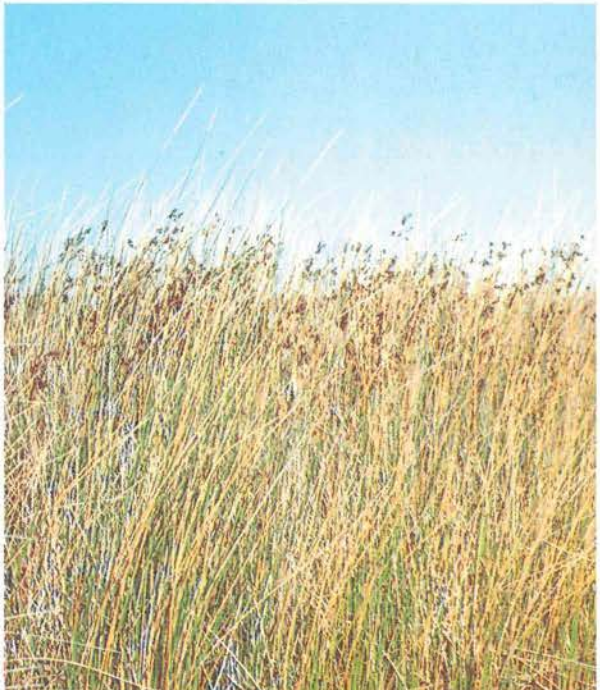
Both in the present investigation and in earlier studies (Thomson, 1957; Boulden *et al.* 1970), *Palaemonetes* has been shown to form an important part of the diet of estuarine fish. It is the largest invertebrate species to be eaten in quantity and it was found in stomachs of most fish species examined and in over 25 per cent of guts from five of the more abundant species (Tech. Rep. 5).

Knowledge of the biology of this species derives mainly from a recently completed study by Bray (1978) and this is the source of most of what follows here. Bray's studies were undertaken mainly on populations in the Blackwood and Swan estuaries, with observations also in adjacent freshwater bodies.

P. australis occurs throughout the Blackwood estuary, from the Deadwater, where surface salinity is greater than 30‰ for 5-8 months, to its head where surface salinity does not exceed 5‰. However, it is

▲ Marginal vegetation, western shore of the basin.

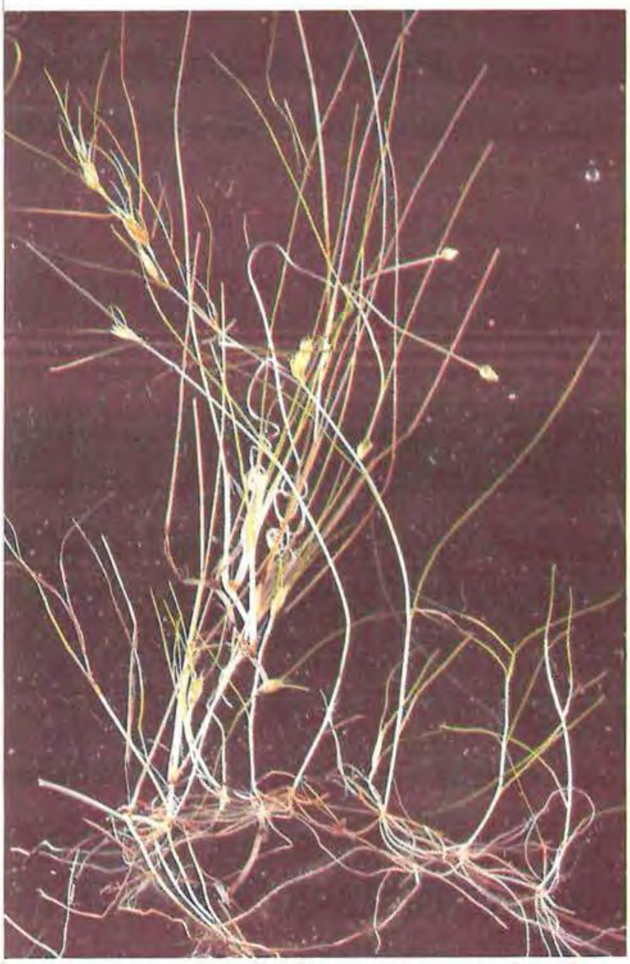
◀ Rush islet with a *Melaleuca cuticularis* bush.



▲ Rushes, *Juncus krausii,* shoots growing from rhizomes.

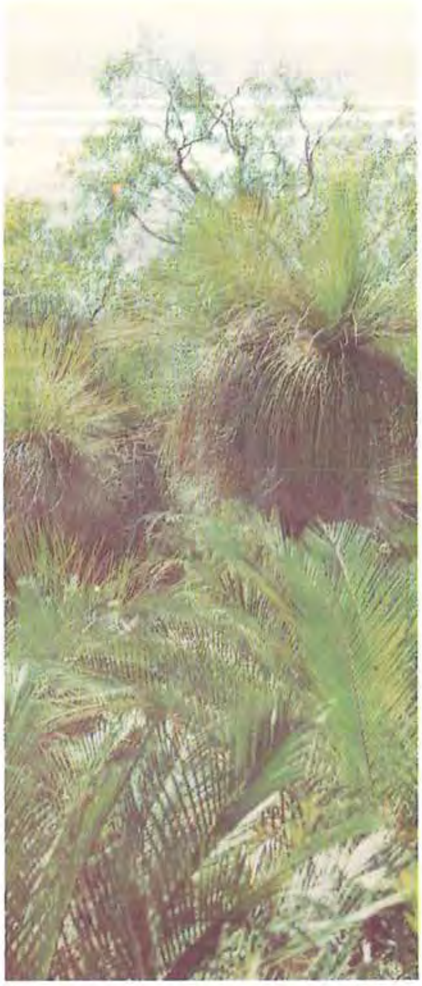
◀ Eroding rushes, North Bay.

▲ Marginal vegetation near Molloy Island. *Melaleuca cuticularis* at the water's edge.

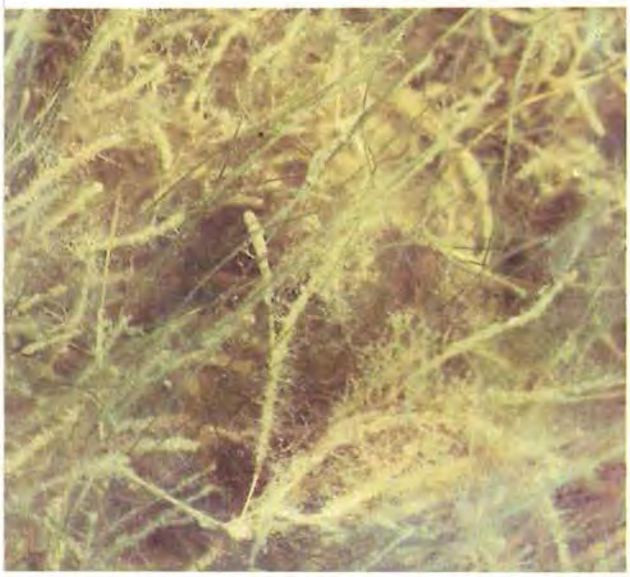


◀ *Ruppia maritima*. Foliage, male and female flowers, rhizomes and roots.

▲ Salt-marsh on Point Pedder with *Arthrocnemum* and dead paperbark trees.



▲ Thicket on sand ridge at Point Pedder; *Macrozamia* and *Xanthorhaea*.



◀ *Ruppia* encrusted with diatoms and other epiphytic algae.

▲ Point Pedder, September.

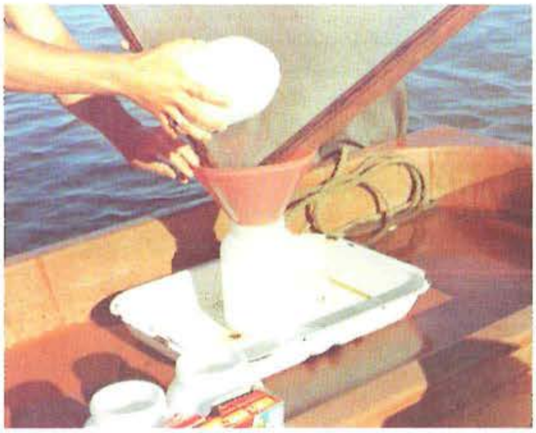
▼ Dry salt-marsh, Point Pedder, March.

▲ Salt-marsh with samphire (*Salicornia*), rushes and *Melaleuca*. North Bay.

◀ *Salicornia blackiana* in flower.

Scirpus validus; in the tidal river. ▶

▼ Marginal swamp of the basin.

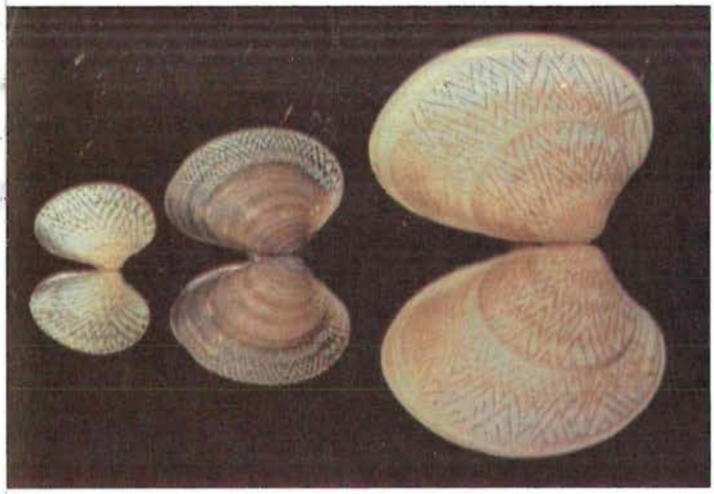


Above: Sampling for bottom fauna—
Taking a core sample
Sieving the sample.
Washing sieved animals into a jar.

◀ Sorting samples in the field laboratory.

▲ *Sanguinolaria biradiata* burrowing.

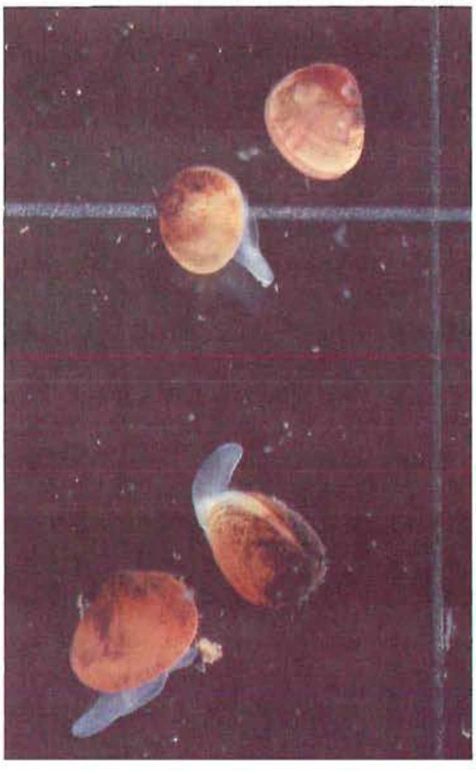
▲ *Nassarius burchardi.*



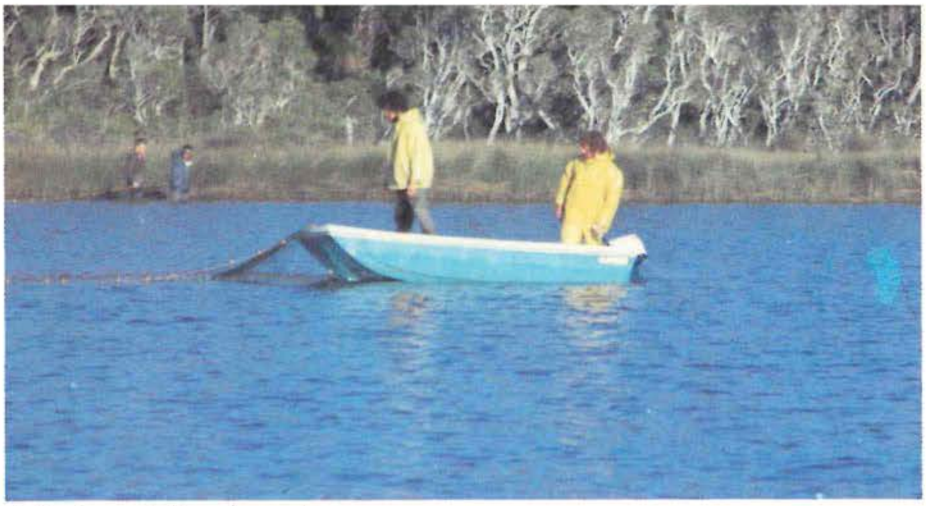
◀ *Katelysia scalarina* shells, 0^+, 1^+, 2^+ years old.

▼ *Arthritica helmsii.*

0 5mm

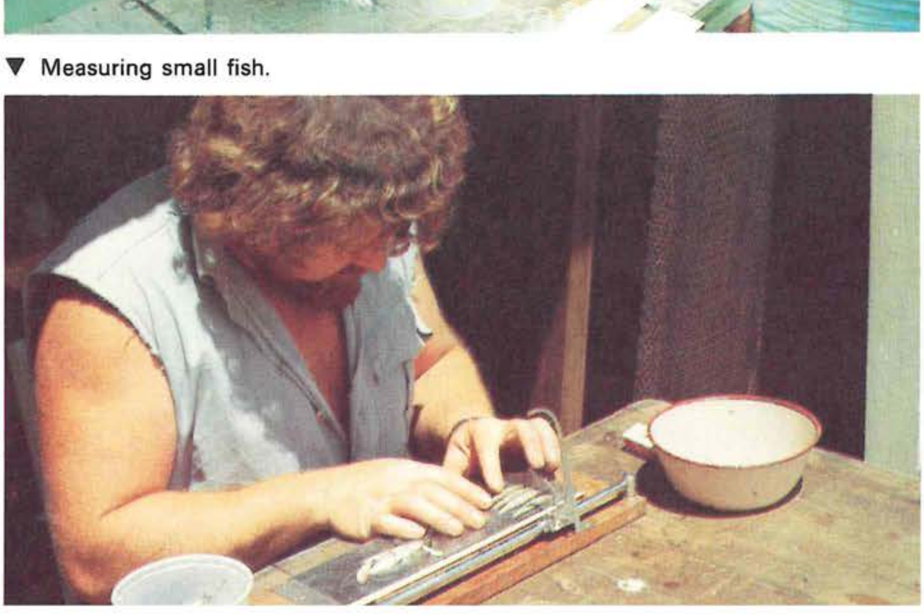


▼ *Palaemonetes australis,* female with eggs.



▲ Paying out the seine net.

▼ Measuring small fish.



▲ Sorting the catch. Photo: R. Lenanton.

◀ Hauling the net in the Deadwater.

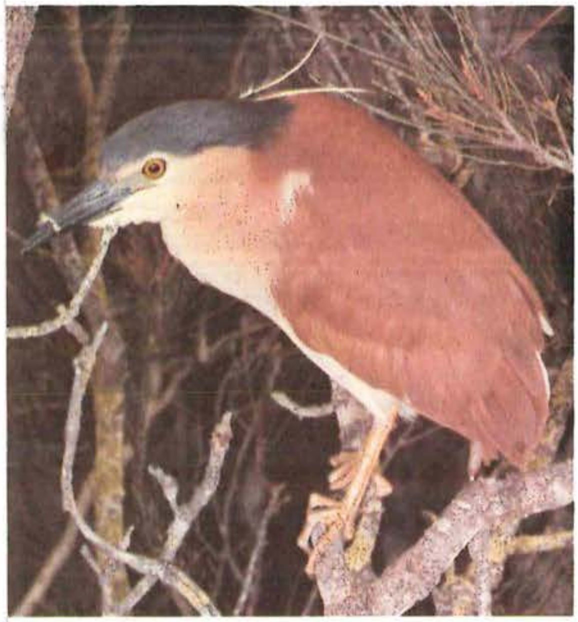
◀ Taking fish gut samples.

▼ Juvenile fish from a haul in the Deadwater.

▲ Black swans feeding in Swan Lake.

▼ Bar-tailed godwit. Photo: Graeme Chapman.

▲ Musk duck. Photo: Ray Garstone.



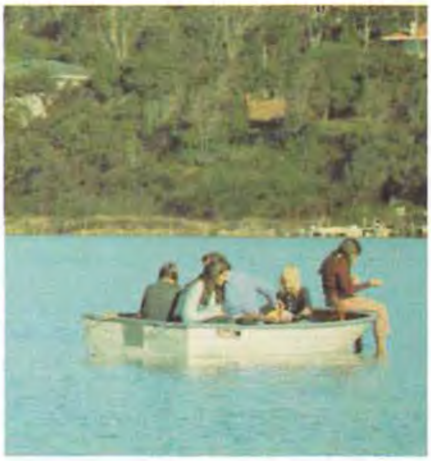
◀ Nankeen night heron. Photo: Graeme Chapman.

▼ Curlew sandpiper. Photo: Graeme Chapman.

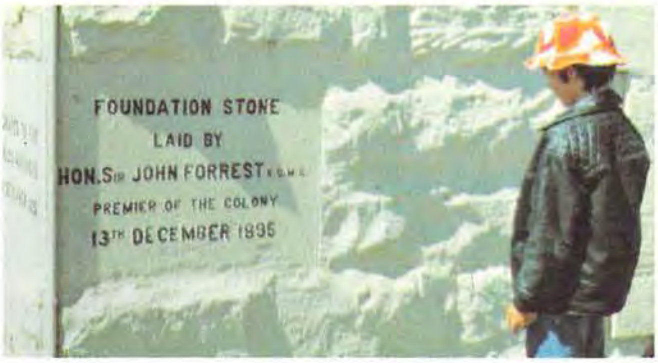
▼ Black cormorants. Photos: Graeme Chapman. ▼ Osprey.

New homes in Augusta and on the river bank.

Fishing is a popular pastime for residents and visitors alike.



Foundation stone of the lighthouse. ▶

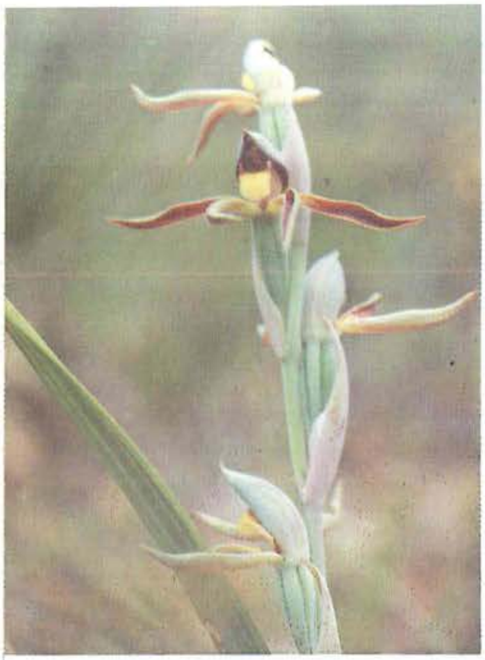


▼ The old waterwheel, Cape Leeuwin.

The old cemetery and Pioneers Memorial. ▶

A hot fire on Molloy Island has caused regrowth from trunks of jarrah and marri trees. ▼

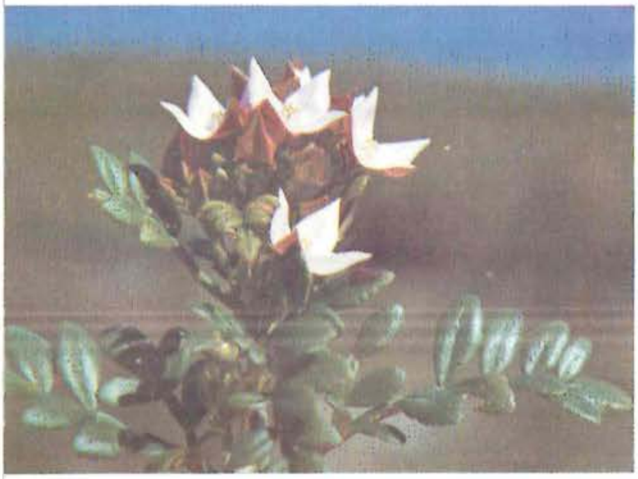
▼ Foredunes are a narrow barrier between Flinders Bay and the Deadwater. Burning off coastal scrub on the Leeuwin ridge.



LOCAL WILDFLOWERS

Above:

Lyperanthus serratus.
Hovea elliptica.
Banksia occidentalis.
Photo: W.A. Herbarium.



◀ *Boronia alata.*

Banksia meisneri. ▶
Photo: W.A. Herbarium.

Boronia molloyae. ▶

◀ *Lambertia orbifolia.*
Photo: W.A. Herbarium.

Below:

Kennedyia macrophylla.
Photo: Canberra Botanic Gardens.

Wattles in the tidal river.

also common in non-estuarine waters: saline and completely fresh (<0.5‰), flowing and still. It breeds successfully in all these situations and is one of the very few species of animal adapted to such a wide range of natural waters.

Thus *P. australis* is euryhaline. Physiologically, this is explained by its ability to osmoregulate over the salinity range 0.5‰ to 40‰. Adult animals maintain an internal osmotic concentration equivalent to about 20‰ S (Fig. 4.10). Moreover, shrimp survive the sort of sudden transfer from high to low salinity to which they are liable to be subjected in estuaries, without significant mortality.

Within the Blackwood estuary, *Palaemonetes* populations are restricted to situations where there is aquatic vegetation and shrimp are seldom found far from the cover afforded by *Ruppia* or *Potamogeton*. Submerged grass, algae, or other vegetation afford cover in fresh water localities. Furthermore, population density reflects density of weed cover and probably also density of algal epiphytes. At Deadwater and Swan Lake sampling Stations 0.2 and 5.5 where *Ruppia* was always thick (about 3 000 g/m^2 dry wt), population density averaged about $750/m^2$ in contrast to about $100/m^2$ at stations in the channel and basin where *Ruppia* was relatively sparse (about 500 g/m^2 dry wt at Stations 13, 17, 61). With the disappearance of *Ruppia* from the latter stations in summer, *Palaemonetes* populations declined to very low levels.

Palaemonetes is omnivorous and feeds on both plant and animal matter: on algal epiphytes and diatoms on *Ruppia*, on a variety of small living and dead animals, and probably also on detritus.

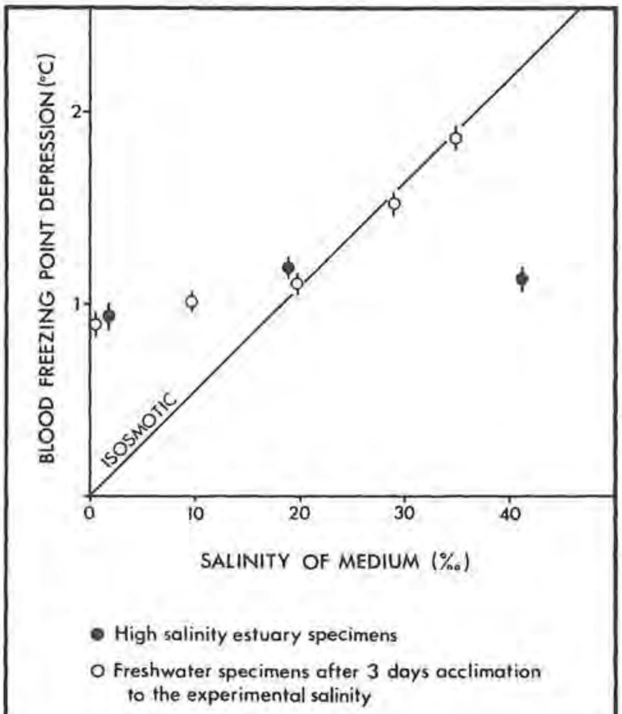


Fig. 4.10 Response of Palaemonetes australis *to osmotic stress. The Figure shows that the blood is isosmotic with the external medium at a salinity of 20‰; below this animals maintain blood osmotic concentrations equivalent to 18-20‰ S, i.e. they osmoregulate. At salinities above 20‰, animals from a high salinity water continued to osmoregulate, to 40‰, but animals from fresh water could not do so, their blood was in osmotic equilibrium with the medium (they were osmoconformers).*

Breeding starts in spring and continues through summer. Females carry eggs from September to March with a peak in November (Fig. 4.11). Eggs take about 25 days to mature, while still attached to the female. The brief larval development, during which larvae do not feed, lasts another 6 days at summer temperatures (20-28°C), so that juveniles are mainly recruited to the population from October to December.

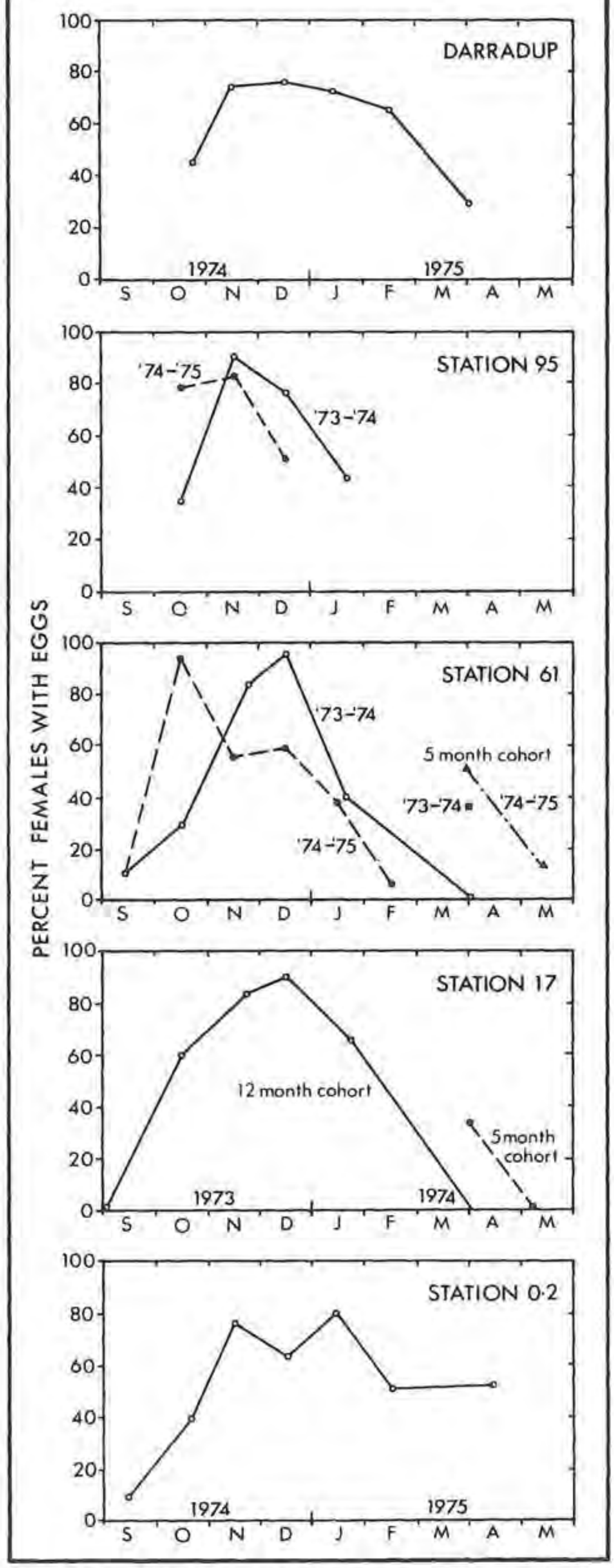


Fig. 4.11 Seasonal variation in percentage of egg bearing females of Palaemonetes australis *at five stations in the Blackwood River estuary.*

TABLE 4.16—Reproductive capacity of *Palaemonetes australis*.
Estimated number of eggs produced per m² in samples taken at five stations in the Blackwood estuary
A: 1 year age class B: 5 month (spring) cohort
nd: no data available

Station	Date	Class	S	O	N	D	J	F	M	A	M	Total
95	1973-74	A	nd	91	265	195	17	0	0			568
	1974-75	A	nd	262	132	72	23	0	0			490
61	1973-74	A	38	92	272	40	27	1	0	0	0	470 } 930
		B					0	195	123	142	0	460
	1974-75	A	134	137	291	111	14	0	0			687 } 718
		B						23	8			31
17	1973-74	A	10	40	87	34	17	0				187 } 457
		B						0	166	104	nd	270
02	1974-75	A	535	990	1560	135	985	442	86	nd	nd	5333

Some of these early recruits reach maturity and spawn in late summer (February to April). Again productivity is related to weed density and Bray estimates an egg production in the Deadwater weed beds, almost ten times that in the estuary proper (Table 4.16).

Reproductive capacity is not high; 2 to 3 batches of eggs are produced during the season with 20 to 60 eggs per batch, according to size of female. It is clear that predation pressure by fish largely accounts for shrimp mortality. This pressure varies with seasonal changes of abundance of fish in the different parts of the estuary and wlth the density of weed cover available to the populations (Table 4.17). An interesting aspect of Bray's study is evidence of other density dependent effects, particularly the delayed juvenile development observed in the dense Deadwater population.

It is evident from the foregoing that *Palaemonetes australis* is a very successful estuarine species, with a remakable flexibility of response to environmental change. It is equally at home in fresh waters outside the system and estuarine populations may be recruited from the river and its tributaries especially when there is strong river flow. However its abundance, if not its survival, within the estuary is largely dependent on the persistence of its preferred habitat *Ruppia* and *Potamogeton* beds.

An estuarine-marine snail, *Nassarius.*

Two species of this genus of snail are found in the Blackwood estuary. One, *N. burchardi*, was rare here but common in the Swan estuary, the other, *N. pauperatus*, was common in the Blackwood but rare or absent from the Swan. A recent study by Smith (1975) has provided a good understanding of the biology of these snails and their response to the estuarine evironment.

It is evident that both species are euryhaline marine animals, which are successful under estuarine conditions by virtue of their ability to tolerate reduced salinity. They are not confined to estuaries and also live in sheltered marine localities. Most of Smith's work was with *N. burchardi*, but what follows probably applies equally to *N. pauperatus*, with the significant exception of rate of development.

TABLE 4.17
Estimated fish predation pressure on *Palaemonetes australis*. Predation pressure = mean number of fish per sample of 8 principal species x proportion of fish with *P. australis* in diet.

Station	Sept. '74	Nov. '74	Mar. '75
Swan Lake	50.6	44.8	70.9
Deadwater	74.7	59.3	45.3
Inlet channel	11.6	60.6	78.6
Basin	19.3	47.6	8.4
Molloy Island Basin	13.3	11.6	35.1

The snail is a scavenger and possibly also a predator; it lives on the sand flats, moving through the surface sediment, and is most abundant where there is growth of sea grasses. In the Blackwood, it is confined to the vicinity of the mouth and in the Deadwater in winter, but invades the basin to Station 90 during the saline phase.

This distribution is explained by the response of the snail to lowered salinity. It remains active at salinities above 7‰, but below this level all activity ceases, the animal withdraws into its shell and closes the operculum, thus isolating itself from immediate osmotic stress. However, when exposure to salinities below 7‰ was prolonged, about half the animals were found to survive for two months, but all died within three months.

On the basis of hydrological conditions experienced in the estuary, the observed distribution of *N. pauperatus* corresponds closely with what would be expected, the operative factor being the length of time during which low salinity conditions persist. The hazardous nature of this situation for the population is emphasised by the large numbers of freshly empty shells found in Seine Bay, in contrast to the more favourable conditions experienced in the lower Swan estuary. There *N. burchardi* were exposed to daily tidal changes of salinity during winter runoff; they were inactive at salinities below about 10‰ but become active again with the return of marine water.

Success in such an environment is also dependent either on regular recruitment from a marine population or a successful reproductive strategy within the estuary. Both species were able to breed in the estuaries studied. The eggs are laid in flat capsules which are attached to the substrate. *N. burchardi* eggs were laid in and developed at salinities of 10.5‰ to 35‰, though hatching rates were low in salinities below about half sea water. Eggs hatch to veliger larvae, which are planktonic for about 4 weeks. Small snails settle from the plankton and they had grown to about 5 mm shell length before they appeared in the populations sampled. They continue to grow until they are adult and sexually mature (*N. burchardi* 8.5-9.5 mm; *N. pauperatus* 11-12 mm), after which the shell does not increase in size.

In the Swan estuary, *N. burchardi* breeds both in spring and autumn and is able to complete its development in five months in favourable salinities (greater than half sea water), so that there is certainly one and probably two generations in a year. *N. pauperatus* appears to have only a single spawning in the Blackwood estuary, in spring, and is slower growing than *N. burchardi*. Under favourable conditions, it can be expected to complete development from egg to adult in less than a year. However, with the prolonged period of unfavourable conditions experienced in the Blackwood estuary, animals require 12 to 15 months to complete development. At best only one generation a year is produced and many animals will not reproduce until they are two years old.

Thus *Nassarius* shows both physiological and behavioural adaptations to life in estuaries. On the one hand it is able to remain active at salinities down to about 10‰ and on the other, when salinity drops beyond this limit, it is able to isolate itself from the environment for prolonged periods by closing the operculum. In this condition 50 per cent of animals survived exposure to salinities less than 7‰ for 2 months; all were dead after 3 months.

An estuarine-marine crab, *Portunus pelagicus.*

The blue manna crab is a euryhaline marine animal which enters estuaries and marine embayments after its larval and early juvenile development in the sea. A study of the biology of this crab was made in Cockburn Sound and Leschenault Inlet by Meagher (1971). The findings of that study can be applied to the Blackwood estuary.

Distribution of this crab is mainly in tropical waters and the Blackwood is near the southern limit of its range. Meagher stressed the temperature dependence of adults; he found crabs to be completely inactive below 16°C and only fully active above 17°C (males) or about 20°C (females), and showed that it is the higher water temperatures which attract crabs to enter estuaries of the south west. Once inside they are additionally favoured by the greater food availability.

Crabs may be expected to enter the estuary in January or February. Young crabs continue to grow and moult in the warm shallow water during the summer and early autumn. Adult females will ovulate soon after they enter the estuary; batches of a million or more eggs attach to and develop on the pleopods for two or three weeks, depending on temperature. The females then return to the sea, where the eggs are released and larvae hatch. They may then re-enter the estuary and produce further batches of eggs during the summer, returning to the sea each time to release them. Many animals leave the estuaries for adjacent marine embayments in response to the drop in temperature some weeks before the first heavy rain and consequent freshwater flush.

Although *Portunus* is euryhaline and osmoregulates at salinities less than 35‰, it does not long survive very low salinities. After two or three days in salinities of less than 9‰, some animals die and few live for more than five days. This presents no problem in Leschenault Inlet, where salinity generally remains above this figure and adult and juvenile crabs can survive in the Inlet through winter, inactive because of the low temperature, and buried in the sediment where salinity is probably even higher. When buried, they have very low respiratory rates and therefore there is little irrigation of the gills from the overlying fresh water thus reducing osmotic stress.

Crab numbers vary greatly from year to year in the Blackwood as in other estuaries of the south west; there are good and bad seasons. They are reported to have been so plentiful some years ago that professional fishermen turned from scale fish to crab fishing. This great variation in abundance is probably related to duration of the fresh phase and time of onset of the saline phase, also to success of the pelagic stages and movements of ocean currents which return juveniles to the vicinity of the estuary mouth when hydrological conditions are favourable. Development of the pelagic stages has been studied, but little is known of their movements except that larvae are carried a considerable distance to sea before returning as juveniles to the coast.

"A magnificent and peaceful river". The estuary near Alexandra Bridge.

CHAPTER FIVE SOCIAL ASPECTS

This Environmental Study aimed primarily at an understanding of the Blackwood estuarine ecosystem, of how this has been affected by human activities and how it may, in the future, be influenced by such activities. It was not proposed to make a detailed social study of the human population; all that has been attempted here is to understand the nature of human usage of the area and the attitudes of residents to the amenities it offers and to possible environmental change however caused. Specifically, we wanted to know more precisely the attitude of the local population to the proposed mining and dredging and to understand the nature of and motivation behind the known objection of many people to the proposal. We wanted to know too, to what extent these attitudes were based on knowledge and understanding of the problems involved and the extent to which they were based on emotional responses to perceived threats to their way of life and aesthetic values.

Objections to the proposed mining were based on social, aesthetic, and environmental grounds. Therefore it was desirable to gain a knowledge of the social background to these and to try to understand how this influenced the expressed appreciation of the environment by the people who use the estuary and its environs. Aspects of the social studies which relate specifically to the mining proposal have been reported more fully elsewhere. The present chapter is concerned primarily with broader social issues: who use the area? in what way do they use it? what are their attitudes to it? and what are their anticipations for it and for themselves in relation to it?

This report is based on individual studies in each of which the objectives, methods employed, results, and conclusions are reported in much greater detail than is possible here. Technical Reports 10, "Perception of Environmental Change at Augusta, Western Australia," and 11, "Study of Attitudes Towards Environmental Change in the Blackwood River Area," discuss findings about the resident population of Augusta town and the adjacent rural area respectively (Fig. 5.1). They present demographic data about the populations and analyses of the results of questionnaires designed to elicit both social information and information on the attitudes of the population to aspects of their environment and to actual or potential change in this, whether caused by the possible mining, tourism, or other forms of development.

Because both populations were small questionnaires were given to all residents. Even so there were inevitably biasses and the more important of these are noted in section 5.1. The questionnaires were distributed and collected personally after wide publicity and every effort was made to involve the community in the study. In consequence there was a very good response with 78 per cent. returns in the town, most non-returns being from holiday cottages, and 98 per cent. in the rural area. Open as well as closed questions were included so that respondents could amplify their responses and there was abundant evidence of careful thought having gone into completion of questionnaires. Some quotes are included in Technical Report 10.

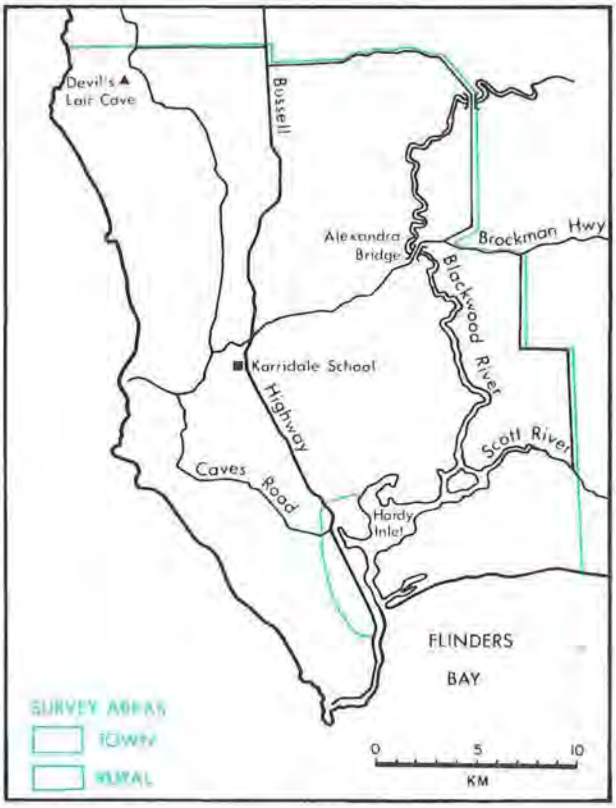


Fig. 5.1 The social survey. The areas of survey.

Technical Report 9 "A Survey of the Recreational Usage of the South Coastal Estuaries of Western Australia", records the results of a study which aimed to quantify the different recreational activities commonly pursued by visitors to the estuary. This was part of a more extensive survey. Holiday log registers were supplied by the Department of Fisheries and Wildlife to the owners of all venues catering for campers, caravanners, and people staying in holiday cottages and flats. These gave information required by the owner and data on recreational activities, the latter on a tear-off slip which was returned to the Department. In addition, the visitors were given individual party log sheets to complete during their stay (Fig. 5.2). Inevitably there were problems with both the registers and log sheets resulting in incomplete data and requiring further statistical manipulation, however the generally good response made it possible to present valuable data on tourist usage of Augusta and the activities of tourists.

Technical Report 12 on "Augusta Tourism" records the growth of Augusta as a tourist centre, discusses the attractions and facilities offered to tourists, and describes the origins, activities and movements of tourists; the last was part of a more extensive survey made into tourism in the south west.

Technical Report 13 "The Blackwood Estuary: Recreation Versus Sand Mining, an Economic Appraisal is discussed more fully in the report by EMAC: "Anticipated Effects of Dredging in the

THE HOLIDAY MAKER

This logsheet is part of a survey being undertaken by the research branch of the Department of Fisheries and Fauna on the usage of the estuaries of the South Coast.

This information is vital for the future planning of recreational facilities and your co-operation in completing this form is greatly appreciated. Your name and address is not required.

B. K. BOWEN,
DIRECTOR'

RESORT NAME

DATE		NUMBER IN PARTY		PLEASE TICK (✓) THE APPROPRIATE COLUMNS													
				OWN BOAT			MAIN HOLIDAY ACTIVITIES										
							ESTUARY FISHING										
IN	OUT	ADULTS	CHILDREN UNDER 14	POWER	YACHT	OTHER	ROD OR LINE	NET	CRABBING OR PRAWNING	PLEASURE BOATING	BEACH ACTIVITY	WATER SKI-ING	OCEAN FISHING	SPEAR FISHING	SIGHT-SEEING	ORNITHOLOGY	NOTHING SPECIFIC e.g. general holiday
....../....../......	....../....../......																

WHEN COMPLETED, WOULD YOU PLEASE RETURN THIS FORM TO THE PROPRIETOR OF YOUR HOLIDAY RESORT.

Fig. 5.2 Tourist Log sheet issued by the Department of Fisheries and Wildlife.

Blackwood River Estuary", but aspects relating to tourism are also considered here. This was a desk study based on information from a variety of sources.

The estuary of the Blackwood river is used by the permanent residents of Augusta and of adjacent rural areas, by owners of holiday homes, and by tourists. The last range from overnight visitors who come by coach or car to campers and caravanners some of whom spend their entire holidays at Augusta. They all have their impact on the environment, however minor, and their attitudes and views about the estuary are relevant to decisions about its future.

Demographic data with respect to the popultaion of the town and of the rural area adjacent to the estuary is presented in section 5.1 and the attitudes of the people to their environment, and to the estuary in particular, are discussed in section 5.2. Information relevant to tourists and tourism is considered in section 5.3 and section 5.4 gives an account of the influence of man on the estuary from prehistoric times.

5.1 Demographic Data

The demographic data presented here are from published census material, from earlier records supplied by the Australian Bureau of Statistics, and data collected during the survey at Augusta. The latter (Tech. Reps. 10 and 11) are not fully comparable with official statistics because of different objectives from those of census authorities and because the study was made in mid-summer instead of mid-winter. However, in some respects they give a better understanding of the structure of the population.

The Augusta population differs considerably from that of the Shire as a whole and of the State. Augusta town has grown rapidly since 1947; both population and number of houses have increased about three times in the last thirty years (Table 5.1). This is not reflected in the shire generally where the population has decreased since 1954. This growth is attributable to a large extent to the influx of retired persons. The survey shows that 39 per cent of the population is over 60 years (12 per cent for W.A.) (Table 5.2). The continuing

TABLE 5.1—POPULATION DATA FOR AUGUSTA 1901-1971. Source - Australian Bureau of Statistics. nd - no data available.

	Males	Females	Total	Occupied Dwellings	Unoccupied Dwellings	Persons in Augusta/ Margaret River Shire
1901	43	16	59	12	nd	574
1933	46	35	81	21	nd	2952
1947	79	63	142	48	nd	2790
1954	118	99	217	72	nd	3625
1961	149	131	280	96	55	3590
1966	nd	nd	308	107	80	3238
1971	166	184	350	138	123	3106
1977	229	235	464	208	164	3010

Table 5.2—Age Composition of the Population

	AUGUSTA URBAN				AUGUSTA RURAL		AUGUSTA-MARGARET RIVER SHIRE				W.A.
	male	female	total	%	total	%	male	female	total	%	%
0-17	—	—	88	18.5	—	(36)[1]	636	553	1189	38.3	35.9
18-19	9	1	10	2.1	4	1.3					3.5
20-24	9	7	16	3.4	24	8.1	103	98	201	6.5	9.1
25-29	12	15	27	5.8	18	6.0	87	88	175	5.6	7.6
30-39	13	12	25	5.3	30	10.1	179	169	348	11.2	12.5
40-49	15	23	38	8.0	49	16.4	215	198	413	13.3	11.6
50-59	39	46	85	17.8	35	11.7	167	163	330	10.6	8.8
60 +	88	202	290	39.0	31	10.4	232	218	450	14.5	11.0
TOTAL	185	202	476		191		1619	1487	3106		

1. An assumed figure on the basis of Shire and W.A. data.
Sources: Australian Bureau of Statistics and Technical Reports 10, 11

growth of the town is also shown by figures for recent building activity (Table 5.3). On the other hand, the school population has remained virtually static over the last eight years (Table 5.4).

5.2 The Resident Population

The town survey included "permanent residents", people who normally live and work in Augusta, and "non-permanent residents" who own a cottage and have come to Augusta each year for the last five years, but do not live or work there.

The large proportion of retired persons in the Augusta population and the skewed age distribution give a special character to the town community. Job-centred interests are less important here than in a more typical community while leisure time activities assume a greater importance. There are a number of well-supported community organisations and a sense of community responsibility, which is well illustrated by the response to the envisioned threat of mining and the interest in and co-operation given to this study.

Even though many residents have only lived in the town for a relatively short period many have had long contact with it, having holidayed there for many years before establishing their homes in the town.

There is also a high level of community interest in the rural area, with participation in community organisations, although the interests of the population naturally differ from those of the town. In some respects their stake in the area and concern for it strikes deeper. To them their environment is their livelihood rather than something to be appreciated for the pleasure it affords. Many have lived there for twenty or more years and have themselves established the farms on which they live and from which they derive their income, and have experienced hard times in the process. Most of them expect to retire in the area (Tech. Rep. 11, Table 12).

TABLE 5.3—Building Activity in the Augusta—Margaret River Shire. Figures show number of building permits issued. Source: Augusta—Margaret River Shire.

	June 71-74	June 74-75	June 75-76
Margaret River Town	71	19	29
Margaret River Rural	82	5	6
Augusta Town	117	34	55
Augusta Rural	10	4	0
TOTAL	280	62	90

The part played by community organisations in dissemination of information about the mining proposals and formation of attitudes was shown by answers to the questionnaires. Such is their function. The Leeuwin Conservation Group, with 66 members among residents, was particularly important in this respect; it circularised members with information about the mining proposal. Membership of community groups correlates strongly with environmental concern both in town and rural area.

It is unfortunate that at least in the early stages of the mining controversy, a lack of confidence was expressed in the attitude of the Shire Council. This was probably inevitable with the Council activities concentrated in the larger centre of population and the very different composition of the population of Augusta and the rest of the Shire. It is evident from the study of the rural population how localised was the concern for the welfare of the estuary: "of the population surveyed, those north of Alexandra Bridge shared a declining interest in Augusta and in particular over mining issues".

It is perhaps trite, but nevertheless necessary, to point out that there is a continuous spectrum of residents in the area from those who would be labelled "drop outs", because they have deliberately chosen the simple life in a quiet part of the State, to well-to-do people who have built themselves homes that would not be out of place in Peppermint Grove, but many of whom rate "peace and quiet" just as highly. Each and all have a right to their say, a say which may be obscured by the means and percentages in which our findings are necessarily expressed.

TABLE 5.4—School populations Augusta-Margaret River Shire.

Government Schools	Total Enrolment at 1st August							
	1969	1970	1971	1972	1973	1974	1975	1976
Margaret River Primary School	290	266	297	273	269	235	254	243
Margaret River High School	249	262	232	206	193	206	204	202
Cowaramup Primary School	117	115	128	113	88	108	99	106
Karridale Primary School	80	76	69	59	50	50	51	40
Augusta Primary School	34	35	50	39	36	37	36	45

Source: W.A. Department of Education

Responses of people to questions about attitudes represent thinking at a point of time (December 1974—April 1975) and there was plenty of evidence during the study of changing views. This was partly because the questionnaires and dissemination of information about the study, stimulated people to think about "problems" which they had not previously envisaged.

It is also relevant to note the change in type and standard of housing; most houses now being built are brick and tile in contrast to the older, smaller timber and asbestos houses. The 47 per cent "unoccupied dwellings" is indicative of the large number of non-resident holiday-home owners, a group that was not fully represented in the survey.

The population of the rural area on the other hand shows a fairly normal age distribution, biassed only by date at which people settled in the area, many land holders having settled during the 1950s while in their twenties or early thirties. About half the adult rural population has lived in the area of study for 20 or more years while only 16 per cent of the town population has done so (Table 5.5).

It will be noted that a considerable proportion of the residents of Augusta come from a farming background (Fig. 5.3). Half came to Augusta from rural areas of Western Australia, mostly the south-west Division and 35 per cent from the Perth Metropolitan area (Tech. Ref. 10, Table 8). In recent years the pattern has changed and there has been an increasing proportion from the metropolitan area. Of the non-permanent residents, three quarters come from the metropolitan area.

The principal agricultural activities of the area are beef farming, dairying with an increasing wholemilk production, some sheep, and crop cultivation. Farmers and their wives constitute 75 per cent of the population and no doubt many of the 20 per cent "retired" were also farmers (Table 5.6). Two small elements of the rural population were not adequately sampled: "hippies" and people who have recently settled on the Scott River plain, both proved difficult to contact.

There is little difference in educational background between permanent residents of Augusta and the population of the rural area (Table 5.7). In contrast to this is the high proportion of non-permanent residents of Augusta with a tertiary education. The relatively high proportion of people in the rural population with University or other tertiary education is largely attributable to a group of recent settlers from the United States.

TABLE 5.5—Length of residence (permanent residents only).

Length of residence	Augusta urban		
	Frequency	%	Adjusted %
Less than 5 years	150	38.6	41.4
6-10 years	77	19.8	21.3
11-25 years	96	24.7	26.5
Over 25 years	39	10.1	10.8
No response	26	6.7	—
TOTAL	388		

Length of residence	Augusta rural		
	Frequency	%	Adjusted %
less than 5 years	37	17.2	25.2
6-10	14	6.5	9.5
11-20	26	12.1	17.1
over 20 years	70	32.6	47.6
No response	68	31.6	—
TOTAL	215		

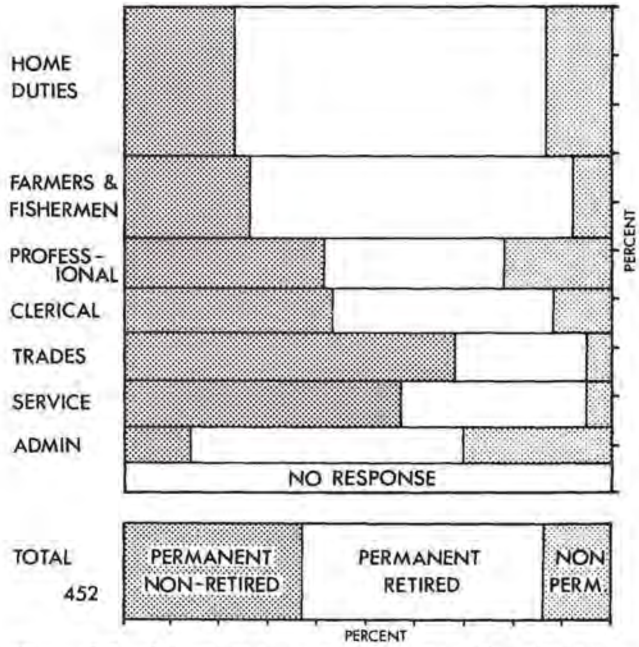


Fig. 5.3 Occupational categories of Augusta residents (adults only).

TABLE 5.6—Occupational categories of Augusta rural area residents (adults only).

OCCUPATIONAL CATEGORY	% (N = 215)
Housewife/home duties	20.0
Farmer	53.5
Farm work	2.3
Other and retired	20.0
Unemployed	0.5
Non-response	3.7

A bias to be noted with respect to the town population, is the high proportion of females in the over 40 age groups. At a time of agricultural insecurity the economic status of the rural community is depressed, though there is no indication how this may have affected responses to the questionnaires.

It is evident that the natural attributes of the area rate highly both in the recalled initial decision to live in the area and present appreciation of it (Table 5.8; Tech. Rep. 10, Figs. 7 & 8). Important among these are the estuary and peace and quiet of the area. The responses of the town and rural populations do not differ greatly, the differences probably representing the different economic interests; for example farmers rated climate higher than did town dwellers. Economic aspects did not figure in the relevant questions which were concerned with "natural" attributes, but availability of cheap land was stated to be an important reason for taking up farms in the area.

TABLE 5.7—Education Levels of Respondents to Questionnaires

	Augusta urban				Augusta Rural		W.A. (Estimates)
	Permanent Residents		Non-Perm Residents				
	Frequency	%	Frequency	%	Frequency	%	%
Primary	116	29.9	4	6.2	53	24.6	16.5
High school to 3 years	136	35.1	20	31.2	74	34.3	45.2
High school to matriculation	31	8.0	9	14.1	24	11.2	17.8
University etc.	30	7.7	16	25.0	10	4.6	3.7
Trade and business schools	58	14.9	11	17.2	23	10.7	9.8
Non-response and other	17	4.4	4	6.2	31	14.5	7.0
TOTALS	388	—	64	—	215	—	

Sources: Australian Bureau of Statistics and Technical Reports 10, 11

Table 5.8—Attractions of the Augusta area.

(a) Features Respondents initially liked about the Augusta area, in rank order.

	Town	Rural
Peace and quiet	1	3
Climate	2	1
River	3	4
Surrounding environment	4	2
Other (born in Augusta, work, business, farming)	5	5
Views	6	—
People	7	6

(b) Features Respondents now like about the Augusta area, in rank order.

	Town	Rural
River estuary	1	3
General views and scenery	2	4, 6
Coastline	3	4
Peace and quiet	4	1
Flora and fauna	5	4
Climate	6	2
Activities based on natural environment	7	—
Friendly community	8	7
Other	9	5

It is inevitable that people who have come to Augusta because they want peace and quiet and because they appreciate the natural beauty of the countryside, are going to be opposed to any development which they believe will destroy these values. This is true even though most people are realistic enough to admit that growth is inevitable; their concern is that the growth process should involve the minimum of change to the natural environment.They realise that this is something which has to be jealously guarded, not merely for their own selfish advantage but for like-minded sections of the wider community and for future generations.

The expressed attitudes of a number of residents are similar to those of Charles Bussell (1830): "for those who have contemplated on one of our spring or summer evenings, a calm and copious river, in which the reflection of the surrounding objects is as perfect as the objects themselves—flowing before their windows and glossed by the beams of the setting sun, while not a breath disturbs the never dying verdure of the gigantic trees upon its banks" (Shann, 1926; 21).

These attitudes to the environment clearly motivate responses to proposals for development of the area, whatever form these may take and especially to mining, as shown by the strong association between responses to mining and appreciation of attractive features (Tech. Rep. 10, Table 11). Apart from mining the principal changes envisioned were building in the town area and the clearing associated with it, the growth of tourism, the change in the composition of the population, and the effects of "burning off".

Because of semantic difficulties it is not easy to determine by questionnaire just what people see as environmental problems and the effects of possible developments. Figures in Table 5.9 show responses to questions as to whether the area faces environmental problems and the nature of such problems. The first part (a) is probably more indicative of involvement than appreciation of environmental problems, but the second (b), summarises answers to an open question and is a useful indication of what people see as "problems" for the area. Responses of the town and rural communities do not show any great difference in perception of environmental problems generally but their response with regard to mining did differ greatly. Only 7.5% of respondents in the town disagree with the statement "under no circumstances at present should there be mining and dredging of Hardy Inlet" (Tech. Rep. 10, Table 10), in contrast to 42% acceptance of mining development by the rural population (Tech. Rep. 11, Table 15).

Table 5.9—Attitudes to environmental problems.

(a) Are there environmental problems facing Augusta?

	Town		Rural	
	Absolute Frequency	% Frequency	Absolute Frequency	% Frequency
YES	152	33.6	94	48.4
NO	259	57.3	100	51.6

N.B. 'Mining' was excluded in the town survey, but it was included in the rural survey.

(b) Specified environmental problems except mining.

Problem	Town % Frequency*	Rural % Frequency
Destruction of natural beauty, flora and fauna	41.4	23.6
Related to river estuary	31.5	18.0
Conservation of landscape generally	27.6	4.4
Related to Tourism	25.0	30.5
Foreshores	19.7	—
Population	18.4	6.9
Other	15.1	16.6
Motorised disturbances and noises	10.5	—

The rapid growth of the town in recent years has resulted in an obvious change in character. Questions relevant to the desirability of continued clearing produced a bipolarity of response between those who appreciate the better facilities and the larger population and those who regret the suburban type of development and associated destruction of native vegetation and other attractive features of the area. Almost equal numbers of Augusta residents agreed and disagreed with the statement: "Some people say that continued building development and clearing of land for houses along the inlet is detracting from the natural beauty of the area and spoiling the views". This bipolarity did not correlate strongly with age, occupation, or length of residence in the area.

Although 34% saw Augusta as a better place in which to live than it was five years ago there was a substantial 11% who thought it worse (Tech. Rep. 10, Table 13). Another 15% saw no change, even though 160 new houses had been built in that time, with continued encroachment of housing on the foreshore and exclusion of the public from the water's edge, of which others had complained.

Approval was expressed by many of the value of tourism to the area (town 68 per cent, rural 61 per cent), but 15 per cent of the town population did not agree that it was good for the area and 27 per cent of the rural population said "no" to it (Tech Rep. 10, Table 14; Tech. Rep. 11, Table 18). Reservations were however, expressed about the inevitable impact of tourism: noise, litter, undesirables causing trouble, and their effect on the natural beauty of the town. This last was largely motivated by enlargement of the town caravan park and destruction there of a grove of karri trees. The expressed attitude ranged from: "open the place up to tourism before it dies," to a condemnation of tourism because of the associated destruction of natural beauty and, in between, a resigned belief that an increase in tourism is inevitable. In the view of some in the farming community tourism is considered as a more desirable way for Augusta to develop than as a retirement village, even though it is seen as one of the major environmental threats.

The number of non-permanent residents included in the town questionnaire (64) is only a small proportion of those who have holiday homes at Augusta, probably between 250 and 300, so that there is only limited information about their attitudes. Moreover the persons sampled had been coming to Augusta each year for at least five years.

It seems unrealistic for so large a proportion of this group to agree with the statement: "Some people say that continued building development and clearing of land for houses along the inlet is detracting from the natural beauty of the area and spoiling the views" (34 agree/strongly agree; 15 disagree Tech. Rep. 10, Table 17 (c)). Nevertheless, the view that Augusta has been spoilt by the recent growth of the town is one which is frequently and forcefully expressed by holiday home owners, particularly by those who have known it well for a long time, often since childhood. For them what was a quiet village is now suburbia, the growth of the town has destroyed the character which appealed to them.

It would be interesting to know of the attitudes of the large number who have established holiday homes during the last five years. Many individuals have expressed strong opposition to the mining proposal, but no survey has been made of their attitudes.

To round off this discussion of the resident population and their attitudes it is relevant to quote from the concluding remarks by Frawley (Tech. Rep. 10) and Wooller (Tech. Rep. 11) respectively.

> "As a retirement town, holiday resort and areas of attractive natural environment, Augusta has drawn to it people of long and diverse backgrounds who provide the area with a special character. Some of the retired residents as well as some of the younger people have come from overseas in search of a peaceful, unpolluted environment. Others have come from many parts of Western Australia and their knowledge and experience of the state are a virtually untapped historical reservoir. Many of these residents consider the right to retire in peace a reward for the years involved in helping develop the state. Many respondents emphasised the small community, the presence of other retired residents and some made particular reference to interesting 'characters' or outstanding local conservation 'spokesmen'. It is my observation that besides the concern for the river estuary over mining there is also concern over what changes would occur in the social structure of this community."

> "Although there was no large environmental lobby amongst the respondents they remain concerned but clearly are not overall the types of people who are likely, en masse, to join the 'crusade to stop' movements. The issue of mining is no more important than other factors that affect their lives, increasing tourism, rural poverty and fluctuating markets are all part and parcel of their life style, each is of concern to them and undoubtedly they have opinions to give."

5.3 **Tourists and Tourism**

Augusta has been a tourist venue since the discovery of the caves of the Naturaliste-Leeuwin Ridge about 1900, but it is only in the post-war era that tourism has become an important industry for the town. Figures for admissions to the caves (Table 5.10) indicate the recent rate of growth, but there are no figures to document the total tourist population before 1972. An indication of its nature is given by the fact that in 1945, the only facilities on the town camping area were two unsalubrious earth closets, whereas there are now two camping and caravan parks (one privately owned) both with hot and cold showers and flush toilets and which between them afford accommodation for about 650 persons. In 1945, the hotel had only 5 bedrooms, from 1956 to 1963 there were 11, whereas present hotel/motel accommodation provides beds for about 110. The present "holiday flats" which have another 120 beds have replaced the earlier 3 or 4 "guest houses".

Table 5.10—Admissions to Caves of the Leeuwin-Naturaliste Ridge (1966-1976).

	Jewel	Lake	Mammoth	Yallingup
1966-67	16 408	6 686	2 574	
1967-68	19 484	6 374	2 458	9 744
1968-69	24 392	10 099	3 644	10 595
1969-70	27 195	8 445	4 236	12 554
1970-71	32 529	8 975	4 668	15 474
1971-72	33 321	9 189	4 955	15 474
1972-73	39 854	11 458	7 594	16 428
1974-75	47 469	12 860	10 780	19 043
1975-76	49 765	13 189	11 973	20 206
1976-77	59 489	16 549	14 993	22 876

About 60% of visitors are from the Perth metropolitan area, but a surprisingly large proportion come from eastern Australia and a considerable number of these would have followed the "Leeuwin Way" tourist route. Table 5.11 presents data from one caravan park and the hotel/motel, but the percentages are probably representative of the tourist population as a whole. As is to be expected, visitors from the South West Agricultural Division were the biggest group from country districts. Even among people from these districts a substantial number came from Bunbury town (83 of 251 from the SW Division) and other urban areas.

Data presented in Technical Report 9 give an estimate of the size of the tourist population (Fig. 5.4). This shows the considerable growth of tourism during the three years 1972-74, also the seasonality of the tourist influx to Augusta. The main tourist usage is over the December-January school holidays and again at Easter. With a stated visitor capacity of under 1000 in the town (R.A.C.Travel and Accommodation Guide, 1975) facilities must have been overstretched in January 1974 with an estimated 43,737 "people days" spent there. Composition of parties also changes seasonally; 37% of the 90,471 January "people days" were children, but only 10% of the July visitors. Party size averaged four in January and three in July.

There is no data on how long persons or parties spent at Augusta. A considerable number who are touring by car or coach stay only one night. Others on tour stay for two or three days if the sun shines and move on at the first sign of rain. At the other extreme are those who set up tents or caravans in the caravan park for several weeks, even establishing their caravans a week or two before the Christmas holiday in order to ensure a good site.

The activities favoured by visitors are given in detail in Technical Report 9 Tables 2 and 3. This shows: boating for fishing or just for pleasure, fishing in the estuary or on the coast, and sightseeing to be the principal specific activities, with a considerable number of parties stating "nothing specific" as their intended activity. Most boating and much of the fishing take place on the estuary. It is interesting to note the large number of "party days" for which the main activity was stated to be "ornithology" (3862, 1974 data).

Just what form "sightseeing" takes is not indicated, but the advertised tourist attractions include the Augusta and Margaret River caves, Cape Leeuwin and the lighthouse, various places of historic interest, coastal scenery generally, and the estuary itself with trips on the "Miss Flinders" tourist ferry to Alexandra Bridge or Molloy Island. Most or all of these attractions are included in the ordinary coach tour and can be crammed into a one-day visit or spread over a prolonged stay by those who prefer to take their pleasures in a more leisurely manner.

The direct value of tourism to the area was estimated at only about $350,000 a year, but there is indirect expenditure of another $1m to $2m by tourists associated with their visits to Augusta.

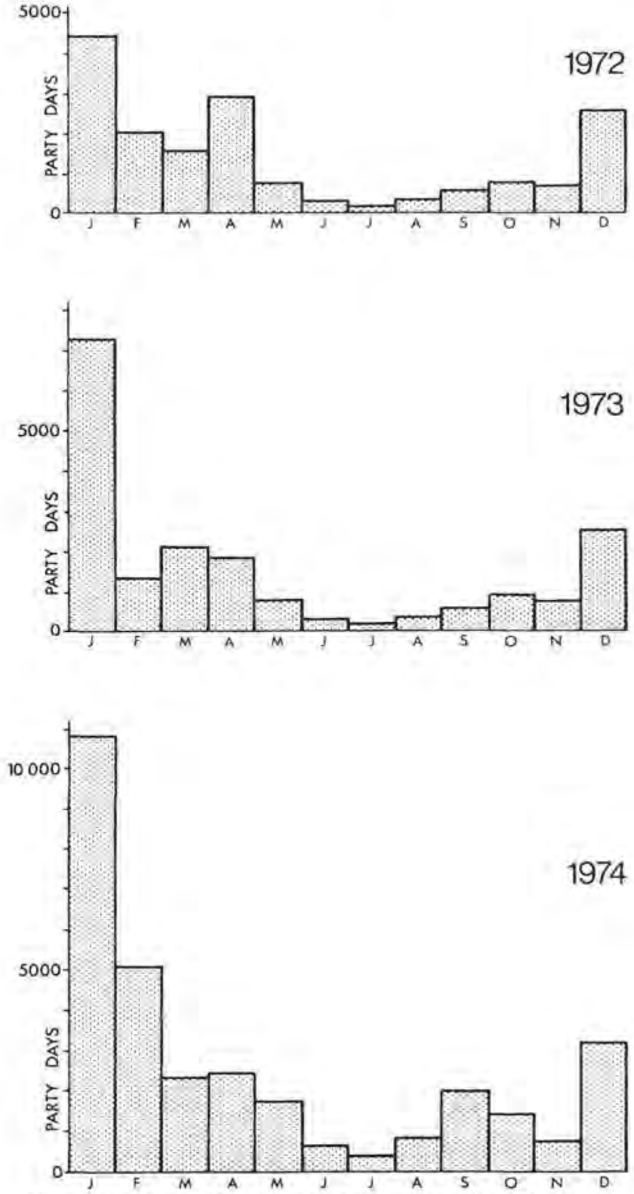


Fig. 5.4 Party days spent at Augusta 1972-1974.

Table 5.11—Caravan Park and Hotel Visitors to Augusta in 1975

(a) All visitors

ORIGIN	Percentage of total	
	Caravan Park	Hotel
Perth Metropolitan Area	54.8	67.3
Eastern Australia	30.5	15.6
South West Agricultural Division	6.3	5.9
Central Agricultural Division	2.7	2.8
Southern Agricultural Division	1.9	2.7
Eastern Goldfields Division	1.3	1.1
Northern Agricultural Division	1.2	1.8
Other WA	0.9	0.8
Overseas	0.5	1.1
TOTAL NUMBER	2 235	1 861

(b) Visitors from Eastern Australia

	Percentage of total	
	Caravan Park	Hotel
Victoria	12.9	6.2
New South Wales	7.1	3.9
South Australia	5.7	3.0
Queensland	3.6	1.4
Tasmania	0.5	0.5
Australian Capital Territory	0.4	0.4
Northern Territory	0.2	0.2
TOTAL NUMBER	681	290

N.B. The caravan park figures are for groups while the hotel data are composed predominantly of individuals or couples.

The views of visitors about the prospect of mining and other development were not sought. There is certainly vociferous opposition and proprietors of holiday accommodation report a general antagonism to either. There can be little doubt that the majority of regular visitors to Augusta value it for its peace and quiet, they are seeking a different form of holiday from those who visit Busselton and other larger resorts and are not clamouring for better facilities.

5.4 **Historical: Human Impact on the Environment**

Early explorers, from the time of the first Dutch voyagers, mention the presence of Aborigines in the vicinity of the estuary. A letter dated 1658 mentions "three black men, hung with skins" and records finding their fires, spears, axes and huts (Heeres, 1899). Hallam (1975) estimates a population density of 18 to 20 per 100 square miles in the south west of WA at settlement, thus on her estimates there were possibly no more than 100 people roaming the area at any given time. Their movements were seasonal and they would have visited the estuary mainly in summer to fish and to hunt waterfowl and other game in the freshwater swamps. They probably built fish traps in shallow parts similar to those of the Serpentine River, or such as has recently been recorded near Northcliffe 90 km to the east (Dortch and Gardner, 1976) or near Albany (Dix and Meagher, 1976) though there does not seem to be any record of these and it is unlikely they had any great impact on the estuary.

There is abundant archeological evidence of prolonged human occupation of the area. Devil's Lair cave, located on the leeward side of the Naturaliste-Leeuwin Ridge (Fig. 5.1) is one of the oldest known sites of human occupation in Australia having been occupied earlier than 25,000 years BP (Dortch and Merrilees 1973). Thus human influence extends back to the time when the coastline was some twenty or more kilometres seaward of its present position.

During the early Holocene when the estuary was more marine than it is now, Aborigines may well have eaten oysters and other shellfish present at that time. Grey (in Hallam 1975) says that south western Aborigines did not eat shellfish. However, various mollusc shells including those of edible species have been found at an Aboriginal coastal occupation site at Cowaramup Point (Dortch pers. comm.).

The use of fire, both the "cool" fires used in small scale hunting and the more extensive fires of summer and autumn certainly influenced the pattern of vegetation in the forest and provided good feed for the abundant kangaroos of which early settlers wrote. There was an intensification of the effects of human occupation on the narrowed coastal plain during the Holocene, a pattern which involved "frequent regular and deliberate firing of the terrain" (Hallam 1975). Even here in the extreme south west, frequent fires left much of the forest with less undergrowth than at the present time, though in other places the undergrowth is said to have been dense.

Thus, although the aboriginal population of this extreme south west corner of the continent was probably sparser than that of the warmer more open forest of the coastal plain to the north, it was sufficiently dense to have had a profound effect on forest vegetation and coastal scrub, and in consequence also on erosion and runoff to the estuary.

On 2 May 1830 Governor Stirling and some fifty settlers arrived at Flinders Bay aboard the *Emily Taylor*. James Woodward Turner, Captain John Molloy, and the four Bussell brothers were allocated land bordering Seine Bay for their town houses. Most of the less wealthy settlers built on the seaward slope of the hill between Dukes Head and Barrack Point. By August they had cleared seven to eight acres on which to build their homes and plant their crops, using hand axes and saws. Thomas Turner's paintings show gardens on the east bank opposite Seine Bay and a map dated 1832-4-8 shows subdivision, but it is unlikely that much was cleared there at any time.

During the 1830s and 40s the small population gradually declined, first the Bussells left (1835), then the Molloys (1839) and finally the last of the Turners in 1849. It is not certain whether any settlers remained after this date, but there appear to have been at least two families in the early 1850s. During this first period of settlement there had been sheep and cattle grazing through the open forests of the large grazing leases up the river; Turner was finally allocated some 20,000 acres on the west bank between Hardy Inlet and Chapman Brook. The only clearing this seems to have involved was the minimum necessary to build houses and grow garden produce at settlements such as Turnwood (on the north shore of the Inlet), Molloy Island, and the Adelphi (the Bussell property at Alexandra Bridge). The estuary was used for transport and fish provided an important part of the diet of the small, isolated community. Throughout this period there had been constant contact between Aborigines and settlers, much of it friendly but at times leading to unpleasant incidents as a result of their different attitude to property.

From 1850 a number of grazing leases were issued and were occupied in summer in coastal areas east and north of Augusta, though very few homes appear to have been built. This did not involve clearing; however, the associated burning-off must have had a profound effect on the vegetation not only of the leases themselves, but on the forest of the sunklands part of the catchment through which hot fires were allowed to burn uncontrolled. The poor quality of much of this part of the forest is largely attributable to this practice, although the soils are often poor and waterlogged and hence unfavourable to jarrah. The cutting of fire breaks after World War II to control the frequent hot fires has unfortunately spread jarrah dieback disease in forest on the poorer soils.

The next phase of exploitation of the area was timber milling; this began in the late 1870s and continued into the early 1900s when the last Millars' mill closed in 1913. M. C. Davies, later Millars, Karri and Jarrah Company, had large timber leases and felled extensive areas of forest between the estuary and the west coast. The timber was exported from Hamelin Bay in summer and Flinders Bay in winter. Felling would have been selective and most of the forest was left to regenerate. The population of the Shire was 679 at the 1901 census, concentrated mainly in the timber settlements. It was however an isolated community with poor communication with Busselton which was then a town of only 477 inhabitants. Alexandra Bridge was built by Davies in 1897 giving access to the east bank of the estuary, presumably for the transport of timber and of iron ore from Scott River deposits for Davies' smelter. The Nannup Road was gazetted in 1890. Davies was also associated with Wishart in building the Leeuwin lighthouse, in 1895.

The discovery of caves near Margaret River and Augusta and their exploration about 1900 first brought tourists to the area. Horse drawn coaches came from Busselton down the sandy track of the coast road from Yallingup and the number of visitors built up with the advent of motor cars. The Augusta Hotel was opened in 1912 and 1913 at which time there were also three boarding houses.

Molloy memorial plaque, Seine Bay.

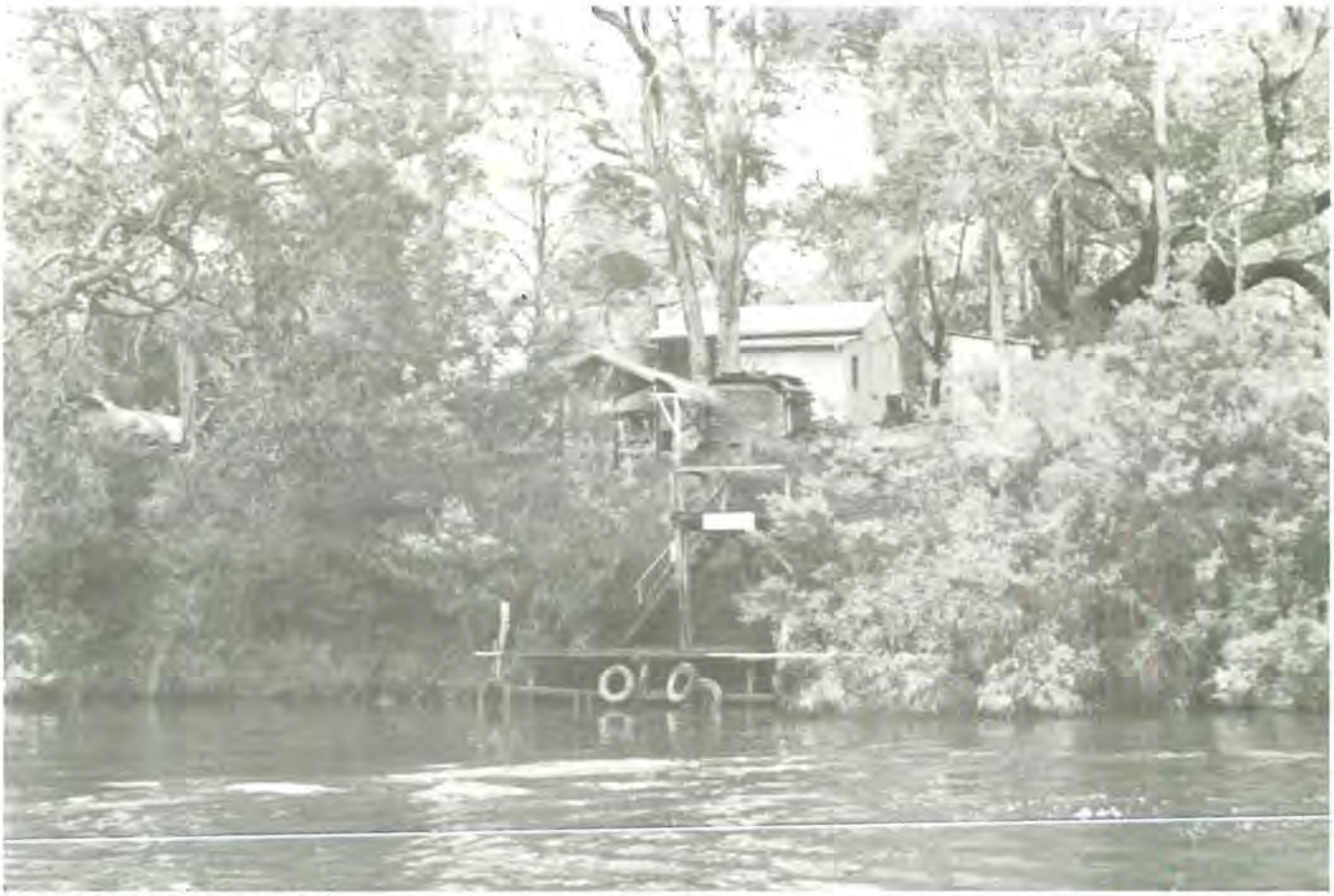
Following World War I the Group Settlement Scheme brought settlers from England to the area. Despite its failure at the time the scheme resulted in considerable clearing, 27 765 acres being cleared to pasture in the Shire during the decade 1921-31. It also brought the railway which was opened to Flinders Bay in 1925. This and much roadwork at this time helped to open up the district.

After World War II the War Service Land Settlement Scheme brought a new influx of settlers and it was proposed to clear a further 20,000 acres, mainly as small holding dairy farms of about 150 acres. This scheme also ran into trouble and by 1955 some 40 to 60 acres had been cleared on each lease, but 35 farmers had given up their land. Since then the rural population has not increased greatly, but clearing has continued and amalgamation of properties has given more economic units. Dairying gave way to beef cattle, though it is now increasing again.

The expansion of agricultural activities has affected the estuary in two ways; through increased runoff and by damage to marginal vegetation. Clearing must have resulted both in some increase in direct runoff to the estuary via Chapman Brook, McLarty Creek, Scott River and other smaller tributaries and an increased nutrient input from grazing land. Both must have had some small impact on the estuarine environment. Destruction of marginal vegetation and cattle grazing to the water's edge is potentially more serious. There is increased risk of damage to banks during flood periods, resulting in further destruction of the vegetation, erosion of the banks, and increased sedimentation downstream. As yet this sort of damage has not been great, but once started it can accelerate rapidly. The sort of ruthless clearing of the banks recently carried out near Alexandra Bridge is especially to be deplored.

The Deadwater is probably the result of quite small scale human interference with the estuarine system early this century, with the further result of the access of salt water to Swan Lake (Hodgkin, 1976). More recently, dredging the boat channel in 1956 and again in 1973 have had their effect on both the physical and biological features of the estuary.

The expansion of tourism, discussed elsewhere, has brought with it greater human usage of the estuary. As yet, this is not on a scale to have caused the great changes that can be seen in the Swan and Murray River estuaries, though already the banks and marginal vegetation have a "used" look in a few places. The Blackwood estuary is appreciated by many for its peace and unspoilt natural beauty, amenities which are not consistent with uncontrolled usage by large numbers of people and power boats. As always in such circumstances the very attractions for which the place is valued can be destroyed by their devotees. Some control will have to be exercised over the use of the river and its banks if this is not to happen.



River bank shack near Alexandra Bridge.

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