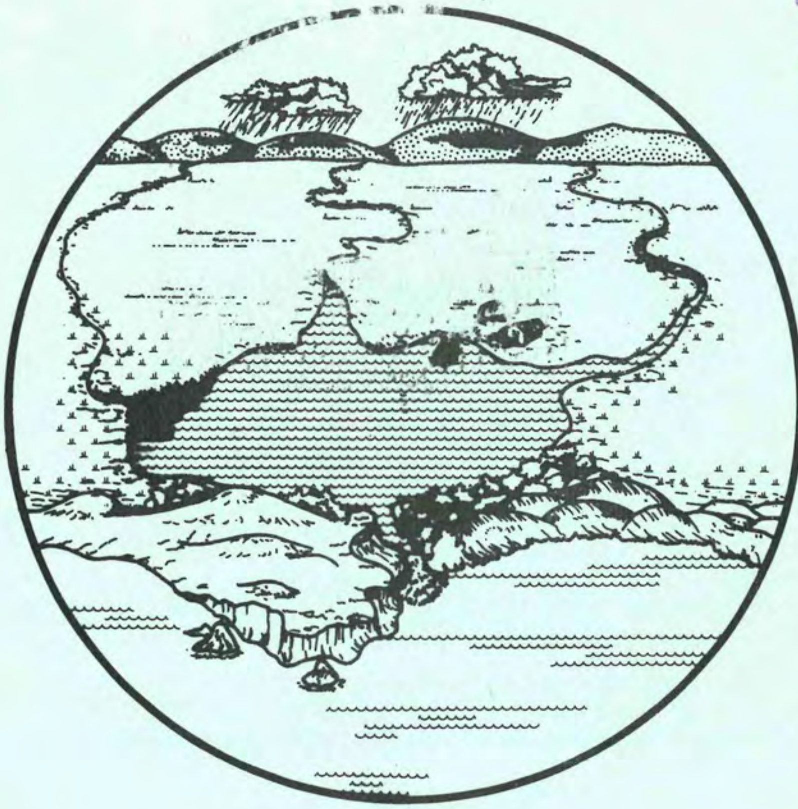

ESTUARINE ENVIRONMENTS OF THE SOUTHERN HEMISPHERE

Bulletin 161

March 1984

Department of Conservation and Environment
Perth, Western Australia

ESTUARINE ENVIRONMENTS OF THE SOUTHERN HEMISPHERE

Papers presented at a Symposium:
Man's Impact on the Estuarine Environment held at the 53rd Congress of the Australian and New Zealand Association for the Advancement of Science in conjunction with the Australian Marine Sciences Association. Perth, May 1983.

Compiled by E.P. Hodgkin

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INTRODUCTION

Ernest P Hodgkin
Department of Conservation and Environment
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The papers included in this Bulletin were presented at a Symposium entitled"Man's impact on the estuarine environment." They dealt more with aspects of the environment as they affect management than with the observed effects of man's activities on estuaries, hence the change in title to "Estuarine environments of the southern hemisphere", a title which more accurately indicates the contents of this volume.

"Estuaries and adjacent environments are ecological systems that are subjected to continual stress by natural and man-induced perterbations" (Vernberg in Kennedy, 1980). The natural perturbations cause rapid change to estuarine environments in geological time, but the same physical and biological processes maintain the integrity of an estuary on the human time scale. A lack of understanding of the processes involved and appreciation of man's ability to truncate the Holocene changes into a human life span is unfortunate in that it has resulted in much unnecessary damage to estuarine environments.

Changes there will inevitably be following any interference with the natural environment, but in such a resilient situation as an estuary they need not be detrimental if properly planned, and can even be beneficial to estuaries which have passed their prime.

The estuaries discussed here differ in important respects from the classic concept of an estuary, a concept derived largely from experience in Europe and North America, and epitomised in the well-known definition of Pritchard (1967) :

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

Many of what we know as estuaries in southern Australia, particularly in Western Australia, and also in South Africa would be excluded by this definition. The definition given by Day (1980) in his book on estuarine ecology is more appropriate to our estuaries, it is:

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

While there is certainly much to be learnt from the extensive studies of north temperate estuaries, this knowledge has to be applied with caution to our estuaries, Williams (1980) stressed the same need for caution with respect to inland waters:

> Because of its distinctiveness, caution is required in any extrapolation to the Australian aquatic environment of limnological or ecological generalisations based only upon investigations conducted outside, or worse, drawn only from north temperate investigations.

The estuaries of southern Australia and South Africa are very different environments from those of Europe and North America. We have no large estuaries such as the funnel-shaped estuary of the Severn River in England, which is almost an order of magnitude bigger than any of ours, and has 12m tides. We have no Chesapeake Bay and nothing comparable with the lagoonal estuaries of the east coast of USA with their extensive *Spartina* marshes. The Gippsland Lakes of Victoria ($400 km^2$) are the largest and they are almost tideless because of the restricted mouths and small ocean tides. Ocean tides are less than 2.5m and those of south western Australia are less than one metre.

River flow is strongly seasonal or erratic, and evaporation rates are high, so that plants and animals are often exposed to an extreme salinity range, not on a daily time scale which they can tolerate or avoid by various devices until the return of favourable conditions, but on an annual time scale which only the more mobile can avoid.

However, different as they may be from estuaries in other parts of the world, they are just as much a focus for human use or abuse.

For the early settlers they afforded safe anchorage and a rich source of protein. But with the growth of populations they have too often been fouled with sewage and industrial wastes, a condition which can only be reversed at great cost. Now many smaller estuaries are the focus for residential and recreational development, activities which need not be incompatible with healthy estuarine conditions if planned with sympathy for the environment.

MacIntyre, in this symposium has stressed that it is the responsibility of citizens, not scientists, to decide what shall be done with our estuaries. Nevertheless, decisions about what can be done and how it can best be done need to be made on the basis of an adequate understanding of the natural processes, physical and biological, which maintain the integrity of these evolving ecosystems. That is what the symposium was about.

The papers in this Bulletin make a valuable contribution to our knowledge and understanding of these dynamic natural environments and it is to be hoped that by doing so they will help towards a rational approach to their conservation. If it is obvious that the level of understanding of the geomorphogical processes at work in our estuaries is very uneven throughout the region, and that there are still great gaps in our knowledge of the biology of these systems, that only serves to stress the urgent need to upgrade our knowledge through research on a co-ordinated basis.

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THE SOUTH AFRICAN COASTLINE, ITS ESTUARIES AND MAN'S IMPACT UPON THEM

BY

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SOUTH AFRICA

ABSTRACT

The 3 000 km of South African coastline is washed by the warm waters of the Agulhas Current in the east, and by the cold upwelling waters of the Benguela Current in the west. Contrasting climatic conditions, together with great diversity in geomorphological features have led to the development of over 300 estuaries with widely differing characteristics. Those on the west coast occur in a dry semi-desert environment, those on the southwest and south coasts under winter rainfall conditions in a mediterranean type of environment and those on the east coast in a sub-tropical environment with summer rainfall.

A brief sketch of the coastal features between the Orange River in the west and Ponta do Ouro in the east is followed by a section on the nature and distribution of the estuaries occurring along various parts of the coastline. Attention is given to problems arising from conflicting interests in their multiple use. This leads to a discussion of the practical implications of their conservation and management of the resources associated with them. Finally, a co-ordinated national estuarine research programme, encompassing both fundamental and applied/interprative work is discussed.

1. INTRODUCTION

While the features and characteristics of coastlines and their estuaries vary from place to place and country to country according to their geographical setting, it is remarkable how similar coastal management problems are all over the world. This paper is aimed at summarizing the situation as it pertains to the South African coastline at present. The first part gives an overview of the major features of the South African coastline and has been adapted from an as yet unpublished text by Heydorn and Flemming which is a contribution to the book "World's coastlines" (editors Schwartz and Bird, in press). The second part deals more specifically with the nature and distribution of South African estuaries and is partially based on an overview prepared for a National Oceanographic Symposium (Heydorn, 1979). The final part of the paper briefly describes how estuarine research is organized in South Africa with the purpose of providing a sound scientific background for the formulation of a cohesive coastal and estuarine policy for the country.

2. MAJOR FEATURES OF THE SOUTH AFRICAN COASTLINE

The South African coastline between the Orange River in the west and Ponta do Ouro in the east, covers a distance of about 3 000 km (Figure 1). This includes the coasts of the two independent States, Transkei and Ciskei, between latitudes 31°04'S and 32°40'S (250 km) and between 32°40'S and 33°30'S (150 km), respectively. The coastline to the west of Cape Agulhas borders on the South Atlantic and to the east on the Indian Ocean. The east coast waters (Figures 1 and 2) are characterised by the warm southward-flowing Agulhas Current and those of the west coast by sporadic upwelling of cold, nutrient-rich waters which typify the Benguela Current regime. Along the southwest and south coasts extensive mixing of water masses occurs.

These oceanographic conditions determine the coastal climate of southern Africa, with summer rainfall along the east coast, bimodal rainfall along the south coast, winter rainfall along the southwest coast and semi-arid conditions along the west coast (Figure 1). The variability of these environmental conditions is reflected in the composition of animal and plant communities both on land and in the sea. For example, a wide variety of Indian Ocean corals harbouring a diverse Indo-pacific fish fauna, occur in the sub-tropical waters of the northern east coast, whereas dense kelp beds provide a habitat for commercially important rock lobster and abalone stocks in the cool upwelling regime of the west and southwest coast. In general the east coast waters are characterised by great biotic diversity while the main focus of commercial fisheries is centred in the more productive waters of the southwest and south coasts where fewer species occur in greater profusion.

The wave climate of the South African coast is profoundly influenced by seasonal shifts (southwards in summer and northwards in winter) of the gale zone of the Antarctic Circumpolar Current region (Figure 2), and by local winds generated by the regular passage of atmospheric lows over the coast from west to east. The southwest coast appears to

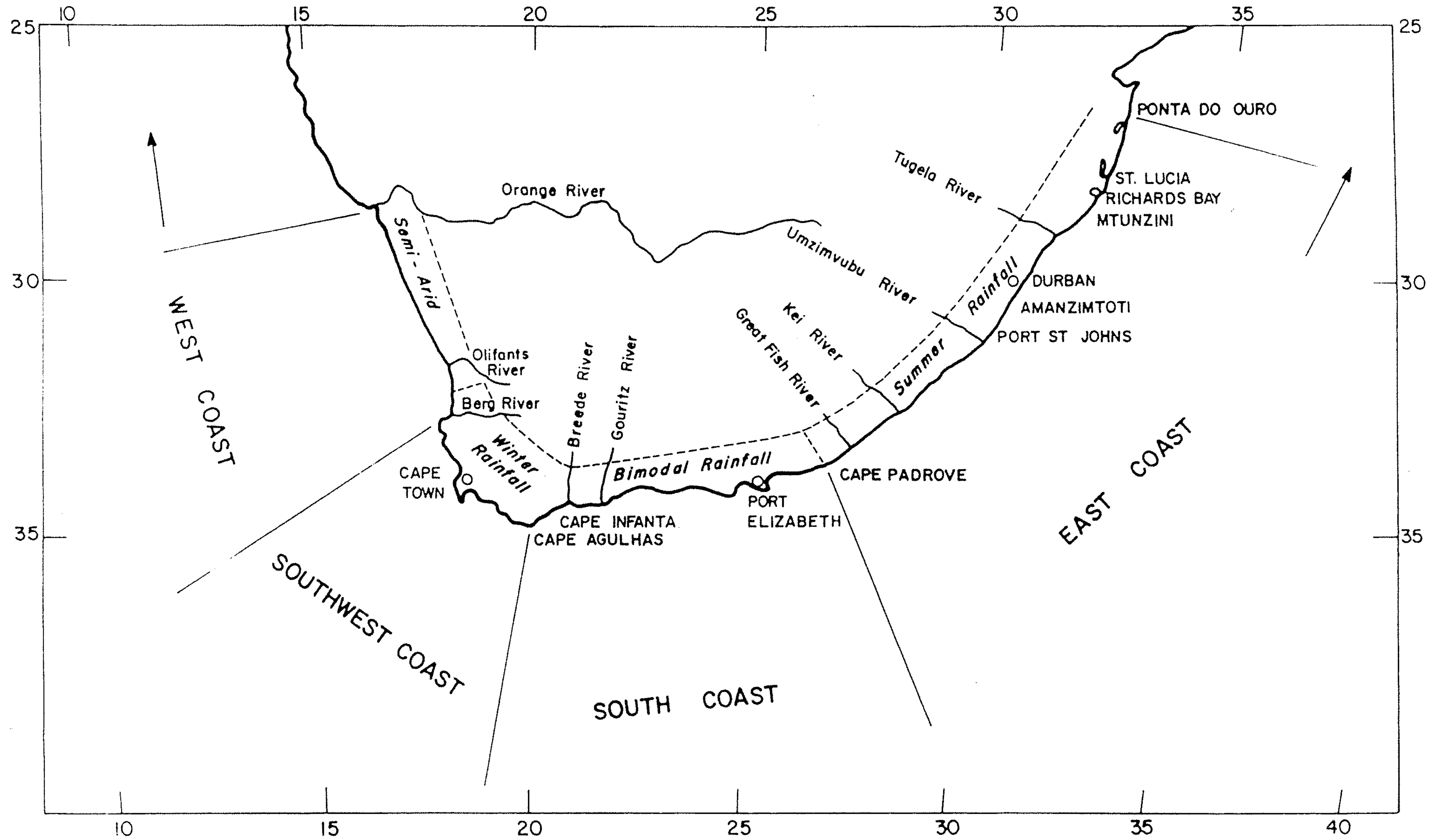


FIGURE 1: MAJOR FEATURES OF THE SOUTH AFRICAN COASTLINE

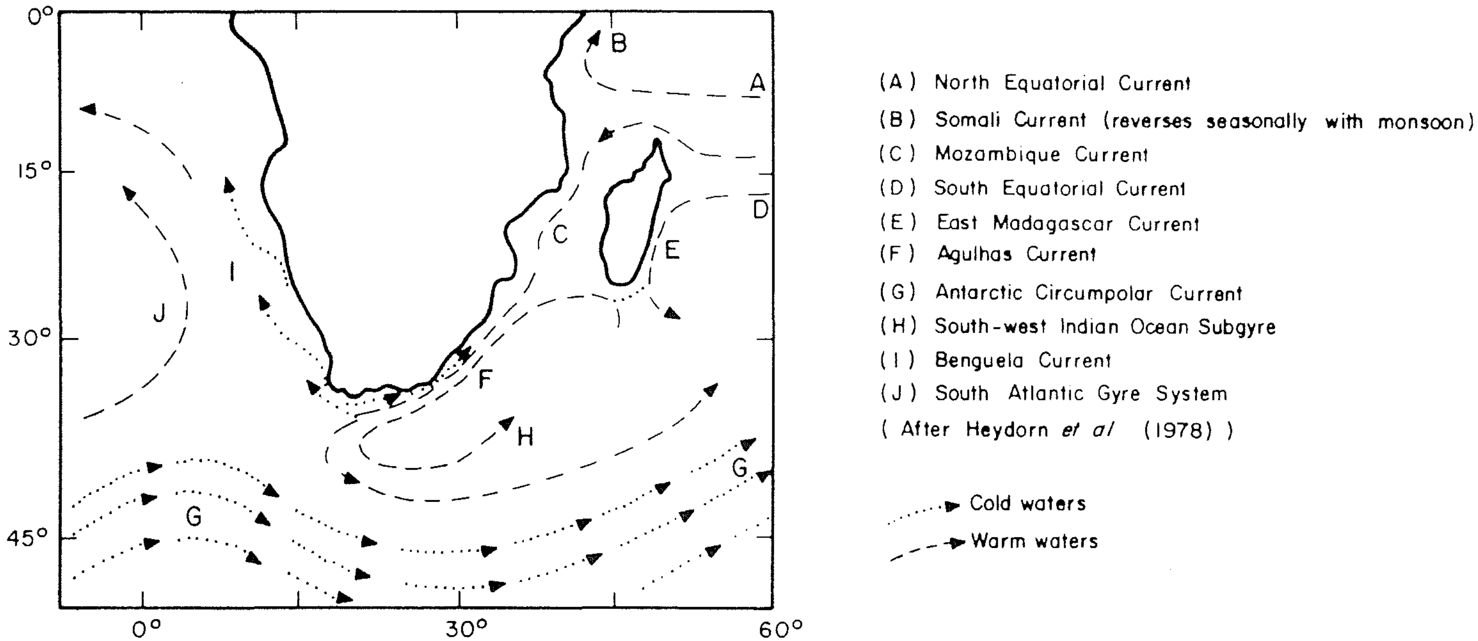


FIGURE 2: MAJOR OCEAN CURRENTS IN THE SOUTHERN AFRICAN REGION

be subjected to the greatest amount of wave energy which decreases somewhat northwards along the west coast and eastwards along the south coast (J Rossouw, pers. comm.). These wave patterns strongly influence coastal processes such as longshore sediment transport and hence coastal features such as the orientation of headland bays, sandspits and the configuration of river mouths.

The landforms of the South African coast can be broadly sub-divided into six physiographic regions each of which imparts special character on the estuaries entering the sea through it (see also Figure 1):

a. Orange River to Olifants River (407 km)
b. Olifants River to Berg River (137 km)
c. Berg River to Cape Agulhas (635 km)
d. Cape Agulhas to Cape Padrone (815 km)
e. Cape Padrone to Mtunzini (745 km)
f. Mtunzini to Ponta do Ouro (267 km)

a. Orange River to Olifants River

The shore of this region is mainly rocky, consisting of Precambrian metasediments. As a result of the semi-arid climate, the coastal vegetation is sparse, semi-succulent, open scrub, highly adapted to dry conditions and classified by Acocks (1975) as Strandveld Proper. The Orange River traverses two thirds of South Africa and represents the country's largest riverine system. Between the Orange and Olifants Rivers, nine smaller rivers enter the sea. In keeping with the present climate they only flow on rare occasions but episodic floods are possible. However, the wide, deeply incised valleys of the presently ephemeral streams suggest considerably greater activity in times gone past. River water tends to be highly mineralized. Some of the rivers have shallow, saline lagoons, separated from the sea by sand bars (except when in flood) and have dunefields fanning out towards the north from their mouths.

The entire coastline between the Orange and Olifants Rivers is economically important as a source of alluvial diamonds.

b. Olifants River to Berg River

To the south of the Olifants River, the coastline undergoes a gradual change from steep rocky shores to increasingly wider-spaced rocky headlands separated by sweeping sand beaches. At the same time the metamorphic bedrock is progressively replaced by quartzitic sandstones belonging to the Table Mountain Group. The change in bedrock lithology is also recorded in the composition of local beaches which now consist predominantly of shelly quartz sand devoid of heavy minerals. The hinterland is still semi-arid, although the influence of winter rains becomes evident towards the south. Most beaches are lined by low, partially vegetated dunes. Coastal fynbos or macchia makes its appearance near the Berg River under the influence of the winter rains. Gypsum deposits found locally in depressions landward of the dunes, betray former sea-level stands, probably of late Pleistocene age, several metres above the present. Many of the beaches act as source areas for large plumes of aeolian sands migrating northwards in response to strong southerly winds blowing mainly in summer.

c. Berg River to Cape Agulhas

A dramatic change in coastal morphology (again associated with bedrock lithology), takes place to the south of the Berg River. The entire coastal stretch between the Berg River and the Cape Peninsula (south of Cape Town) is dominated by granite intrusives. The coast tends to be very irregular and its northern half is characterized by numerous pocket bays, headlands and offshore pinnacles. The largest embayment, Saldanha Bay, forms a natural harbour and has the unique feature of a southern appendix known as Langebaan Lagoon. It is the product of selective marine erosion in the course of the Flandrian transgression (Flemming, 1979) and has little freshwater inflow.

The shoreline between Saldanha Bay and Table Bay is similar to that between the Olifants and Berg Rivers. Again there are widely-spaced rocky headlands, separated by long sandy beaches associated with aeolian activity. The vegetation cover is somewhat denser due to the higher rainfall of the area, with more coastal fynbos elements making their appearance. Table Bay itself is formed by a pronounced offset in the coastline and marks the northern limit of the Cape Peninsula. The relief of the peninsula is dramatic and vertical drops of several hundred metres are common. Set between granite outcrops and plunging sandstone cliffs are numerous pocket beaches producing a landscape of such scenic beauty that it prompted Sir Frances Drake to call it "the fairest Cape in all the world".

The Cape Peninsula is separated from the high coastal ranges of the hinterland by a low plain, the Cape Flats. It consists of Tertiary and Quaternary coastal/marine sands which feed the beaches along the northern shoreline of False Bay. At Cape Hangklip the coastline swings to the southeast, initially being flanked by towering sandstone ridges. The irregular rocky shoreline is interrupted by long curvilinear sand beaches which, in some cases, form the seaward margins of barred estuaries e.g. Bot River Lagoon. The relief gradually diminishes towards Cape Agulhas, although the shoreline remains predominantly rocky, interspersed with short sandy beaches.

d. Cape Agulhas to Cape Padrone

Cape Agulhas marks the southern tip of Africa. To the east of it there is a marked change in coastal morphology. This time the shore is controlled by tectonic factors, rather than lithological ones. The regional strike of the Cape Fold Belt is cut at an oblique angle to the general trend of the coastline. As a result, the alternating sequence of anticlines and synclines has produced a succession of halfheart or crenulated bays opening to the southeast. The valleys extending inland from the bays act as natural drainage channels from inland catchments and usually there are one or more estuaries associated with each embayment. Because of their scenic beauty and the availability of fresh water, these estuarine areas have become focal points for development, especially of holiday villages.

The vegetation in this region is still dominated by coastal fynbos, i.e. a vegetation characterized by Ericaceae, Proteaceae and the wiry, tufted plants of the Restionaceae. Here these plant communities occur typically on the acid soils overlying aeolian calcarenites. It should be noted that this is a transitional area between the winter and bimodal rainfall regions (Heydorn and Tinley, 1980). The intrusion of exotic vegetation, mainly Australian acacias, represents a land management problem of substantial proportions.

To the east of the Gouritz River the character of the coastline changes and becomes dominated by a raised coastal platform bevelled at heights of 150 - 250 metres. These elevated shorelines are probably late Cretaceous to early Tertiary. The drainage systems along these parts of the coastline are deeply incised. Again, these features have great aesthetic appeal. At Knysna, for example, the erosion of softer inlayers has led to the formation of a large estuary connected to the sea via a narrow rocky channel. The Wilderness Lake System, on the other hand, has developed between successive coastal dune ridges occupying gaps in bedrock ridges. Impressive coastal forests, classified by Acocks (1975) as Knysna Forest and dominated by towering yellowwood trees (*Podocarpus* spp.) give further character to this region, as does the blackwater of the rivers and streams draining the sandstone slopes of the Outeniqua Mountain Range.

The City of Port Elizabeth is situated on the shoreline of Algoa Bay near the northeastern limit of the Cape Fold Belt. Algoa Bay, which is the last but largest of the south coast headland bay beaches, ends at Cape Padrone. The topography immediately to the west and east of Port Elizabeth is much flatter than that of most of the south coast. The quartzites and shales of the Table Mountain Group are replaced by conglomerates, sandstones, shales and limestones of the Cretaceous System as well as by unconsolidated sediments of Tertiary/Quaternary origin. Large dunefields are typical of the region. The coastal vegetation is known as Alexandria Forest, of which euphorbias and aloes are striking components. The composition of the vegetation is strongly influenced by the fact that this is a transitional region between the bimodal and summer rainfall regimes. From here northeastwards, conditions become progressively more subtropical.

e. <u>Cape Padrone to Mtunzini</u>

At Cape Padrone, the coastline swings to the northeast, once again accompanied by a significant change in coastal morphology. As in the case of the south coast, there is no coastal plain. Instead, the coastal topography above water level is dominated by more uniform, convex slopes. An exception is the area around Port St Johns, where complex faulting has produced high cliffs and steep slopes. The rocky shoreline is interrupted by short sandy beaches in the vicinity of river mouths. Coastal dunes are mostly of the vegetated hummock type, hugging the slopes of rocky headlands. Typical of this part of the coast are grasslands which almost reach the sea on the interfluves of rounded headlands and forested valleys in between. These coastal forests are perhaps less spectacular than those of the south coast, but none the less impressive with trees such as wild figs, red milkwoods and strelitzias. Typical of most estuaries are mangroves which are absent on the southwest and west coasts.

At Amanzimtoti, some 25 km south of the City of Durban, the sporadically occurring coastal dunes merge into a quasi-continuous ridge, which extends northwards beyond the Mocambique border. This ridge is not entirely a modern feature, but in fact contains a core of Pleistocene dune sands associated with a different sea-level. Its present position on parts of the modern coastline is purely coincidental, as it is preserved along other parts of the coast as a submerged ridge on the adjacent continental shelf (Flemming, 1981). Initially the coastal dunes form a single, well-defined ridge. However, at Mtunzini the convex sloping basement and the coastal dune ridge diverge to form a rapidly widening coastal plain.

f. Mtunzini to Ponta do Ouro

This region is characterised by the Zululand Coastal Plain, which is the only true coastal plain found along the entire South African coastline. Hobday (1979) has discussed its geological evolution. Seaward-dipping Cretaceous and lower Tertiary strata are unconformably overlain by Upper Tertiary to Recent sediments. The Quaternary history of the area is particularly complex and field evidence suggests that there have been several superimposed and re-activated barrier lagoon systems in the wake of successive Pleistocene and Holocene sea-level fluctuations (Hobday and Orme, 1974). At present the region is characterized by a number of large estuarine and coastal lake systems, which according to Orme (1973) and Hill (1975), appear to have developed from more extensive mid-Holocene estuaries by progressive siltation. Further significant changes to the existing estuarine systems have occurred as a consequence of extensive recent siltation resulting from the intensive utilization of almost the entire coastal hinterland, including most riverine floodplains, for the production of sugar cane. Furthermore, the development of a large harbour at Richards Bay and the artificial stabilization of the inlet of the St Lucia lagoon has had a profound influence on the character of these major lagoonal systems. In both cases intensive efforts are being made to maintain viable ecological regimes in spite of the modifications brought about by man.

3. THE NATURE AND DISTRIBUTION OF SOUTH AFRICAN ESTUARIES

For purposes of this paper an estuary is considered to be that portion of a river system which has, or can have, contact with the sea and where at such times, there is within the confines of the land a transition in physical, chemical and biological characteristics from fresh water to seawater. Due to the climatic conditions typical of the South African coast, an estuary can, under flood conditions, become a river mouth with no seawater entering the previous estuarine area. Similarly, under low flow conditions, an estuary can be cut off from the sea through the formation of a sand bar, become a saline lagoon and eventually, a dry pan. The east coast estuaries are most subject to flooding due to summer spates of rain while the west coast estuaries are most subject to periodic lagoon formation and drying up. Thus basic differences between the estuaries of the east coast and those of the south and west coasts are evident. Because of the monoclinal tilting of Natal and Transkei and heavy summer rainfall, water tends to flow at greater velocity over a shorter distance in these regions. Consequently they have greater cutting action, tend to carry a bigger silt load and their estuaries are more dependent on the filtering action of their floodplains. Rivers in the Tsitsikama/Outeniqua/ Langeberg area can also be short and steep. However, they generally drain hard Table Mountain Sandstone/Quartzite formations with little unbound soil cover and they therefore carry a smaller silt load. There are also profound differences in the vegetation and the surrounding areas of the estuaries in subtropical Natal, the more temperate south coast and the arid west coast. Similarly substantial differences in faunal composition occur.

An exceptionally wide range of estuary types with varying characteristics, determined mainly by geomorphological and climatic factors, are therefore found on the South African coastline. Referring again to Figure 1, their distribution is as follows:

Orange River to Olifants River (407 km):	9 estuaries
Olifants River to Berg River (137 km):	5 estuaries
Berg River to Cape Agulhas (635 km):	36 estuaries
Cape Agulhas to Cape Padrone (815 km):	62 estuaries
Cape Padrone to Mtunzini (745 km):	225 estuaries
Mtunzini to Ponta do Ouro (267 km):	6 estuaries

The total area of estuaries along South Africa's 3 000 km of coastline has been estimated at about 600 km^2, of which 400 km^2 occurs along the 570 km of Natal's coast in the northeastern region of the country. Included in this rough calculation of estuarine areas are a number of large permanent lagoon systems, namely:

- on the west coast, Verlorevlei, which is a coastal lake with an area of some 10 km^2 and fringed by extensive wetlands. However, it is sporadically connected with the sea via a narrow channel;

- on the southwest coast the Saldanha/Langebaan system, which is essentially an arm of the sea about 20 km long;

- on the south coast the Wilderness Lakes System in which a series of three coastal lakes are connected with the Touw River estuary by narrow channels meandering through swamps;

- on the east coast, South Africa's largest estuarine system, Lake St Lucia, with an area of about 300 km^2 and also connected to the sea by a channel meandering through swamplands;

- further north on the east coast the Kosi Lake System, consisting of three lakes with a total area of about 35 km^2 and also connected to each other and to their common estuary by channels meandering through swamps.

It is clear that estuaries represent an exceedingly valuable resource of limited proportions and that sound conservational and management techniques must be applied if optimal use is to be derived from them. As in many other countries, they are, however, subjected to multiple use with inherent conflicting interests. Furthermore, complex legislation and divided control renders their effective management difficult. To rectify such a situation in an already highly developed country such as South Africa, is no easy task.

4. MAN'S IMPACT ON THE ESTUARINE ENVIRONMENT

(a) Multiple use and ecological requirements

The interaction of the marine and terrestrial environments gives estuaries characteristics and attributes found nowhere else, which can (and are) put to multiple use in many parts of the world. It is obvious that there must be conflicting interests in such multiple usage. At an international seminar held in 1978 under the auspices of the UNESCO Division of Marine Sciences and the International Association of Biological Oceanography at Duke University in the United States, this dilemma was summarized as follows:

> "Lagoons and estuaries have been historically important as sheltered sites of habitation providing access to both the land and the sea. Not only are they important for transportation, they also provide natural food resources rich in protein and easy dumping places for waste material. Some of these multiple uses are compatible; others not. It is important that the maximum benefit from these areas be obtained without jeopardy to future options or continued use. To achieve this purpose it is first necessary to acquire a knowledge about the systems producing renewable resources and how they are affected by both natural and human effected alterations."

The statement 'It is important that maximum benefit from these areas be obtained without jeopardy to future options or continued use', implies an economic approach to conservation but this cannot be achieved if ecological viability has been destroyed. It must be recognized that estuaries exist in a state of dynamic equilibrium and that their viability and ecological resilience depend on the interaction of numerous factors of which the following are of particular importance:

- from the land they receive fresh water which frequently enters them through swamps or saltmarshes. These swamps and marshes have the vital function of breaking the force of flood waters and acting as filters of silt. They are also areas of very high biological productivity and act as nutrient generators for estuaries;

- estuaries frequently carry underwater beds of aquatic macrophytes (e.g. *Zostera, Ruppia, Potamogeton*), which stabilize the bottom, convert nutrients into plant tissue, contribute to the oxygen balance of estuaries, buffer the effect of pollutants, provide shelter for juvenile fish, prawns and other estuarine and marine organisms, and provide food for fish, birds and mammals.

- the vegetation on the fringes of estuaries gives stability to their banks, contributes detritus and food to the system and also provides a habitat for many living forms such as birds, mammals and juvenile marine and estuarine organisms sheltering amongst their roots in the water. The marginal vegetation has evolved in response to the tidal regime characterising an estuary, which in turn is dependent on;

- the configuration of the mouth of the estuary. This is dictated by the interaction between the forces generated by the waves, currents and tides of the sea and the outflowing river water.

From the foregoing it is clear that a proper understanding of the interaction of physical and biological processes is essential for the formulation of effective management procedures for estuarine environments.

(b) Management considerations

It is not always possible to observe the above criteria in a modern industrially orientated society because of the need to accommodate many conflicting interests. Thus, in South Africa it is accepted that modification of estuarine systems at growth centres such as Saldanha, Cape Town, Port Elizabeth, East London, Durban and Richards Bay is unavoidable. However, every effort must be made to find a reasonable balance between the exegencies of development and conservation. What must be recognized as being unacceptable is avoidable destruction of the estuarine environment through ignorance or wilful disregard of the known ecological requirements. Thus special care must be taken in the planning of:

- road and rail embankments bisecting swamps and floodplains;

- water regulation in catchments, including the construction of weirs and impoundments;

- residential and industrial developments in the immediate environment of estuaries, particularly if these are below 50-year flood levels;

- the disposal of waste products of domestic or industrial origin which can lead to pollution of estuaries;

- modification of dynamic mouth configurations through the construction of groynes or training walls;

- agricultural practices which can lead to soil erosion and silt deposition in estuaries;

- administrative procedures which can lead to subsequent problems of control, e.g. using rivers instead of watersheds as boundaries between administrative or magisterial districts.

Clark (1977) has put forward the concept of the optimum carrying capacity of the coastal environment, which implies, *inter alia*, that if man is to derive the optimum benefit from the resources held by all components of the coastal environment - that is, coastal land, rivers, estuaries, dunes, beaches, rocky shores and the sea - he must plan development in such a way that utilization of one component will not cause undue damage to others. Thus a freeway is of little benefit if its construction damages the part of the coast which is to be made more accessible by it, or if it reduces the economic potential of the region through which it passes. A dam in the catchment might be of benefit to agriculture or to the water supply of metropolitan areas, but justification for its construction is placed in jeopardy if it damages the economic potential of the coastal region downstream. Industrial developments should not take place at the expense of natural resources upon which other facets of the economy (e.g. commercial fishing or tourism) are dependent for survival.

While the rationale behind Clark's concept of optimal carrying capacity is difficult to challenge, it is obvious that it cannot be applied if adequate knowledge about the functioning of the ecosystems and resources concerned, is not available. This points to the need for a co-ordinated approach to research which must be aimed at providing environmental managers with information which is really relevant to them.

5. A CO-ORDINATED APPROACH TO ESTUARINE RESEARCH

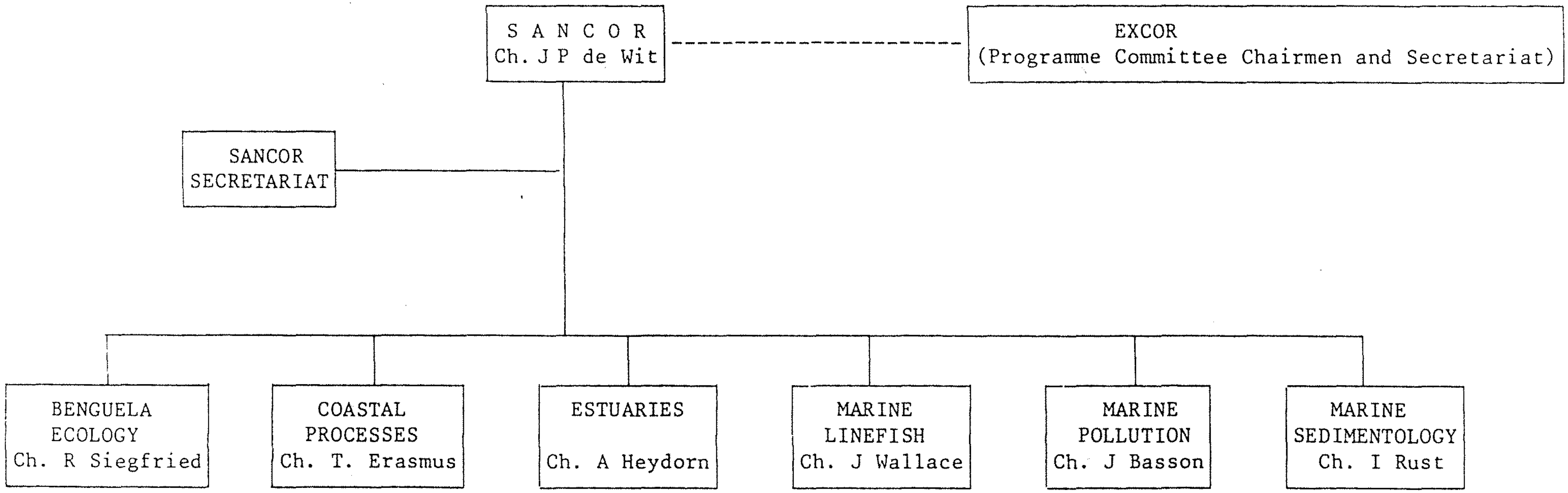
The requirements of environmental and resource management outlined above are to a large measure responsible for the direction in which estuarine and coastal research is moving in South Africa at present. Emphasis in estuarine research is given to three major directions:

(a) Biological studies of the plants and animals occurring in estuaries and the associated freshwater and marine environments.

(b) The interactions between the various components of estuarine foodwebs with each other and their environment.

(c) The physical processes contributing to the character and equilibrium of estuaries. Of particular importance is the understanding of hydrological/hydraulic regimes and the effects of the modification or manipulation of such regimes by man on the distribution of sediments in estuaries.

STRUCTURE OF SANCOR



THE FUNCTION OF EACH COMMITTEE IS TO:

- direct the scientific progress of that programme
- establish specific programme goals and objectives, and direct the programme accordingly
- advise SANCOR on funding requirements
- ensure the transfer of information to user agencies

FIGURE 3: ORGANIZATION OF PRESENT SANCOR PROGRAMMES

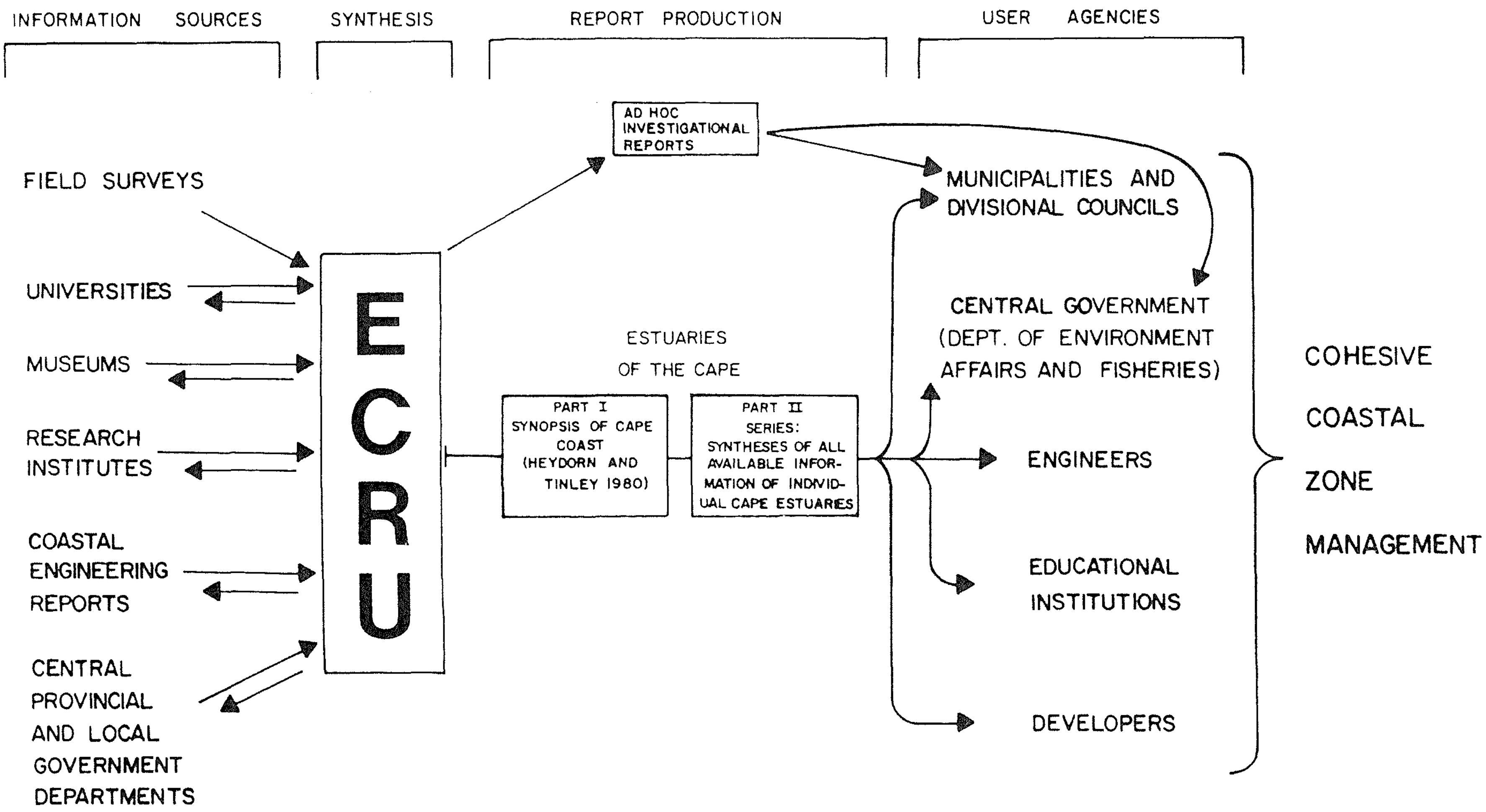


FIGURE 4: FLOW DIAGRAM OF ECRU ACTIVITIES AND INTERACTIONS

Together these three major directions enable the development of a systems approach which is necessary for the achievement of the predictive ability required for management purposes. Thus, typical questions which need to be answered are:

- what are the minimum freshwater requirements of an estuarine system if one or more dams are built in the catchment?
- if artificial breaching of an estuary becomes necessary, for how long must the mouth be allowed to stay open if the migration of organisms between the sea and the estuary is to remain unimpaired so that recruitment patterns are not disturbed?
- what would the effect of specific developments on components of estuarine ecosystems, such as floodplains or dunes, be on the ecosystems as a whole?
- can sewerage effluents or other forms of organic enrichment cause eutrophication or create health hazards?
- what would the effects of engineering works such as marina development or the construction of groynes be upon the equilibrium and ecology of the system concerned?

It is clear that questions such as those posed above can be very specific but that, nevertheless, the overall functioning of estuarine ecosystems is usually addressed. It is equally clear that answers cannot be given by biologists on their own and that a co-ordinated approach to research embracing all disciplines - biology, physics, chemistry, geology/sedimentology and coastal engineering is required if meaningful scientific advice is to be given. Similarly, neither "fundamental" nor "applied" research can provide the required answers on their own - both are needed and should be carried out in conjunction with each other.

The South African National Committee for Oceanographic Research (SANCOR) runs a number of co-ordinated programmes, one of which deals with estuarine research, to achieve the co-ordination and collaboration required. Other SANCOR programmes which have a bearing on estuarine management are those dealing with coastal processes, marine linefish, marine pollution and marine geoscience with emphasis on sedimentology. In this way a serious attempt is made to utilize all available manpower and facilities at Universities, Museums and at other research institutions to best effect in coastal and estuarine research and to ensure optimal distribution of available research funds for the purpose. Figure 3 depicts the basic organization of the SANCOR suite of research programmes. Each is led by a Chairman supported by a Steering Committee. Brochures describing the objectives of each programme, identifying priorities and providing an overview of research opportunities are prepared and published for each programme, e.g. The SANCOR Estuaries Programme, 1982-1986.

Finally the Estuarine and Coastal Research Unit of the CSIR, was set up specifically to transmit all existing and new scientific knowledge on estuaries to the various authorities responsible for management of the coastal zone, in clear and understandable form (see Figure 4).

This is done through the production of a report series dealing with the coastal environment as a whole (The Estuaries of the Cape, Part I, Heydorn and Tinley, 1980) followed by reports containing syntheses of all available information on individual systems (The Estuaries of the Cape, Part II series). This follows similar work which was carried out in Natal (Begg, 1978) and which is still continuing there.

Whether this intensive overall research effort will really be effective, depends to a large extent on the willingness of authorities at various levels of government to apply scientifically based coastal zone management techniques. In South Africa there is reason for optimism as much of the coastal and estuarine research mentioned above is carried out at the request of, and is funded by, the Government. The level of consultation between the Government and scientists is high.

6. CONCLUSION

It has often been stated that the damage which man inflicts upon the estuarine environment is progressive, cumulative and in many cases irrevocable. In our country the problem is compounded by very rapid population increases, particularly in the coloured and black sectors of our population, coupled with greatly improved economic circumstances for these people. This leads to rapidly increasing and certainly justifiable demands for outdoor recreational outlets and this goes hand in hand with greater pressure on the coastal environment and estuaries in particular. Consequently a socio-political dimension is added to the already complex situation concerning the requirements of wise management of our estuarine and coastal resources. Obviously the increasing demands on the estuarine/coastal environment promotes economic development which brings with it a stimulation of the property market, job opportunities and other benefits. However, in the use of any environment, short-term economic benefit and convenience should not be the basic criterion, but rather the need for maintenance of the ability of the environment to continue sustaining an expanding human population. The vital importance of this is starkly illustrated in Third World and Asian countries where starvation as a result of unstemmed population growth and depleted natural resources is already a problem of frightening proportions.

7. ACKNOWLEDGEMENTS

I would like to express my deep appreciation to my Australian colleagues and in particular to Dr EP Hodgkin, for the invitation to attend the 1983 ANZAAS conference. I am furthermore indebted to the South African Council for Scientific and Industrial Research and the Department for Environment Affairs for their financial support and permission to attend in the light of other pressing commitments. Special thanks are due to my colleagues Dr Burg Flemming and Dr Harry Swart who contributed substantially to this paper through direct input and valuable criticism.

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HOLOCENE SEDIMENTATION HISTORIES OF ESTUARIES IN SOUTHEASTERN AUSTRALIA

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Abstract

Stratigraphy and radiocarbon age structure of four estuaries in southeastern Australia are described. They represent two basically different estuary types with contrasting river catchments and sediment discharges. Primary differences, mainly in estuary mouth conditions, established on this coast once the Postglacial sea level stabilised 6,500 years ago. Holocene sediments reach thicknesses of about 50m in the estuaries. Muds have accumulated at rates ranging from 0.1 to possibly as much as 15mm yr^{-1}, a limit imposed by rising sea level. Mud basin deposits are most extensive in estuaries behind bay barriers with restricted tidal inlets. These estuaries experience most rapid environmental changes at mature states of development as terrestrial flood plains spread seawards over shallow estuarine basins. In estuaries with open mouths and full tidal ranges, large tidal delta sand bodies have grown landwards at rates of 1-4m yr^{-1} during both rising and stable sea level conditions. As these estuaries approach maturity they discharge suspended sediment to the sea which retards subsequent infilling. Estuaries with poor flushing characteristics at their mouths experience more radical environmental fluctuations due to both natural and man-induced changes, than do estuaries with unimpeded tidal exchange.

Introduction

Previous geological investigating of estuaries in New South Wales (NSW) has led to the development of a two stage estuary classification: three basic estuary types each of which evolved along characteristic pathways as they infilled with sediment. Differences, firstly in estuary type and secondly in rates of infilling, account for the diversity of present day estuaries along this coast (Roy, 1983 and in press)

This paper explores the rates and nature of physical changes in estuaries from a geological standpoint. Sedimentation in various estuarine environments is documented for estuaries of different types. The intention is to provide a yardstick by which modern (post European) physical changes in estuaries can be evaluated. The geological record shows that, throughout their evolution, estuaries have experienced (and survived) natural changes of major import. Thus, in evaluating the recent impact of man on estuarine ecosystems, the baseline concept of a pristine, natural estuary must incorporate the idea of continuing evolutionary change. Their inherent variability is reflected by estuarine life forms which have evolved a greater resilience to fluctuating natural conditions (salinity, water temperature etc.) than other marine communities.

In Australia the evolution of present day estuaries can be traced back to the end of the Postglacial Marine Transgression (PMT) when rising sea level drowned entrenched valleys at the coast (Roy et al., 1980; Chapman et al., 1982).

The character of the N.S.W. coast is a response to a unique set of environmental conditions: The continental shelf is narrow (less than 60 km wide) and 70% of it is deeper than 50m; it is mostly sand covered. The coast is bedrock controlled with sandy embayments of various sizes exposed to a relatively high energy ocean wave climate and tidal ranges of less than 2m. Unlike areas with large tidal ranges and muddy inner shelves (e.g. northwest Australia, Wright et al., 1978), N.S.W. embayments are dominated by wave-induced sand movements. The climate is temperate with an erratic rainfall pattern that is not strongly seasonal. Thus estuaries here do not experience the marked annual cycle of salinity and water level change typical of areas with a Mediterranean climate as documented in southwestern Australia by Hesp (1983, this volume). N.S.W. coastal rivers have perennial flow interspersed with occasional floods; with headwaters in the eastern highlands less than 150 km inland and catchments less than 50,000 km^2 area, their sediment discharge is small by world standards. This, together with the deep high-energy shelf, accounts for the absence of protruding fluvial deltas at the coast (Roy and Thom, 1981). Ebb tide deltas are also weakly developed.

Superimposed on the physical setting is a Postglacial sea level history characterised by a period of rapid sea level rise prior to 6,500 years BP, followed by stillstand of the sea (Thom and Chappel, 1974; Thom and Roy, 1983). With few exceptions, Holocene estuaries in N.S.W. occur in drowned coastal valleys incised into bedrock and Pleistocene valley fill during the Last Glacial. Inundation commenced at the present coast 9,000 - 10,000 years ago and, unlike other well studied coasts (Kraft, 1978), terminated when sea level stabilised. Estuary water bodies were formed behind deposits of marine sand in coastal embayments. Bay barriers initiated at the end of the PMT fixed most estuary mouths against headlands; this contrasts with their mobility in barrier island situations (e.g. U.S. East Coast, Boothroyd, 1978).

The primary character of the three main types of estuaries in N.S.W. was imprinted in the mid Holocene (Roy, 1982 and in press): Large subaqueous tidal delta sand bodies accumulated in the mouths of deep, drowned river valley estuaries; coastal sand barriers intersected by narrow tidal entrance channels isolated barrier estuaries and, in valleys with very small rivers, barriers with ephemeral inlets impounded saline coastal lakes (Roy, 1982 and in press). During the last 6,500 years of stable sea level, estuaries have continued to infill with sediment from the land (immature, fluvial sand and mud), from the sea (quartzose, marine sand) and with biogenic material produced internally.

All estuaries contain an array of depositional environments characterised by distinctive sediments or lithofacies but the degree to which these are developed varies in estuaries of different type (Table 1, Roy at al., 1980). Estuarine environments and their associated lithofacies are briefly described below: evolutionary changes within these depositional environments are discussed in following section.

Depositional Environments and Lithofacies in N.S.W. Estuaries

Environments of deposition are defined by sediment types, morphologies and the physical, chemical and biological conditions that play a part in the sedimentation process (Reinech and Singh, 1973). Although estuarine environments are extremely diverse, they can be grouped into three main categories: fluvial-estuarine river delta, mud basin and back barrier-estuary mouth. Coastal sand barriers, including dune, beach and nearshore deposits, while not strictly estuarine environments, are often intimately involved in estuary evolution.

Possibly the most complex association of sub-environments, sediment types and ecological habitats are found within fluvial-estuarine delta environments. These occur where rivers and streams enter estuarine water bodies and conditions range from subaqueous (saline to brackish) through intertidal to terrestrial. They include river and distributary channel beds, mid-channel shoals and delta mouth bars, levee banks and crevasse splays, delta top platforms and delta-front slopes, inter-distributary bays, freshwater and brackish swamps and flood plains. Inter-tidal areas may be colonised by mangrove and salt marsh communities although salt marsh peats, used extensively in other parts of the world to date relative sea level change, are poorly developed in N.S.W. Subtidal deposits are often shelly and, in shallow areas are covered by sea grasses. Sediments, which are typically organic-rich and include gravel, sand and mud, often in poorly sorted admixtures, occur in two stratigraphic settings: regressive and transgressive. Regressive deposits have built seawards, principally during the stillstand period, over estuarine mud sequences. Sandy transgressive deposits were laid down during the early Holocene as rising sea level inundated the valleys; they occur beneath the estuarine muds.

Estuarine mud basins are uniform, low energy environments in the deeper and quieter parts of estuaries where fine river sediment, supplied mainly during floods, settles from suspension. The resulting deposits are muds, rich in estuarine shell and foraminifera species and organic fragments. They are extensively bioturbated, mainly by Polychaetes, and virtually all small-scale primary sedimentary structures are destroyed. Fecal pellets often make up a large proportion of the sediment and undoubtedly add to its cohesiveness. Physical conditions are essentially placid except for slow, wind-induced circulations and wave-stirring in shallow water ($<$ c. 2m). Except for occasional biohermal shell banks (Peat and Roy, 1975) and small mounds produced by burrowing organisms, the mud surface is planar. Sandy shoreline facies that occur around the estuary sides are the product of wave reworking and shoreline erosion. These grade into the basin muds and, in the following, are incorporated within the mud basin category.

Back barrier-estuary mouth environments contain shelly marine sands deposited by washover processes and tidal currents. During the PMT these were laid down in transgressive sand sheets as rising sea level over-washed the landward retreating barrier surfaces and currents and waves carried sand into deepening estuary mouths. The sand bodies onlap or interdigitate with muddy estuarine sediments to landward; in shallow valleys (c. $<$ 30m deep) they usually lie directly on the pre-Holocene substrate but in deeper valleys where estuarine conditions were initiated seawards of the present coast, they overlie estuarine muds. Surface morphologies include broad subtidal flats, often seagrass covered and muddy, intersected by tidal channels and bordered by storm ridges elevated above normal water levels.

Marine sands that accumulated in estuary mouths after sea level stabilised form characteristic flood tide deltas at the landward ends of tidal channels. A prerequisite for this style of deposition is the existence of relatively deep mud basin environments to landwards and over which the tidal delta retrogrades by slip face accretion. Delta surfaces form relatively shallow, landward-shoaling sills or thresholds with well developed tidal channels. Water depths in their inner parts are mostly less than 5m and include intertidal sand banks and seagrass beds in protected sites; their seaward faces may be reworked by ocean waves.

Estuarine Stratigraphies and Evolutionary Reconstructions

In the following section rates of physical change are documented for individual estuaries of the drowned river valley and barrier types that have infilled rapidly and slowly. Examples of the former are the Hawkesbury River and Port Hacking; the latter type is represented by the Shoalhaven delta and Lake Macquarie. All the estuaries are situated in central NSW. Their catchments are compared in Figure 1 and their estuarine water bodies and shoreline deposits are shown in Figure 2. Port Hacking and Lake Macquarie have small river inflows and are in marked contrast to the Hawkesbury estuary and the Shoalhaven delta which are both fed by large river systems.

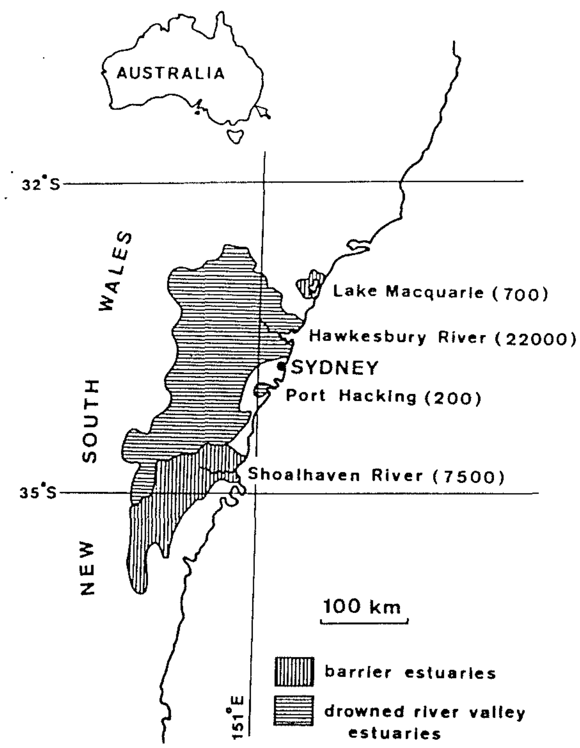

Figure 1. Location map showing river catchments of estuaries discussed in text. Numbers in brackets are catchment areas in km^2

The data base includes seismic reflection profiling, drilling and coring and radiocarbon dating of sediments that have accumulated over the past 10,000 years (the Holocene period). Comparable data is not available for saline coastal lakes which are not included in the following discussions. The stratigraphic data provides a basis for reconstructing an evolutionary history for each estuary but, because of limitations in the data, a high degree of speculation is involved.

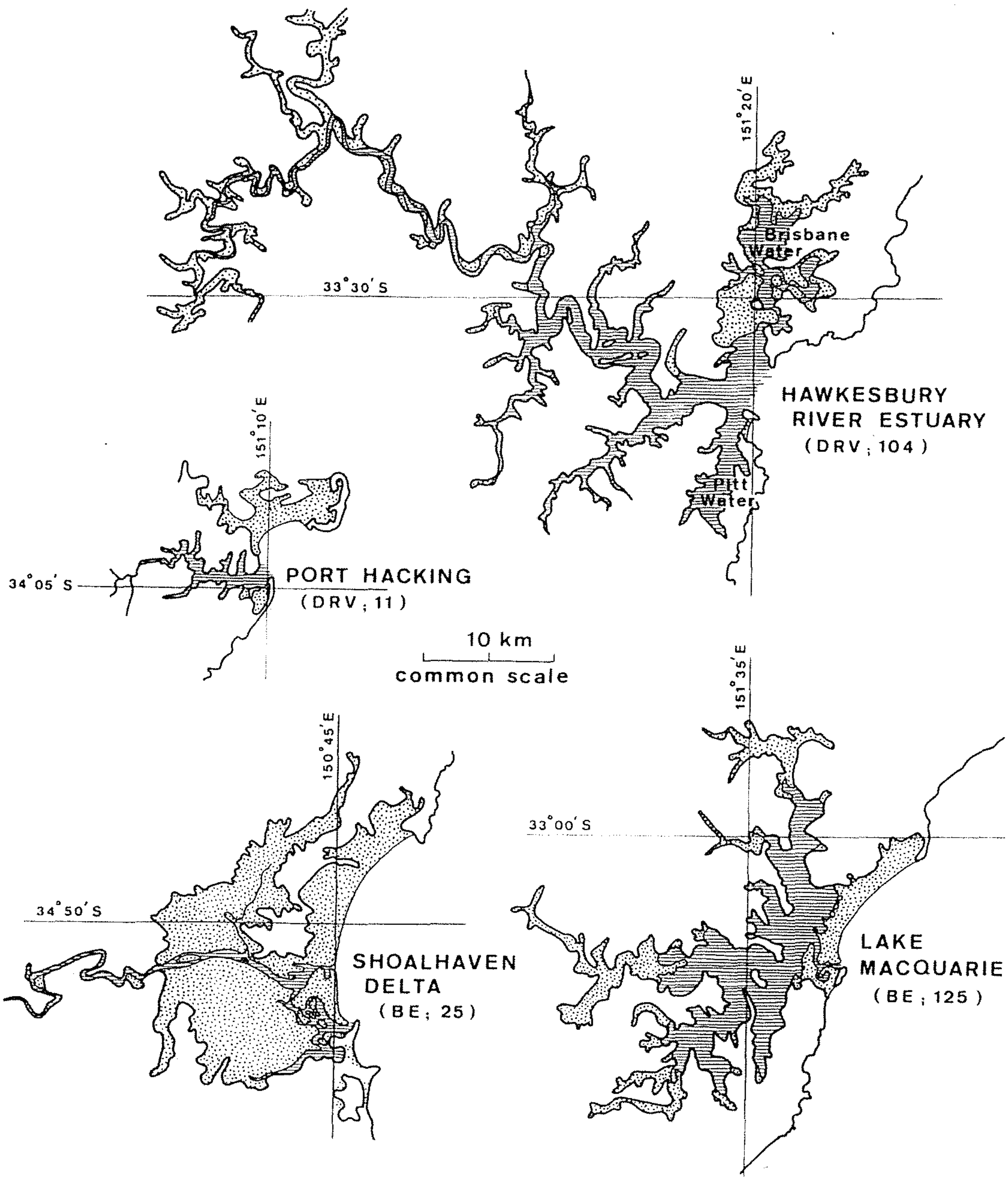

Figure 2. Quaternary sediments (stipled) and water bodies (hatched) of estuaries discussed in text compared at a common scale. Estuary type and water area in km^2 are shown in brackets. (DRV = drowned river valley estuary; BE = barrier estuary)

(1) Port Hacking

Port Hacking estuary occupies a narrow, steep-sided bed-rock valley typical of coastal drainage systems incised into massive sandstones of the Sydney Basin. The inflowing streams are small; the largest is the Hacking River (Fig. 3). Bate Bay at the drowned river valley mouth is a marine dominated, semi-enclosed bay environment. Open ocean tidal ranges extend throughout the estuary which is fully saline except for short periods during floods when stratified conditions develop (Godfrey and Parslow, 1976). The estuary mouth has water depths of 5-10m and is exposed to open ocean waves. Its bed shoals landwards into a central zone characterised by inter-tidal and shallow sub-tidal sand flats intersected by tidal channels 2-3m deep. Basins up to 20m deep occur in the upper estuary and its tributary arms. Small fluvial deltas have formed in the heads of the drowned valleys; the largest is at the mouth of the Hacking River.

The depositional environments and simplified stratigraphy shown in Figure 3 are based on detailed seismic profiling, drilling, vibro-coring and field mapping carried jointly by the Departments of Mineral Resources and Public Works. At the estuary mouth the bedrock valley is 90m deep (Albani et al., 1978). Here Holocene sediments extend to 60m bsl and overlie eroded and weathered remnants of Pleistocene deposits. The geology of Port Hacking is dominated by a large tidal delta sand body up to 40m thick that occupies about 60% of the estuary including the mouths of some tributary bays (Fig.3). On its surface small beach and dune sand ridges have formed in embayments along the estuary's southern shoreline. Over most of the sand body seismic profiling shows steep ($15-25^{\circ}$), landward dipping bedding that parallels the depositional slope on active delta fronts. Clean sands with minor shell ($<5\%$), and low angle bedding occur in its seaward part; the sands become more calcareous (up to 50%) in a landward direction and more muddy with depth (Nielsen and Roy, 1982).

Clean fluvial sands occur in the channels of inflowing streams and, at the mouth of the Hacking River, a shallow, subtidal delta lobe extends about 1 km into the estuary (Fig.3). The fluvial delta is composed of muddy and woody sands in the order of 10m thick (their base was not penetrated by coring).

In the basins between the tidal and fluvial deltas, shelly, organic-rich estuarine muds reach thicknesses in excess of 10m. These extend beneath the delta sand bodies and overlie transgressive fluvial sands in the axis of the paleovalley.

Terrestrial deposits at the coast include leached dune sands that mantle the headlands to the north and south of Bate Bay. Radiocarbon dates on buried soil horizons suggest that the aeolian deposition began in the early Holocene (pre c.8000 yrs BP) (Roy and Crawford, 1981; Pye and Bowman, in press). A sand source located to the south and east is indicated by the transgressive dune morphologies but the present coast is bordered by sheer cliffs and the sand source is no longer obvious. Roy and Crawford (1981) propose the existence of a "proto-barrier" sand body located seawards of the present coast that initially formed an aeolian sand ramp against the cliffs but was later reworked by the transgressing sea.

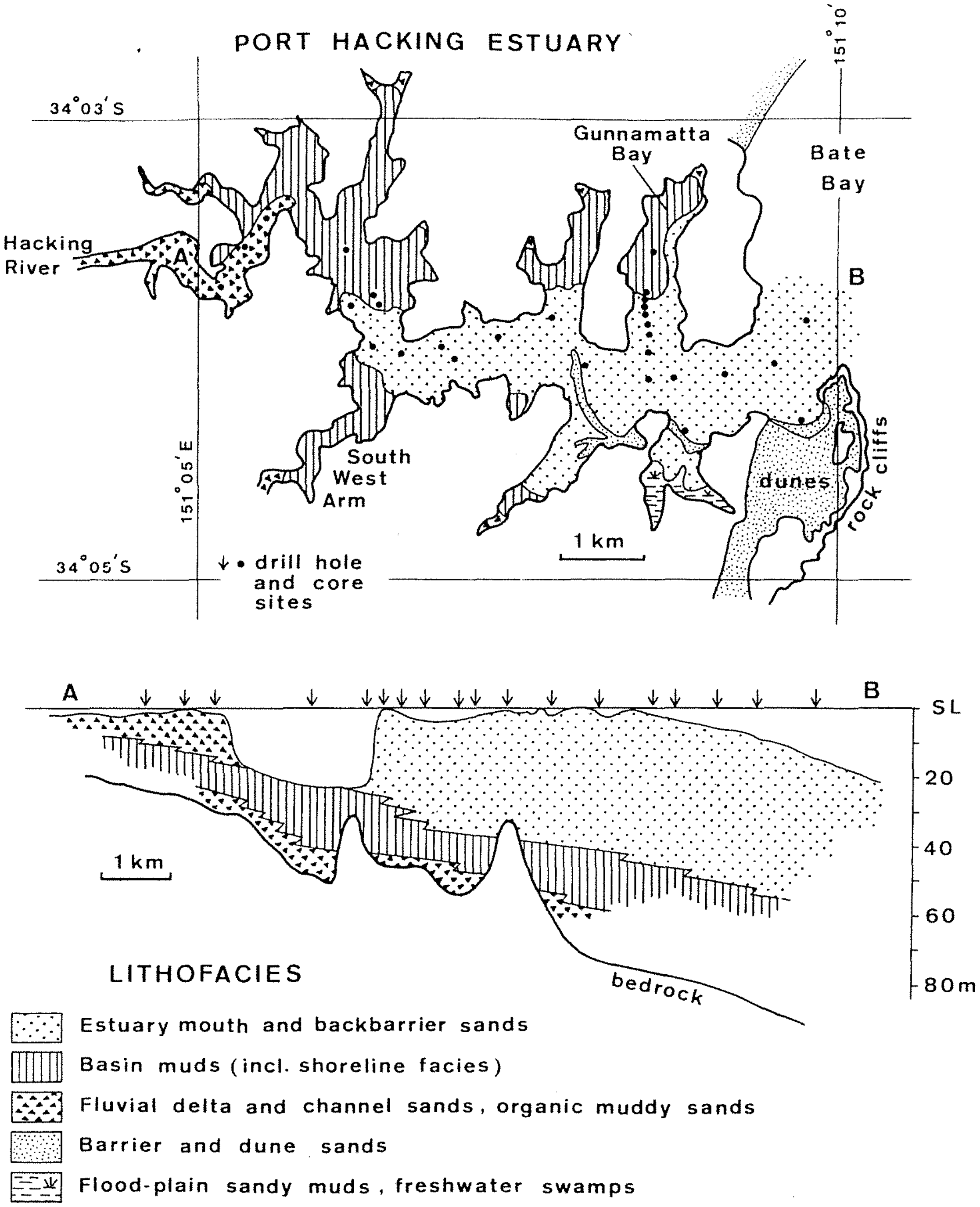

Figure 3. Port Hacking estuary showing simplified lithofacies in plan and axial section

Figure 4 shows depositional time lines based on calibrated radiocarbon dates. These are mainly on comminuted calcareous material from the estuary mouth sand body and are plotted against cumulative sediment volumes determined from seismic profiling and drilling. These data confirm its landward building nature and indicates a tidal deltaic mode

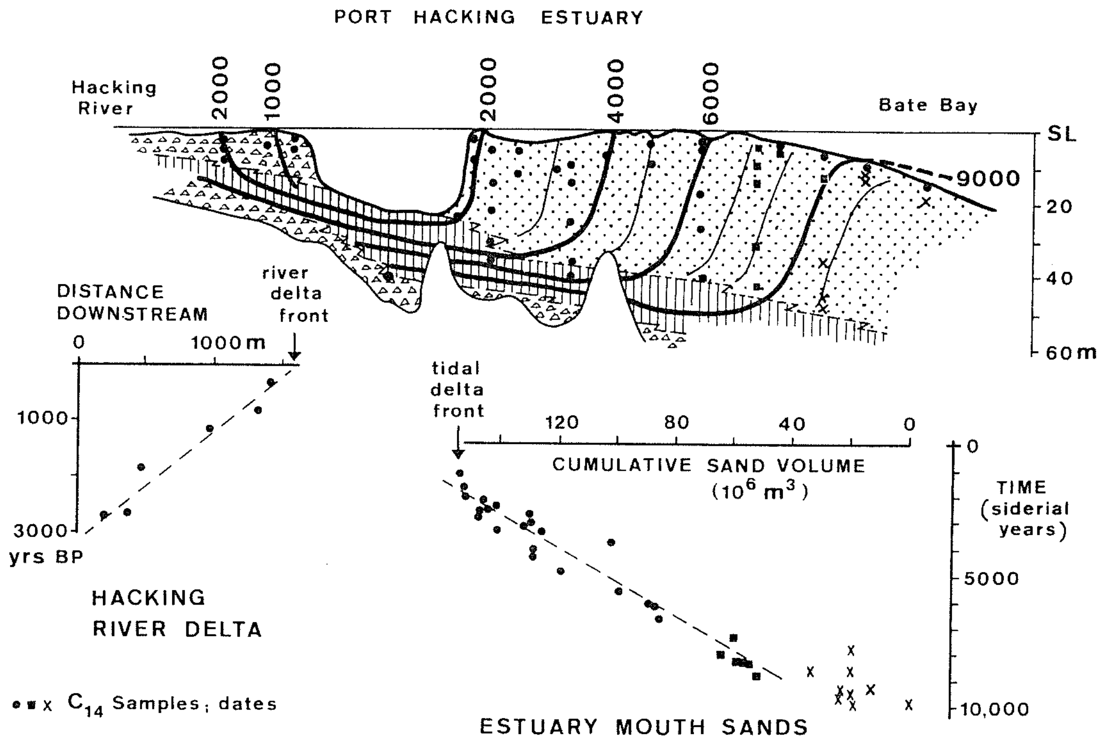

Figure 4. Constructed time lines based on radiocarbon dates superimposed on the stratigraphic section in the axis of of Port Hacking estuary. Time lines in the tidal delta sand body are displaced landwards due to contamination with old reworked shell (see text). Age/distance and age/volume plots show rates of accretion of the fluvial and tidal deltas respectively. Dates shown by solid circles have been calibrated to siderial years (Clark, 1975); samples shown by squares are only approximately calibrated and crosses indicate uncalibrated dates. Dates for the samples in the tidal delta are reported in Neilsen and Roy (1982)

of deposition for sediments younger than about 7000 years. However, the low shell content and gently dipping bedding of its outer part suggests a somewhat different mode of formation: a dune origin, associated with the "proto-barrier" mentioned earlier is one possibility. A regression line drawn through the data points indicates a constant rate deposition at the delta front of c.16,000 $m^3 yr^{-1}$ throughout mid to late Holocene times. Similar, although slightly higher, sediment transport rates have been determined from sand tracing experiments and calculations based on bed-form measurements (c 20000 $m^3 yr^{-1}$; B. Druery, PWD, pers. comm.). These dating results suggest an average rate of delta front advance of about 500 m^2 each year. In Gunnamatta Bay, a tributary arm on the northern side of the estuary mouth, radiocarbon dates indicate a much slower rate of sand supply (c. 1500 $m^3 yr^{-1}$).

Nielsen and Roy (1982) argue that the dates in Figure 4 have been age-shifted due to the inclusion of old shell reworked from further seawards and that the age shift is greatest for the youngest dates. This contamination phenomenon is supported by calibrated ages ranging from 700 to 1400 yrs BP on four surface samples collected from the delta fronts in both Southwest Arm and the main estuary. At the latter site, measurements on fixed bed markers located at the terminus of the flood tide channel document vertical and horizontal accretion on the delta front of 1.27 and 2.82 m yr^{-1} respectively and confirm that the delta front is presently growing rapidly at this site (B. Druery, PWD, pers. comm.). No attempt has been made to correct for this contamination factor; in Figure 4 adjusted time lines would be shifted seawards and slightly compressed while sediment transport rates calculated from the regression line would be decreased by c. 15%.

Also shown in Figure 4 are dated wood fragments from the Hacking River delta plotted against distance downstream. These data suggest that the delta front has prograded about 1500 m horizontally (c. 0.5 m yr^{-1}) over the last 2700 years. Sediment transport rates at the river mouth are not precisely known but are clearly only a fraction (<10%) of those in the estuary mouth.

Less data exists to document accumulation rates in the mud basins. Just upstream from the main delta front, 18 m of mud has accumulated since about 9000 years BP at an average rate of 2.0 mm yr^{-1}. In Gunnamatta Bay rates range from 1.2 to 2.9 mm yr^{-1} in two drill holes.

Stages in the evolution of Port Hacking estuary are depicted in Figure 5. At the beginning of the Holocene epoch, estuarine sedimentation was confined to the axial region of the Hacking valley. Figure 5A shows estuary mouth sands, basin muds and fluvial sands forming a succession of transgressive deposits in an upstream direction. Dunes are diagramatically shown transgressing headlands either side of the estuary mouth which, during the Last Glacial, was joined by the paleo-Georges River in the region of Bate Bay (Roy and Crawford 1981). Possible aeolian sand sources were "proto-barriers" located seawards of the present coast.

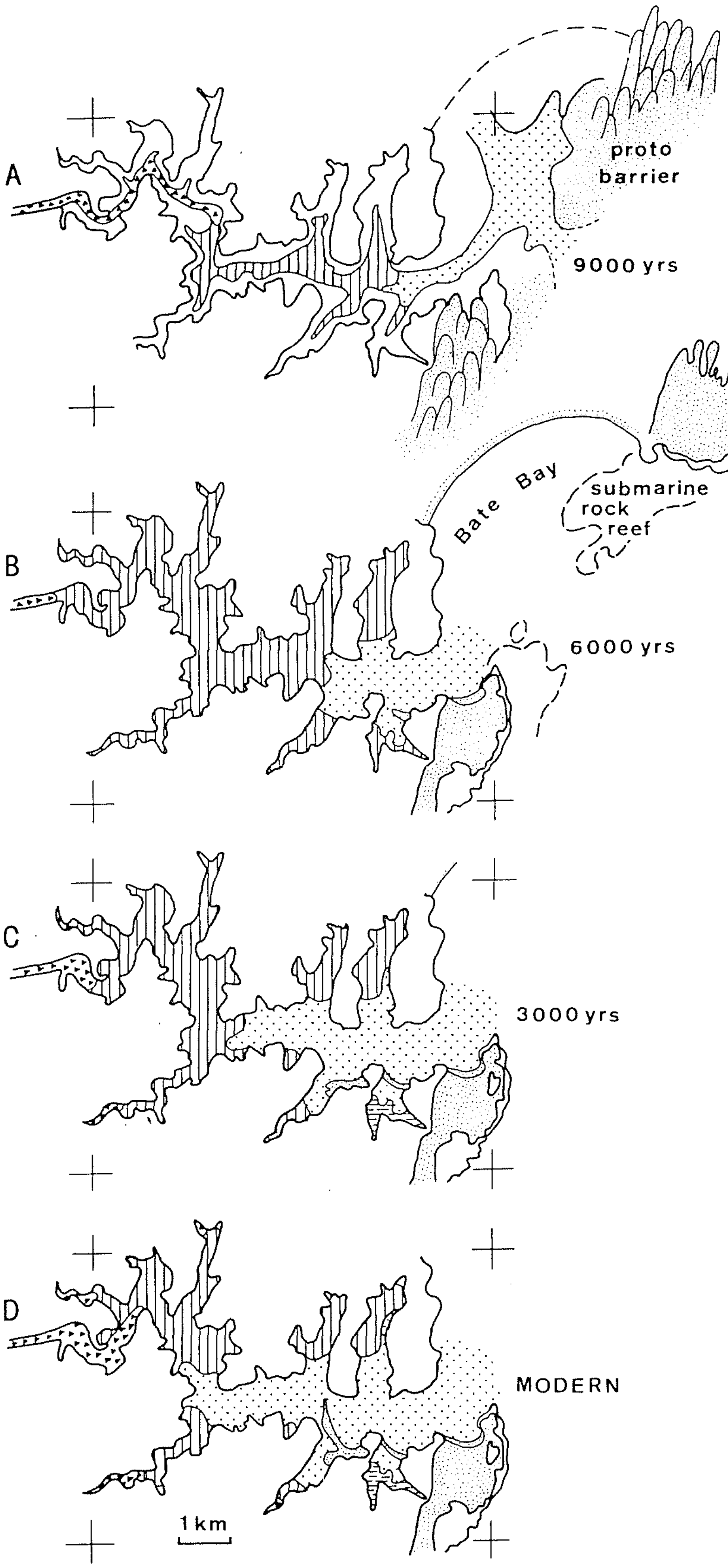

Figure 5. Reconstructed stages in the evolution of Port Hacking estuary. Stages A and B also cover Bate Bay and Kurnell headland on its northern side. The present-day distribution of rock reefs is indicated in Stage B; these have been exposed as sand from the proto-barrier migrated into the estuary.

By 6000 yrs BP (Fig. 5B) the Hacking estuary had attained its present dimensions and the former mouth of the Georges River was blocked by a beach ridge barrier on the northwestern side of Bate Bay (Roy and Crawford,1981). Reworked remnants of the "proto-barrier" in Bate Bay probably acted as a sand source for the tidal delta in the estuary mouth which had built upwards and into the estuary about 2 km by this time.

In the following 6000 years (Figs. 5 C and D), refracted ocean waves formed small barrier ridges and spits, initially just inside the estuary mouth (Jibbon Beach) and progressively later further upstream (Bundeena Beach, then Deeban Spit most recently). The tidal delta continued to grow upstream not only in the main estuary but also into the mouths of tributary arms. Over the stillstand period approximately 3 km^2 of mud basin environment was converted to shallow sand flats. In some areas these are seagrass covered and in others sand banks extend into the intertidal zone. While this accretional trend had little impact on tidal or salinity regimes, it dramatically changed biological environments and habitats in the central estuary. From delta front geometry and past rates of growth, the transition from deep mud basin to shallow sand flat took place over an interval of 75-150 years in the main estuary. The present delta front morphology suggests that tidal delta growth is non-uniform. Deposition is fastest at the terminus of the main flood tide channel where the delta front develops a lobate plan-form (Fig. 5 D). Meandering and switching of the tidal channel in time and space has probably caused the delta front to continuously change in shape.

A similar lobate morphology is also shown by the fluvial delta at the mouth of the Hacking River (Fig. 5 D). Here sediment transport and deposition presumably is confined to a jet stream emanating from the river mouth during floods. Throughout the last 3000 years the delta lobe has prograded over an area of about 100 m^2 annually. Seaward of this, fine suspended sediments and biogenic material have accumulated slowly in deep basins. While the basins remain unfilled, both deltas will presumably continue to grow inwards. There is no indication from the radiocarbon dates that rates of sediment supply to the tidal delta have changed significantly during the late Holocene. It is probable that the main source of marine sand is from erosion of the delta surface in the estuary mouth and Bate Bay. Here a shelly and charcoal-rich surface layer c. 1m thick directly overlies very early Holocene sand. Shell hash in the surface layer ranges in age from 3170 to 2600 years (5 dates) and represents a zone of modern wave reworking which, under suitable conditions, supplies calcareous sand to the upstream delta front. Support for this contention derives from historical evidence that the estuary mouth has deepened by up to 3m over the last 100 years (B. Druery, PWD, pers.comm.). While local reworking is the most likely source of tidal delta sand, a contribution from offshore cannot be ruled out. Marine sand deposits located further seaward in Bate Bay and extending along the base of the coastal cliffs are stirred by storm waves to depths of c. 60m and may also experience net alongshore transport (Field and Roy, 1983).

(2) Hawkesbury River

This is the largest drowned river valley estuary on the east coast and is characterised by a sinuous, deeply incised bedrock valley extending about 50 km upstream to its tidal limit (Fig. 6). Except at its mouth, the sediments are fluvial - deltaic in character with channel deposits predominating; flood plains and typical delta morphologies are poorly developed in the narrow valley (Fig. 2). As well as occasional river floods, the estuary experiences moderately strong spring tidal flows of 0.5-1.0 m sec^{-1} (PWD, Hydraulics Laboratory, unpublished reports). Its lower reaches, which are the subject of the following discussion, contain drowned tributary valleys that are infilled to varying degrees (Roy, 1983). Broken Bay at the river mouth is a marine dominated bay environment similar in many respects to Bate Bay at the mouth of the Port Hacking estuary. Its landward shoaling bed is 20-10m deep and is exposed to refracted open ocean waves. The Woy Woy beachridge plain, at the mouth of the Brisbane Water valley, forms the northern shoreline of the Bay (Roy et al., 1980; Roy, 1983)

Quaternary sediments in Broken Bay and the Lower Hawkesbury estuary are described in Roy (1983) and are summarised in Figure 6. Tidal delta sands in the estuary mouth extend upstream for a distance of 8 km in the subsurface (their surface extent is somewhat less). Muds principally occur in deep basins in the tributary valleys; in the axis of the main river channel they grade laterally into more sandy deposits forming shoals and point bars. Fluvial channel sands are coarse and gravelly above the tidal reach and become increasingly muddy and finer grained in a downstream direction; (Neville, 1976; A.Jones, Aust. Museum, pers. comm.). Just inside the estuary mouth they intermix with marine sands on the tidal delta surface and form a surficial mixed layer on the bed of northern Broken Bay (Fig. 6). This figure shows the location of drill holes in the lower estuary and on the Woy Woy beachridge plain; additional data includes seismic reflection profiling in the lower estuary and drilling at bridge and pipeline crossing sites further upstream. The bedrock valley of the Hawkesbury River is 125 m deep at its present mouth (Albani and Johnson, 1974). In it, Holocene sediments occur to about 60-70m bsl and overlie weathered Pleistocene deposits (Roy, 1983). The simplified stratigraphic section in Figure 6 shows a 30m thick estuarine mud sequence overlying regressive fluvial sands at -50 to -60m. A tidal delta sand body onlaps the muds; it ranges from 30m thick at the estuary mouth to less than 20m at its inner edge. The sand body is characterised by steep, landward-dipping bedding; clean shelly sands occur in its upper and outer part and become finer and more muddy downwards and in a landward direction. Its inner margin is overlain by sandy fluvial sediments less than 5m thick which, further upstream, reach thicknesses of 10-15m and grade into estuarine muds. Detailed coring and drilling in the channel 30 km upstream at a pipeline crossing (Dames and Moore, 1979, unpublished data) encountered complexly interbedded sands and muds rich in organics and shells. A similar juxtaposition of rippled sand and cohesive mud characterises the present channel bed at this site and elsewhere in the central estuary.

Radiocarbon dates on shell and charcoal from scattered drill hole samples along the axis of the main estuary (Fig. 7), suggest that the estuary infilled very rapidly during the PMT but much more slowly during the stillstand. In this figure, the time/depth plot of samples bracketing the period of basin infilling documents a mud sedimentation rate of 10-15 mm yr^{-1} between 10,000 and 8000 yrs BP. This parallels the

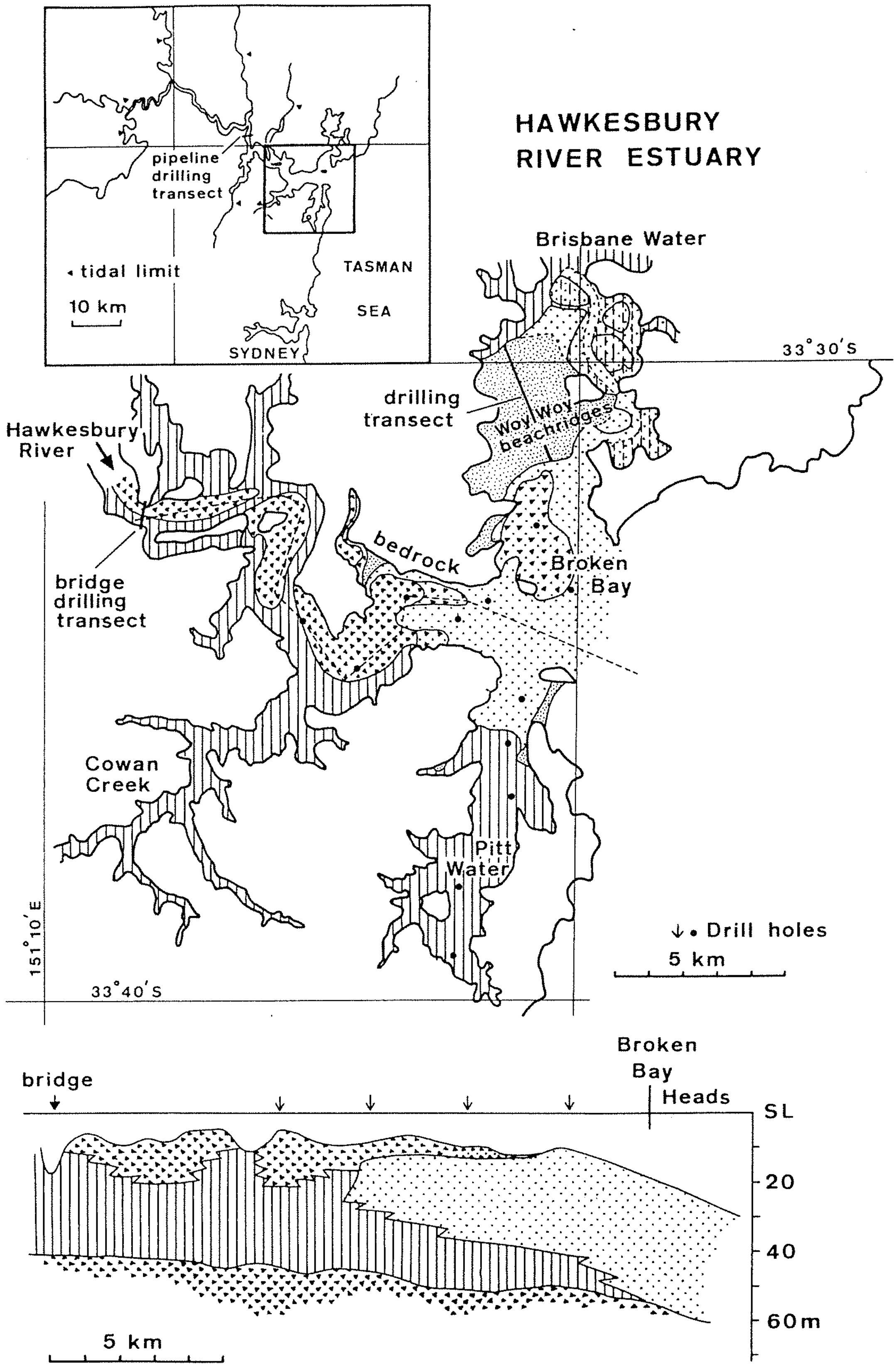

Figure 6. Lithofacies in the lower Hawkesbury River, Broken Bay, Pitt Water and the mouth of Brisbane Water. A dashed line shows the position of the stratigraphic section in the main estuary. Lithofacies symbols as shown in Figure 3.

Postglacial sea level rise over the same period (Fig. 7). A transition from estuarine mud to sandy sediment at 21 m bsl just upstream of the delta front marks the beginning of fluvial-deltaic sedimentation in the lower estuary. This occurred at about 8000 years BP. Tidal delta growth prior to this time was extremely rapid although dates at the base of the sand body are undoubtedly age-shifted due to the inclusion of transported (old) shell (see Nielsen and Roy (1982) for a discussion of this phenomena). A date of 3385 C 14 years (SUA 1431) at the base of the fluvial sediments onlapping the inner tidal delta surface provide a minimum age on delta growth. In the mouth of Pitt Water the surface of the tidal delta (1.2m below the present sea bed) was in place 7150 C 14 years BP (SUA 1433). Here the delta is still slowly accreting into the deep Pitt Water basin but, in the main estuary, delta growth was terminated once the mud basin upstream of the delta front infilled level with the tidal delta surface (c. 14m bsl). From the sedimentation curve in Figure 7, this was probably achieved around 7000 years ago.

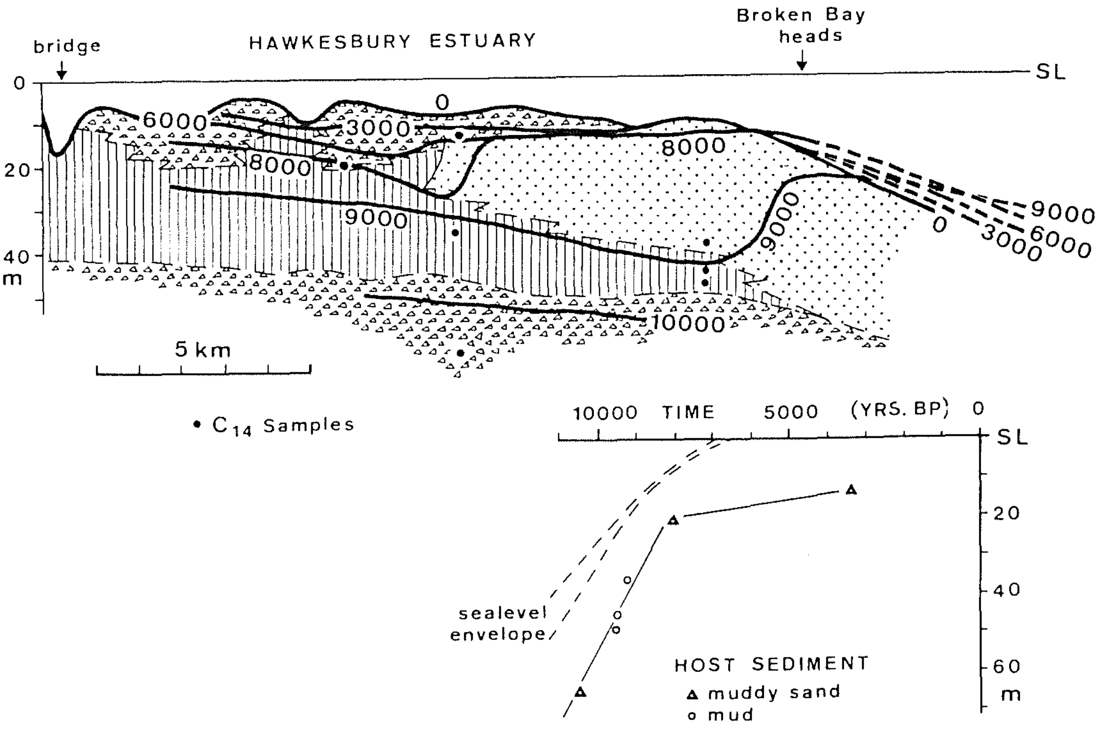

Figure 7. Time lines superimposed on the stratigraphic section in the Hawkesbury River based on uncalibrated radiocarbon dates reported in Roy(1983). The dates plotted against depth indicate approximate accumulation rates of estuarine mud and fluvial muddy sand in the lower estuary. The Postglacial sea level envelope is from Thom and Roy (in press).

In the last 3000 years, up to 5m of fine, fluvial muddy sand has prograded over the inner tidal delta surface. Further upstream, a similar build-up (c.5m) of somewhat coarser sand and mud has occurred over the same period on the channel bed (Dames and Moore, 1979, unpublished data). These rates of upward accretion (c. 1-2mm yr^{-1}) are almost an order of magnitude slower during the late Holocene than during the PMT.

In northern Broken Bay, beach ridge progradation was initiated once sea level stabilised. Probably the bulk of the sand was reworked from the tidal delta surface. Radiocarbon dating of drill samples from the transect shown in Figure 6, suggest that 80% of the barrier formed between 7000 and 4000 yrs BP (Thom et al., 1981). Subsequent progradation was slower although a date of c.1000 yrs from just behind the present shoreline may be due to contamination of old shell (Chapman et al; 1982) and the possibility of present-day growth cannot be ruled out (Roy, 1983).

In reconstructing the evolution of the Hawkesbyry River estuary, the pattern of drowned channels shown in Figure 8 A is based on marine seismic and drilling. Sea level 9000 yrs BP was 15-20m below its present level and deep narrow basin environments existed landwards of rapidly accreting tidal deltas in the mouths of the Hawkesbury and Brisbane Water valleys. The basins acted as settling sites for the large suspended sediment load carried by the Hawkesbury River. Rates of deposition were extremely fast and possibly matched that at which sea level was rising. With the large sediment discharge, mud basin environments were progressively superceded in a downstream direction by fluvial-deltaic deposits and by 8000 yrs BP (Fig. 8 B) sandy channel sediments had reached the lower estuary. Simultaneously, massive inputs of marine sand were responsible for rapid tidal delta growth upstream. The primary sand source was offshore although in Figure 7 it is suggested that erosion on the delta's seaward face was a contributary factor. Approximate rates of upstream accretion at the delta front were in the order of 2-4m yr^{-1}. From 10,000 to c. 7000 years BP about 8 km^2 of the lower estuary was converted from a placid mud basin environment to a clean sand substrate reworked by tidal currents and refracted ocean waves.

By 6000 years BP (Fig. 8 C) the main Hawkesbury estuary upstream of the tidal delta was dominated by fluvial sediments. Sandy marginal shoals had begun to onlap the tidal delta surface which had virtually ceased growing by this time. Low energy mud basin environments were mostly confined to slow filling tributary valleys such as Pitt Water and Cowan Creek (Roy, 1983) (Fig. 7).

At the close of the PMT, barrier building had commenced in the Brisbane Water valley (Fig. 8 C). Leached marine sands encountered beneath the Woy Woy beach ridge sequence at c. 4-10m bsl (B. G. Thom, pers. comm.) are presumably remnants of an earlier barrier that occupied this site in Pleistocene times. (In Figure 8 these old deposits are shown diagramatically).

Contrasting styles of estuary evolution are illustrated on either side of Broken Bay; Brisbane Water is a barrier estuary with attentuated tidal flow through a narrow entrance channel; Pitt Water is a drowned river valley estuary with an open mouth and a full tidal range. Their catchments and sediment supplies are similar but exposure to open ocean

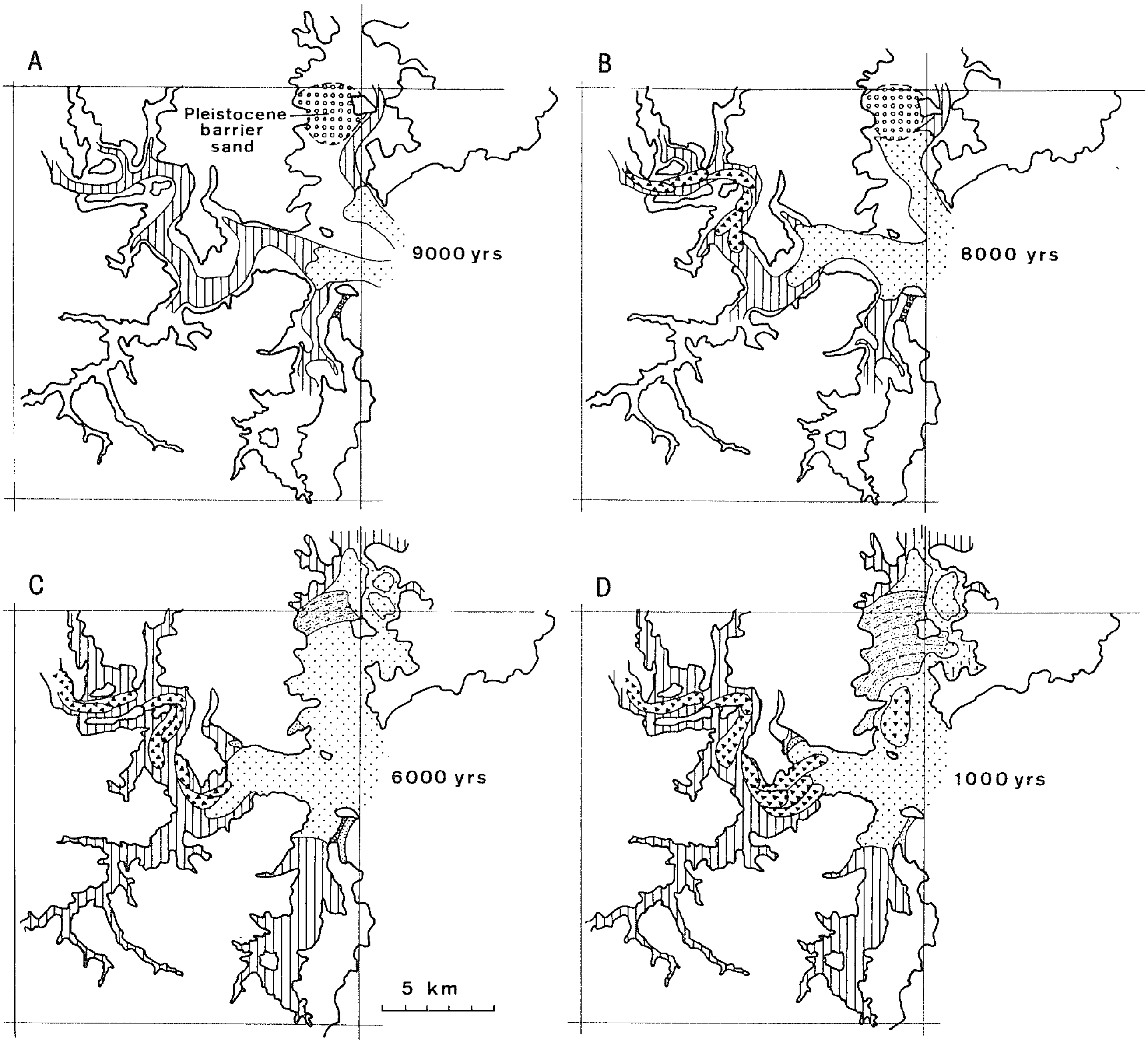

Figure 8. Reconstructed stages in the evolution of the lower Hawkesbury estuary - Broken Bay region. Lithofacies distribution in the mouth of Brisbane Water are largely speculative.

waves differs markedly. This factor, together with the shallow Pleistocene substrate, is responsible for barrier building in the south-facing mouth of the Brisbane Water valley but not in the more protected and deeper mouth of Pitt Water. In the last 6000 years, the Woy Woy beach ridges grew to their present dimensions (Fig. 8 D) converting an area of about 10 km^2 of what previously was a shallow, marine-dominated bay to a terrestrial environment.

In the main Hawkesbury estuary fluvial sediments on the channel bed have aggraded slowly during the stillstand (c. 5m in the last 2000 - 3000 years) and reflect a dramatic retardation of estuarine sedimentation compared with pre-stillstand rates. Following Castaing and Allen (1981), this is attributed to the slow but continuous leakage of fine sediment out of the open estuary mouth under the combined influence of spring tides and river floods. Clearly the net sediment flux has reversed from landwards during the PMT to seawards during the stillstand. An intermediate stage in this bypassing process is represented by the surficial layer containing fine river sand on the bed of northern Broken Bay (Fig. 8 D), a site exposed to reworking by storm waves (Wright et al., 1978).

The present estuary is characterised by relatively high ambient energy levels due to tides on which are superimposed on more dramatic short-term fluctuations due to river floods and storm wave reworking in the estuary mouth. Floods, and the sediments they supply, have been dramatically reduced in recent times by the construction of dams in the river catchment. Aggregate extraction (sand and gravel) from the channel immediately upstream of the estuarine reach has had a similar effect on the supply of coarse sediment to the estuary. Specific impacts on the estuary attributable to these man-made changes have yet to be documented and will be difficult to recognise within the spectrum of natural events. However, it is reasonable to assume that a reduction in fluvial sand input will retard the systems' natural evolutionary transition from estuarine (tidal) to fluvial dominance.

Present interest, kindled by a proposal to dredge construction sand from offshore (Wright et al., 1978), has focused attention on water and sediment movements in Broken Bay (L. Nielsen, PWD, pers. comm.). Bryant (1980), from comparison of historical charts, found significant accretion in the estuary mouth (10-20m depth zone) between 1872 and 1950, but geological evidence concerning tidal delta evolution argues against a net upstream movement of marine sand at present.

(3) Lake Macquarie

Lake Macquarie is a large barrier estuary occupying a number of coalescing bedrock valleys with small river catchments. The estuary basin, located behind a coastal sand complex, ranges from 5 to 11 m deep and is one of the deepest estuaries of its type in NSW. It is connected to the sea by a narrow entrance channel; tidal ranges in the channel are attenuated to less than 10 cm in the lake which is saline under most conditions (Roy et al., 1980; Roy and Crawford, in press).

The simplified pattern of surface sediments shown in Figure 9 is based mainly on work reported by Roy and Peat (1975). Shelly muds and sandy shoreline deposits, that thinly mantle the bedrock valley sides, cover about 90% of the estuary basin. The valley heads contain small flood plains and, at the mouths of the larger creek (e.g. Dora Ck), delta lobes protrude into the estuary. The coastal sand complex is a composite feature comprising a Pleistocene core of leached marine and aeolian sand onlapped by a Holocene barrier of the receded type with associated transgressive dunes (B.G. Thom pers. comm.). Estuary mouth sands that intersect its southern end, cover an area of approximately 13 km^2.

Subsurface data include detailed seismic reflection profiling (Ringis et al., 1974) and drilling in the estuary, on the coastal sand complex and in the delta of Dora Creek. The stratigraphic sections in Figure 9 represent a synthesis of the drilling data; they illustrate the general situation in the estuary basin and at major creek mouths and show two sections through the estuary mouth sand deposits and coastal barrier. At the coast the bedrock valley extends to about 60m bsl. Holocene

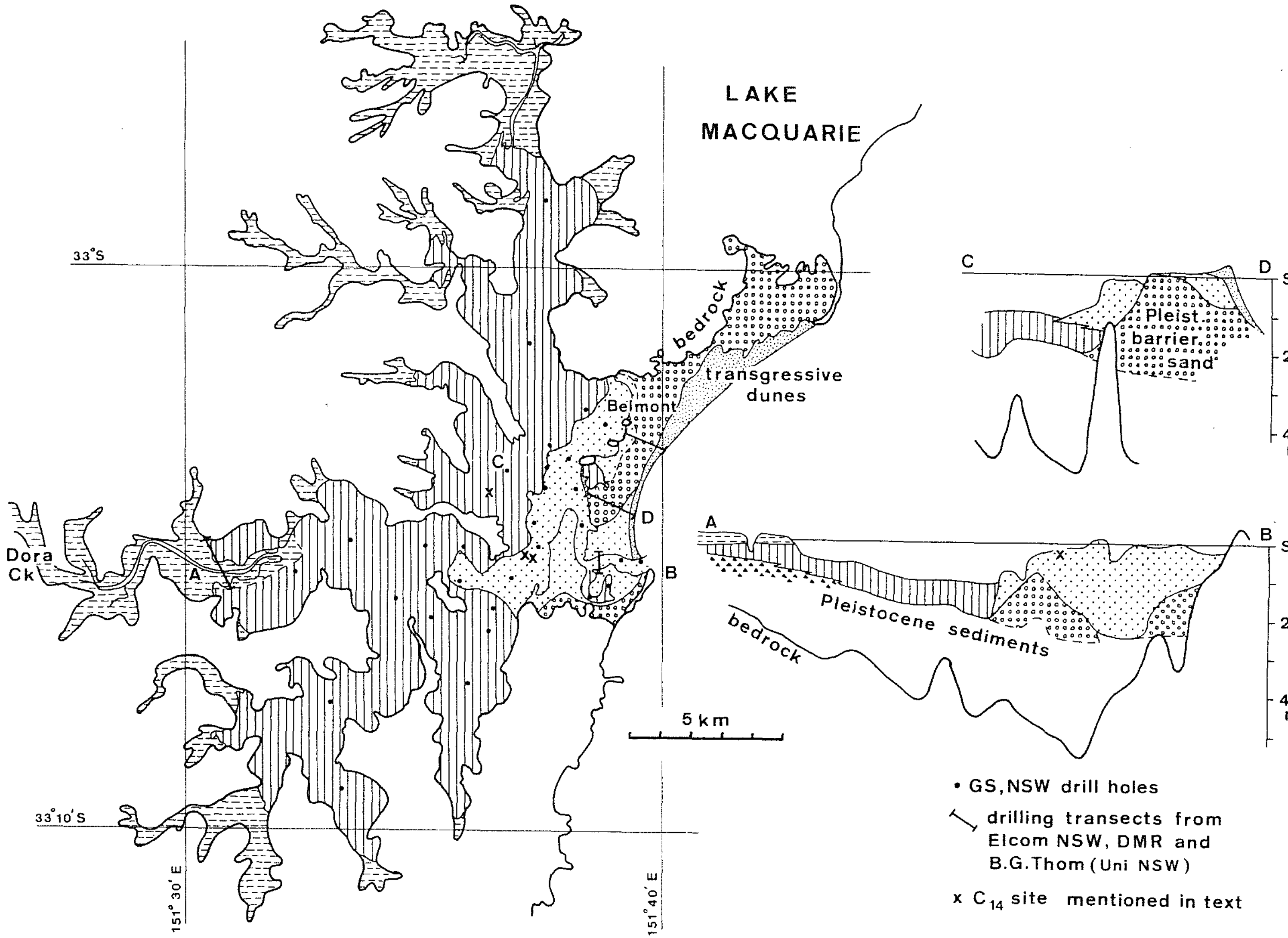

Figure 9. Lithofacies in Lake Macquarie. Stratigraphic sections A - B and C - D are based on a synthesis of most drilling data; their horizontal scale is only approximate. The mouth of the present entrance is near "B". Lithofacies symbols as shown in Figure 3.

sediments range from 10 to almost 30m thick in the valley axes and are thickest (c.27m) in the estuary mouth (Fig. 9, Section A-B). Over much of this latter region shelly marine sands directly overlie a sculptured Pleistocene surface. Here the absence of intervening muds suggest that at no time did Lake Macquarie estuary extend seawards of the present coast (c.f. the Shoalhaven stratigraphic record). Infilling of the prior valley with tidal channel and washover sands presumably occurred as sea level rose. A markedly different stratigraphic relationship was encountered in a small area (c. 5% of the estuary mouth region) around the inner end of the present tidal channel (Fig. 9 section C-D). Here clean marine sands overlie estuarine muds in excess of 5m thick and indicate a phase of quiet water sedimentation followed by tidal delta building into the estuary basin. The presence of shelly marine sand deposits in peripheral parts of the estuary mouth (e.g. near Belmont) is probably the result of insitu wave-reworking of the Pleistocene sand substrate.

Holocene muds in the estuary basin contain an abundant estuarine shell fauna (Roy, 1981). They rarely exceed thicknesses of 10m and overlie weathered Pleistocene sediments (oxidised clays and fluvial sands). Towards the present river deltas, muds grade into regressive fluvial channel sands and underlie delta levee deposits composed of muddy fine sand up to 3.5m thick (Electricity Commission of N.S.W. (Elcom), unpublished drilling data).

Age relationships of the Holocene deposits in Lake Macquarie are poorly documented in terms of radiocarbon dates and the time lines depicted in Figure 10 rely in part on Postglacial sea level changes proposed by Thom and Roy (1983). Most dates were obtained as part of a study of trace metal contamination in the upper part of the basin muds (Roy and Crawford, in press). Here, insitu estuarine shells (mainly <u>Notospisula</u>) range in age from 520 to 4700 years BP and indicate an average sedimentation rate of 0.26mm yr^{-1} (range 0.14-0.86mm yr^{-1}, 8 samples). A date of about 8000 years BP at -16 m near the base of the mud sequence (Fig. 10) indicates an overall sedimentation rate of 0.83mm yr^{-1} and suggests, when compared with the sea level curve, that the estuary was at least 5 m deep at this time.

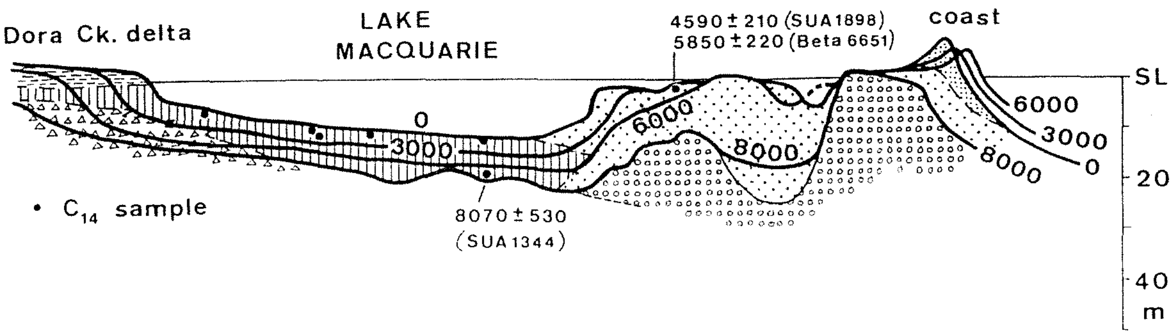

Figure 10. Inferred time lines superimposed on a diagrammatic east-west section in Lake Macquarie. Radiocarbon ages are calibrated according to Klein et al (1982).

The stratigraphic setting of the estuary mouth sand body is in accord with its emplacement during and shortly after the PMT. This is supported by calibrated ages ranging from 4500 to 5900 years BP on Anadara shells from 1-2m below the inner surface of the sand flat at the site shown in Figures 9 and 10. Localised tidal delta accretion around the present channel outlet into the lake post-dates the main phase of estuary mouth infilling (Fig. 9, Section C-D).

The proposed evolutionary sequence for Lake Macquarie, shown in Figure 11, is notable for the very slow rates of infilling over the last 8000 years. In Figure 11 A, a pattern of fluvial drainage channels incised into the Pleistocene substrate are shown to be inundated by this time. Slow infilling with estuarine muds occurred behind a plug of marine sand in the estuary mouth. A relict Pleistocene barrier, including remnants of what were probably ancient estuary mouth deposits, occurs on the seaward side of the estuary.

By the end of the PMT, 6000 years BP (Fig. 11 B), the valley was drowned and the bulk of the estuary mouth sands were in place. Parts of these deposits extend above present sea level and are presumably storm ridges formed during periods of high lake level; now they are covered by urban development. It is hypothesised that, initially, the entrance channel was located against the southern bedrock ridge and subsequently migrated northwards. At this stage, river deltas were located upstream of their present position and, because of the small river inputs, only a few metres of mud had accumulated on the estuary bed.

There is no absolute chronology to establish rates of stream delta progradation and it is likely that the alluvium shown in Figure 9 includes sediment of Pleistocene as well as Holocene age. Drilling in the Dora Creek delta about 3 km upstream of its mouth encountered Holocene muds in the shallow subsurface (Fig. 9, section A-B). This suggests that the delta has elongated by at least this amount in the last 6000 years. However, the fluvial deposits here are limited in areal extent and it is likely that fluvial-deltaic sedimentation has diminished the estuary water area by less than 10% in the late Holocene (compare Figs. 11 B and C).

The modern situation is shown in Figure 11 C. The early estuary mouth sand deposits are relict and their periphery is mantled by estuarine mud, the result of slow accretion in the estuary basin. Active estuary mouth sedimentation is restricted to the present entrance channel (mainly tidal reworking) and to recent tidal delta growth at its inner end.

Because of the size and depth of the estuary water body, Lake Macquarie has acted as an almost total trap for suspended sediment throughout the Holocene; minor bypassing is only effected during major floods. Thus the resulting 5-10 m thick layer of estuarine mud and an unknown, but presumably small, amount of delta progradation accounts for more than 7000 years of stream erosion of the lakes' catchments. This budget is further reduced by a significant amount (c.10-20%) of biogenic material - shell and organics - produced within the estuary. In terms of its maximum capacity, Lake Macquarie is less than half filled with sediment, a phenomenon largely attributable to the small size of the inflowing streams. It also reflects a surprisingly slow rate of supply of marine sand via the entrance channel over most of the stillstand period. This suggests that frequently in the past, the estuary mouth was partially blocked by sand bars, a situation that has recently been changed by the construction of training walls and breakwaters at the

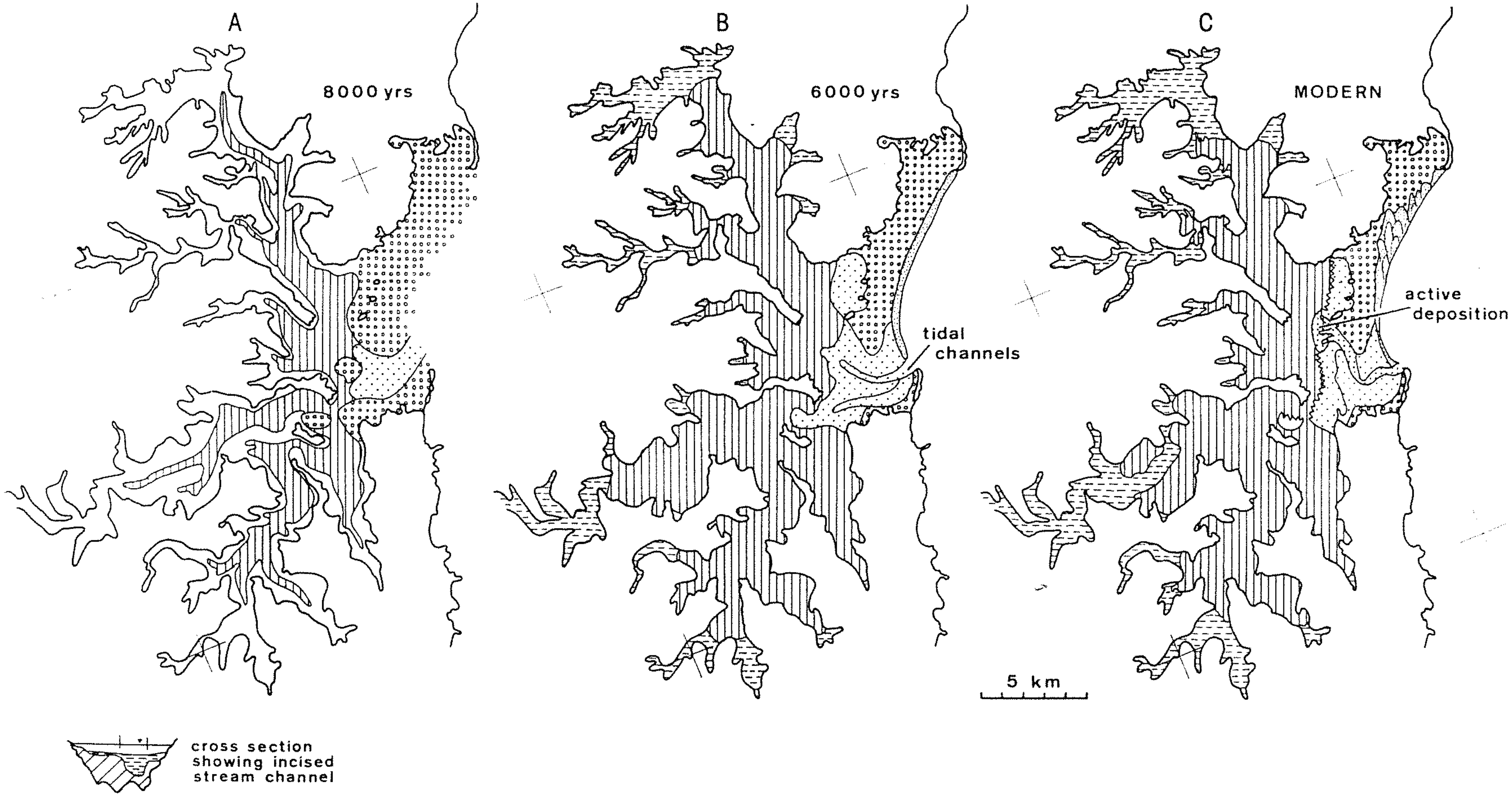

Figure 11. Reconstructed stages in the evolution of Lake Macquarie. The pattern of incised stream channels shown in Stage A is based on detailed seismic profiling.

channel mouth. These were constructed around the end of last century and appear to have had a marked impact on channel morphology not only at the mouth but also at its inner end (PWD, 1976). In the mouth region, increased wave penetration resulted in shoreline erosion, possibly leading to a gradual increase in tidal discharge. Historical records over the last 100 years show that the entrance channel has scoured and its terminus has migrated c. 1 km northwards (PWD, 1976). Drilling in this region encountered tidal delta sands, presumably deposited during this period of migration, overlying estuarine muds (Fig. 11 C). The time interval represented by the thick mud sequence underlying the sand unit (Fig.9, section C-D) is in accord with the latter feature forming quite recently.

Careful documentation of similar effects in the entrance to Wallis Lake shows that breakwaters constructed at the estuary mouth 11 years ago have caused a threefold increase in the tidal prism (Nielsen and Gordon, 1981). This has been accompanied by severe scouring of the channel bed, the movement of large quantities of sand (mainly seawards) and a corresponding increase in tidal range in the body of the estuary. Predictive modelling suggests that these trends will continue, possibly for as long as 50 years, before a stable regime is re-established at which time tidal ranges may be as much as 10 times their former amplitude.

(4) Shoalhaven Delta

An extensive flood plain, approximately 125 km^2 in area between Nowra and the coast, occupies what was once a large barrier estuary at the mouth of the Shoalhaven River (Fig. 12). The delta plain lies behind an extensive beachridge barrier at the present coast (Thom et al., 1981); it is intersected by the river mouth at Shoalhaven Heads and by the Crookhaven estuary at the southern end of Shoalhaven Bight (Wright, 1970). The river has a coarse sand bed and, downstream of Nowra, flows between levee banks; other levees border Broughton Creek and mark prior river courses in the flood plain (Fig. 12). At present, estuarine conditions exist only in the seaward part of the delta channels. Under low-flow conditions, the Shoalhaven River enters the sea at Crookhaven Heads via a man-made cut in the levee; the main river mouth is often blocked by beach deposits and is only breached by flood discharges (Wright, 1977).

Drilling in the barrier and delta region, reported by Thom and others (1981), shows that the flood plain is underlain by up to 27m of shelly organic-rich estuarine mud. Basal fluvial sands occur in the deeper parts of the paleo-valley. The mud sequence extends to near present sea level and in the eastern part of the embayment, it encloses a seaward thickening tongue of marine sand and muddy sand. A transgressive, backbarrier (washover and estuary mouth) origin is inferred for the sand body which grades into, and underlies, prograded barrier deposits at the present coast (Comerong Island) (Fig. 12).

Muddy, organic-rich overbank and backswamp deposits that form the subaerial flood plain are generally less than 2m thick increasing to c. 5m beneath levees. Fluvial channel sands intersect the estuarine muds. Where the river is confined between bedrock at the Nowra Road bridge they reach thicknesses of 15m (DMR, unpublished drilling data) but within the delta plain, channel sands are probably somewhat thinner.

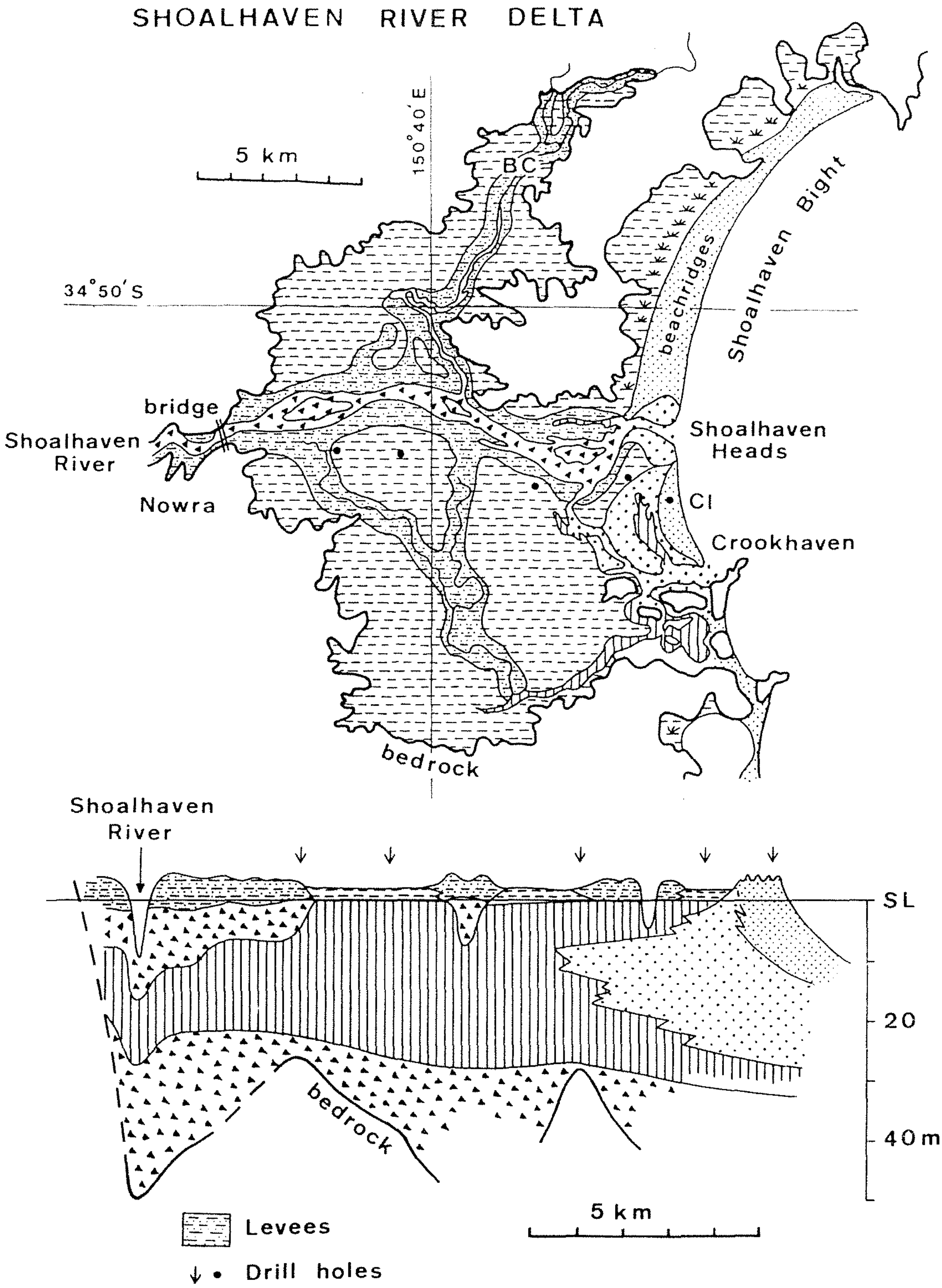

Figure 12. Lithofacies in the Shoalhaven delta region based on data reported in Thom et al. (1981) supplemented by drilling at the Shoalhaven River bridge. Lithofacies symbols as shown in Figure 3 (BC = Broughton Creek; CI = Comerong Island).

Radiocarbon dates on insitu shells (Notospisula) and transported charcoal fragments from 2 drill holes in the estuarine mud unit provide an indication of the sequence of depositional events (Thom et al., 1981) (Fig. 13). Calibrated ages, plotted against depth in this figure, show that low-energy, estuarine conditions were initiated about 10,000 years ago behind a landward retreating barrier complex. Associated washover and estuary mouth processes, active during the PMT, deposited backbarrier sand sheets in the valley mouth. A date of c. 9500 years BP on shell fragments from -11m in these sands is abnormally old and indicates reworking of old shell from further seawards. Drilling and dating in the main beachridge sequence shows that the shoreline stabilised and progradation commenced about 6500 years BP (Thom et al., 1981). This would have coincided with the transition from active washover deposition to placid mud basin conditions in the seaward part of the estuary. Accordingly, in Figure 13 the muds blanketing the estuary mouth sand sheet are shown to be less than 6,000 years old.

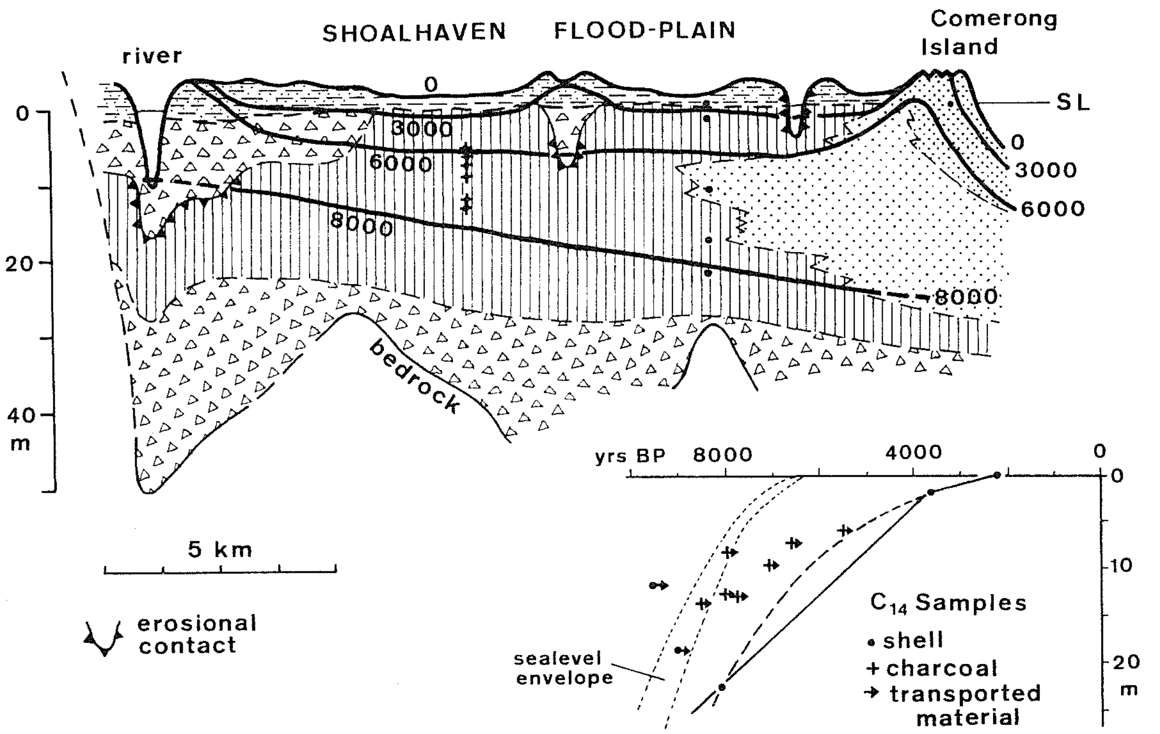

Figure 13. Time lines superimposed on an east-west stratigraphic section through the Shoalhaven delta based mainly on inferred mud accumulation rates indicated in the age/depth plot. Accurate determinations of sedimentation are precluded by the transported nature of much of the dated material.

Rapid mud deposition (c. 4-5mm yr^{-1}) is indicated until c.4000 years BP then more slowly to c.2000 years BP (Fig. 13).The precise times of deposition of the host sediment cannot be determined because of the incorporation of transported charcoal in many of the samples dated. It is probable that rates of infilling were fast initially but decreased as the mud basin expanded to its maximum dimension at the end of the PMT. By this time muds had infilled the estuary to within 8m of present sea level. In the next 3000-4000 years they built up to near present sea level and over the last 2000-3000 years they have been superceded almost everywhere by terrestrial overbank deposits. The Crookhaven is a remnant of the former estuary that escapes rapid infilling by the recent tendency of the river under flood to bypass it and discharge its sediment load directly to the sea at Shoalhaven Heads.

Subsurface data are not sufficiently widespread to accurately delineate the planimetric changes of the Shoalhaven estuary during its Holocene evolution; the infilling patterns shown in Figure 14 are thus largely speculative. Figure 14 A depicts an early stage of drowning of the palaeo-Shoalhaven valley system 9000 years ago when sea level was 15-20m below its present position and estuarine muds were accumulating behind a barrier located seawards of the present coast. Storm breaching and overwash deposition were common features of the retreating coast, especially in the Shoalhaven valley mouth. Initially, muds accumulated rapidly in the estuary basin while upstream of Nowra, fluvial channel sands and gravels deposited in the drowned valley gorge.

By 6000 years BP (Fig.14 B) the sea had risen to its present level and the estuary had attained the approximate dimensions of the present delta (c.140 km^2). Washover and estuary mouth sands had spread to their maximum extent by the end of the PMT and formed wide sub-tidal sand flats in the valley mouth. This form of deposition virtually ceased once the coastal barrier stabilised. Barrier growth constricted the estuary mouth which was presumably located at Crookhaven Heads where wave action in Shoalhaven Bight is lowest (Wright, 1970). According to the radiocarbon dates, the estuary at this time was less than 10 m deep and was principally a placid environment in which shelly muds accumulated. Fluvial deltas at the mouths of the Shoalhaven River and Broughton Creek were beginning to build into the estuary at this stage but, because of the water depth, their extent was probably not large. Around the estuary sides a discontinuous fringe of muddy shoreline deposits - the precursors of the present flood plain - were probably beginning to form between rocky promontories. Because of restricted entrance conditions, tidal ranges in the large estuary basin were presumably small (Roy, 1982 and in press) and it is likely that mangroves were restricted to the estuary mouth region. For the Shoalhaven estuary, the first 3000 years of the stillstand period was a time of slow environmental change despite relatively rapid build-up of mud on the estuary bed. In contrast, the last 3000 years has seen dramatic changes culminating in the widespread conversion of estuarine environments to terrestrial flood plains and freshwater swamps.

Figure 14 C shows conditions 3000 years ago at which time the estuary basin had shoaled (to c. 2m) and muds had blanketed most of the backbarrier sand flats. From about 4000 to 2000 years BP the estuary water body shrunk rapidly as levees and flood plains expanded to form restricted sub-embayments with diverse shallow-water habitats. Wind-wave stirring of the shallow estuary bed undoubtedly produced turbid water conditions and resuspension of sediment in this way is thought to play an important role in the accretion of sedimentary shorelines (Roy, 1982 and in press). It is hypothesised that, in barrier estuaries, a reduction in water area is accompanied by an increase in tidal range which promotes the spread of mangrove and salt marsh vegatation in the estuary. To some extent this tendency in the Shoalhaven would have been countered by periodically reduced salinities due to large floods - an impact that became more pronounced as the water body decreased in volume.

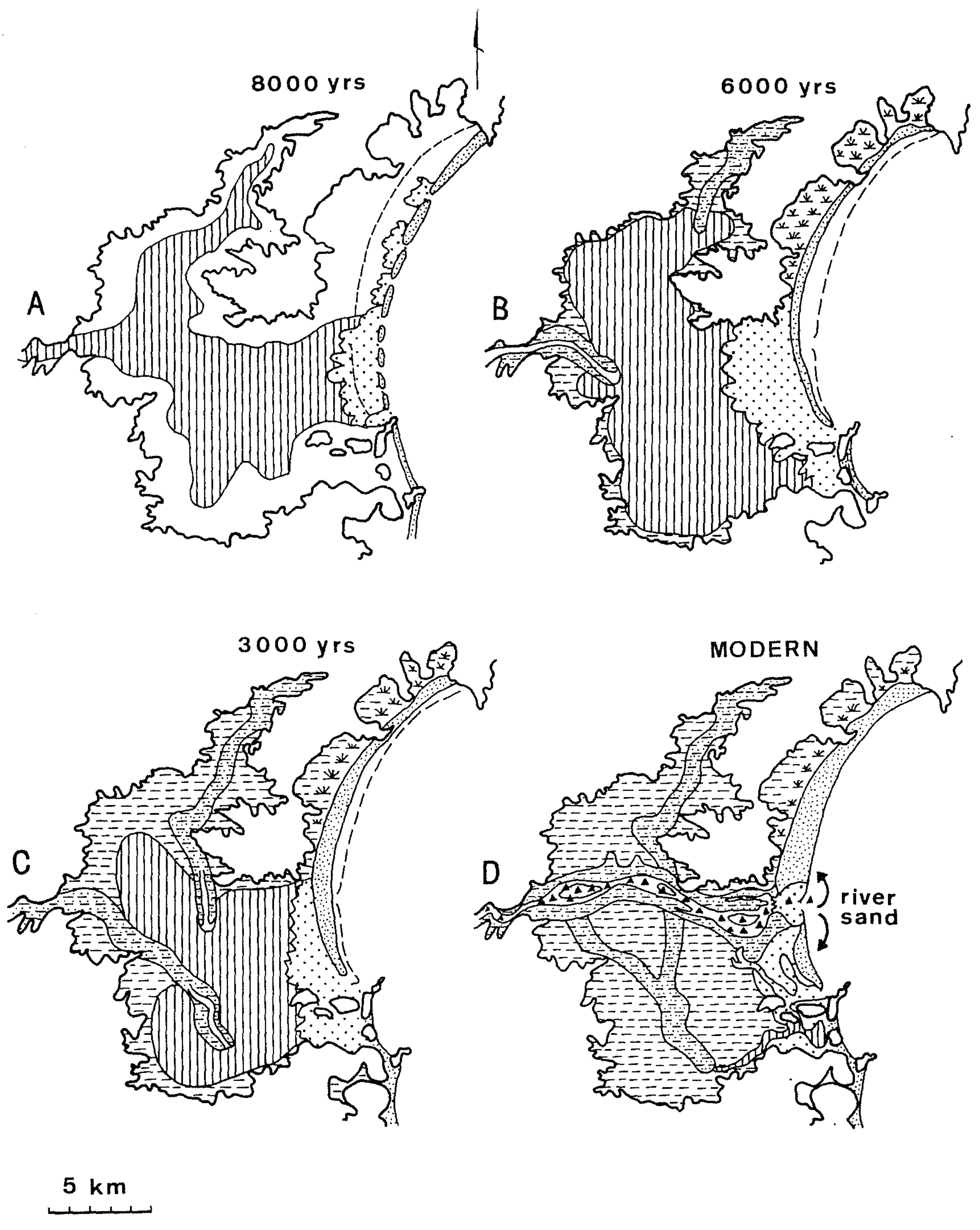

Figure 14. Reconstructed stages in the evolution of the Shoalhaven delta.

Precise rates of change during the final stages of infilling are difficult to document. Although vertical accretion was slow, horizontal displacement of the estuary shoreline was extremely rapid. The present reconstruction suggests that flood plains expanded at an average rate of about 20,000 m^2 yr^{-1} during the last 3000-4000 years. Fullerton Cove, a cut-off embayment in the Hunter River delta, provides an analogous situation. Here a 1 km wide mangrove fringe has encroached into the estuary at between 4 and 8 m yr^{-1} over the last 40 years (Roy, 1980). With the spread of flood plains, river flow increasingly became channelised between levee banks and converged on the Crookhaven entrance. Eventually floods in the main channel breached the earlier levees and cut a more direct course to the sea at Shoalhaven Heads.

Figure 14 D shows the modern situation. Except for a remnant of the former estuary at Crookhaven, infilling is complete and the Shoalhaven estuary is confined to a sinuous river channel. During floods its bed is reworked, mid-channel shoals erode and reform, sand banks at the river mouth scour and sediment is discharged to the sea. Sedimentological studies of the coastal sand deposits show that the seaward most beach ridges contain significant amounts of river sand. However, the supply of modern fluvial sand to the coast is a discontinuous process not only because of the erratic nature of flood events, but also due to a sediment exchange cycle involving river mouth scour and offshore sand transport followed by coastal erosion as beach sand migrates alongshore into the river mouth. Studies at Tathra (Gordon et al., 1980) suggest that a decade or more may elapse before river sand, flushed out of the river during a major flood, migrates back onshore to contribute to beach accretion.

Discussion

Differing modes and rates of estuary evolution documented above indicate that two factors are of prime importance; river sediment supply and estuary mouth conditions. The latter is intrinsically related to estuary type but the former is not. During youthful stages of evolution the factors operate largely independently but as estuaries infill they increasingly interact. The role of rivers in estuarine sedimentation is preserved in the geological record of fluvial-deltaic and mud basin lithofacies; that of the estuary mouth is interpreted from the associated marine sand deposits.

The Role of Rivers in Estuary Sedimentation

Comparison between estuaries of different type but with similar river sediment inputs reveal that accumulation trends in river delta and mud basin environments differ in degree and change radically as the estuaries evolve along different pathways. Absolute rates of sedimentation in delta sand bodies are not available for most estuaries but their development generally parallels that of basin (prodelta) muds for which more long-term data is available.

The Hawkesbury and Shoalhaven epitomise estuaries with large fluvial sediment supplies. The very high rates at which estuarine muds accumulated in the Hawkesbury River during the PMT (c. 10-15mm yr^{-1}) reflect its large catchment and high sediment discharge. The duration of mud sedimentation in the lower estuary was, however, quite brief (between c. 10,000 and 7,000 years BP) and when, towards the end of the

PMT, basin environments were superceded by sandy channel sedimentation, mud in increasing amounts was expelled from the estuary. The loss of a substantial fraction of the river sediment load reduced deposition on the channel bed to 1-2mm yr^{-1} and presumably also retarded the spread of subaerial and intertidal deposits along the channel sides. During the latter part of the stillstand, estuarine environments in the Hawkesbury appear to have changed little, although tidal energy levels are high and sediment through-put is large.

Compared with the Hawkesbury River, mud accumulated less rapidly in the Shoalhaven estuary (c. 4-5mm yr^{-1}) due to its smaller river catchment and its larger settling basin, but it occurred over twice as long a period (from c. 9,000 to 3,000 years BP). Except for gradual shoaling of the estuary bed, environmental conditions during this interval changed little compared with the dramatic events that followed in the last 3,000 years of the Holocene. These centred on the spread of a terrestrial delta-plain over the shallow estuary bed and culminated in the Shoalhaven River becoming channelised and cutting a new course through the flood plain to the sea. Large, rapid-filling barrier estuaries such as the Shoalhaven show the most dramatic environmental change of any coastal landscape in NSW. The Hawkesbury and the Shoalhaven have now reached mature states of development and both rivers discharge sediment to the sea. However, in drowned river valley estuaries such as the Hawkesbury, by-passing apparently involves winnowing of fine sand and mud which are transported offshore; there is no evidence that river sand has been added to beaches in Broken Bay. In contrast, mature barrier estuaries such as the Shoalhaven discharge a wide range of grain sizes at the coast including a substantial amount of relatively coarse sand that eventually finds it way onto the adjacent beaches.

Port Hacking and Lake Macquarie lie at the other end of the spectrum in terms of river sediment supply. Their fluvial deltas show contrasting growth modes which, in some respects, reflect differences in estuary type. The delta at the mouth of the Hacking River is a lobate, subaqueous feature composed of relatively coarse, muddy sands 8-10m thick, while Dora Creek in Lake Macquarie has built narrow, subaerial levee jetties composed of fine sand and mud only 3m thick. Subaerial levees are also a feature of the Shoalhaven delta and indicate periodically elevated water levels. This occurs in barrier estuaries when flood waters are impounded behind barriers with narrow outlets to the sea. In contrast, the open mouths of drowned river valley estuaries allow flood waters to escape without significantly raising water levels in the estuary. This, together with tidal reworking of their surfaces and the greater basin depths, are responsible for the morphology, thickness and subaqueous nature of the Hacking River delta and also accounts for the predominance of subaqueous channel environments in the Hawkesbury River.

Rates of mud accumulation in both Lake Macquarie and Port Hacking are slow: about 0.1-1.0mm yr^{-1} in the former and 1-3mm yr^{-1} in the latter. The difference is mainly due to estuary basin size, with Lake Macquarie being 10 times larger than Port Hacking. It is reasonable to expect that most present-day estuaries have rates that lie within this range since faster sedimentation over the stillstand period would have infilled them by now. Unfortunately this study was unable to directly address the question of whether contemporary sedimentation rates in estuaries have significantly increased since river catchments were developed by European man. Potentially, the record is most complete in the estuarine mud sequences but these are extensively bioturbated and geological techniques are unable to provide sufficiently fine scale resolution. Comparative studies of shoreline changes using old survey data usually cover too short a time span or lack sufficient detail for the pre-historical period.

The Role of Estuary Mouths on Sedimentation

Net sediment movements in NSW estuary mouths are in a landward direction during youthful stages of development and are dominated by marine processes, but at mature stages they are directed seawards mainly under the influence of river floods. This reversal in sediment flux marks a critical stage in estuary evolution; in the Hawkesbury it apparently coincided with the end of the PMT, but in the Shoalhaven it probably took place within the last few millennia.

Prior to this critical stage being reached, estuary mouth sand bodies developed characteristic stratigraphies and age structures in estuaries of different type. The open mouths of drowned river valley estuaries promote upstream flood-tide delta growth during both rising and stable sea level conditions. In the Hawkesbury River mouth and Broken Bay, approximately $200 \times 10^6 m^3$ of marine sand had accumulated by about 7,000 years BP, at which time the tidal delta was overwhelmed by riverine sediment. Rapid growth at the delta front of between 2 and $4m\ yr^{-1}$ was due to the general onshore movement of sand accompanying the PMT and the existence of a large sand source on the inner shelf offshore from Broken Bay. In Port Hacking where slow rates of fluvial sediment input have left basin environments unfilled, about half of the $160 \times 10^6 m^3$ of tidal delta sand was emplaced during the stillstand (Fig. 4). Estimates of average rates of delta-front accretions of $16{,}000 m^3 yr^{-1}$ (c. 1.0m horizontal growth yr^{-1}) based on radiocarbon dating, may be conservative, as present-day measurements suggest somewhat faster accretion. Certainly in this estuary, there is no evidence that rates have diminished in the late Holocene. In Port Hacking the question of primary source of the delta tidal sand is complicated by the probable development of a proto-barrier in Bate Bay towards the end of the PMT. At present, erosion of the seaward face of the tidal delta is providing much of the sand for its continuing upstream growth.

Unlike drowned river valley estuaries, marine sand deposition in the mouths of barrier estuaries was principally during the latter stages of the PMT and occurred in close association with the transgressive phase of barrier building on this coast (Thom, 1983). Since then, tidal channels have migrated laterally and elongated to some extent (e.g. Lake Macquarie) but, unlike estuaries in southwestern Australia (Hodgkin and Kendrick, 1983, this volume) there is little geological evidence to suggest that tidal flushing or salinity regimes have changed substantially over the stillstand period. Stratigraphic and radiocarbon age data, not only from Lake Macquarie and the Shoalhaven delta but also from Narrabeen Lagoon, a small barrier estuary on the outskirts of Sydney (Roy, 1982), suggest that estuary mouth sand bodies were in place 5,000-6,000 years ago. Post-stillstand deposition of marine sands in these estuaries was very limited and, in the case of Lake Macquarie, is possibly related to recent engineering works at its mouth. Certainly this is the case in Wallis Lake but here, and also in Tuggerah Lake, an intermediate-sized barrier estuary to the north of Sydney, radiocarbon dates ranging from 3600 to 160 years BP on insitu shells from tidal channels and marginal shoals show that some marine sand has continued to migrate into these estuaries under stillstand conditions. The extent of this phenomena remains to be documented by stratigraphic studies as well as by hydrodynamic measurements to assess estuary mouth efficiency in a range of estuaries with different morphologies and coastal settings.

As barrier estuaries infill with sediment and mud basin environments expand seawards over the estuary mouth sand deposits (e.g. Shoalhaven), river flow becomes channelised. In mature estuaries their mouths are increasingly prone to flood scouring and sediment movements in them increase in magnitude and frequency (e.g. Shoalhaven-Wright, 1977; Bega River - Gordon et al., 1980). The development of subaqueous, crescentic river mouth bars up to 1 km seawards of the larger river mouths (Floyd and Druery, 1976; Druery and Nielsen, 1980) shows that the locus of sedimentation in mature barrier estuary mouths extends well seawards of the coast. How far sand is transported seawards during major floods is open to speculation (Roy and Stevens 1981). After a scouring event, sand from the open coast moves back into the river mouth for a limited distance upstream. Roy and Crawford (1977), found that modern marine sands occur in the seaward-most 1-3 km of large rivers in central and northern NSW; this defines the landward limit of sand exchange in mature estuaries. Dredging of 800,000m^3 of sand that was carried out in the Tweed River within this zone initiated a massive influx of sand from the updrift beaches (Druery, 1980) and demonstrates the dynamic balance that exists between coast and estuary mouth.

Some Effects of Short-Term Fluctuations on Estuaries

The estuaries described in this study represent extremes of the evolutionary spectrum - very fast and very slow filling - and, with the exception of Port Hacking, are amongst the largest Holocene estuaries in NSW. Compared with these, most estuaries are intermediate in terms of infilling rates and size and some show responses to weather fluctuations not experienced by large estuaries with better flushing characteristics. For example, many of the smaller barrier estuaries, and all saline coastal lakes, have inlets that close during periods of low river flow. At these times, open ocean processes build sand deposits above sea level in the estuary mouth (PWD, 1983) and trigger a sequence of environmental fluctuations that may cause quite severe stress in the estuary. Under drought conditons, evaporation lowers estuary water levels (which are normally elevated slightly about mean sea level) to expose marginal sand banks and sea grasses which die or are predated. Water temperatures and salinities may rise, nutrients increase locally and algal blooms may initiate eutrophication in shallow basins. With the onset of rains, lake levels rise and cause local flooding before they overtop the estuary mouth shoals. Once these are breached the entrance channel scours and, for a time, becomes more efficient in terms of tidal exchange. While these conditions last, tides in the body of the estuary increase but mean water levels fall, again exposing seagrass-covered shallows. Gradually the estuary mouth begins to shoal, tidal flows diminish and lake waters rise to their former levels. It may take many years for seagrasses to recolonise the marginal banks but eventually the estuary returns to its former state. Although in their extreme form, these changes occur infrequently in NSW, they damage estuarine ecosystems and give rise to numerous complaints from residents objecting to the noxious odours of rotting vegetation, etc. In areas with a pronounced seasonal rainfall pattern (Hesp, 1983, this volume) this cycle becomes an annual event and its effects are often greatly exaggerated (e.g. Peel - Harvey Estuary, Hodgkin et al., 1978).

Conclusions

Microtidal estuaries on the high energy coast of southeastern Australia attained their primary character at the end of the PMT when deposits of marine sand accumulated in the mouths of coastal valleys and established characteristic tidal regimes. Subsequent infilling during the stillstand has been with sediments supplied by rivers and exchanged between the estuary and the coast via the estuary mouth.

Average mud sedimentation rates in existing estuaries range from 0.1 to 3.0mm yr^{-1}. Faster rates in the past ($>$4mm yr^{-1}) characterise estuaries at the mouths of large rivers but, in these cases, low energy mud basin environments have now either completely infilled and are covered by flood plains (e.g. Shoalhaven delta) or been superceded by higher energy channel sedimentation (e.g. Hawkesbury River). In the latter estuary, leakage of fines seawards through the open estuary mouth has greatly retarded subsequent sedimentation thus preserving its present status despite large sediment through-puts.

All estuaries trapped large quantities of marine sand during the PMT but only slow-filling drowned river valley estuaries, such as Port Hacking, continued to do so after sea level stabilised. In estuaries associated with bay barriers (barrier estuaries), narrow entrance channels which attenuate tidal flows and impede the landward movement of marine sand, were established essentially in their present position shortly after sea level stabilised. Except in a few cases, these estuaries do not appear to act as major sinks for marine sand during the stillstand. This contrasts with the situation on receding barrier island coasts where tidal delta sand bodies migrate laterally as estuary mouths change position, and may make up the dominant lithofacies in the subsurface (Reinson, 1983)

As well as net accumulation trends, NSW estuaries experience a range of natural fluctuations due to changing weather conditions. This comparative study suggests that their impacts vary substantially between different estuary types.

In drowned river valley estuaries, the tendency for infilling to be retarded during mature stages of development preserves a large estuarine water body with moderately high ambient energy levels. These buffer the full impact of floods and storms which appear to have relatively small long-term effects on the estuary regime. Even major man-made changes, such as the construction of dams and the extraction of aggregate from the channel bed, seem more likely to retard the already slow rate of infilling and preserve the present estuary status rather than to cause major physical impacts. (This conclusion ignores deterioration of estuary water quality due to reduced fresh water discharges, especially if accompanied by increased nutrient inputs - A. Jones, Aust. Museum, pers. comm.). This is not the case in barrier estuaries where changes in the estuary mouth region due to natural events (floodscouring or shoaling) or entrance works (breakwaters, dredging, etc) may have widespread and long-lasting impacts on the estuary and its biota. These include changes to the tidal range, mean water level, salinity and water quality in the body of the estuary and increased current velocities and sediment movement (deposition and erosion) in its entrance channel. Even the adjacent coast may suffer long-term erosion as severely scoured river mouths infill with sand from updrift beaches.

Barrier estuaries are thus potentially more sensitive to human interference than drowned river valley estuaries, although remedial measures to counter past deleterious changes may also be more feasible in the former. Clearly European man has impacted on some NSW estuaries by adding contaminants, increasing nutrient levels and by engineering works. While the resulting physical changes in some cases have unexpected ramifications, they generally lie within the spectrum of natural events experienced in the course of estuarine evolution. This does not apply to chemical changes relating to pollutants or high nutrient inputs for which there is no known geological counterpart on this coast.

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ASPECTS OF THE GEOMORPHOLOGY OF SOUTH WESTERN AUSTRALIAN ESTUARIES

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ABSTRACT

The estuaries of southwestern Australia vary greatly in character, ranging from large barrier types which are permanently open through small barrier types, normally to 'permanently' closed, to narrow fluvial dominated channels which are seasonally closed. This paper presents firstly, a brief review of the environmental conditions which appear to determine the morphology of the estuaries, secondly, a morphological classification of these estuaries, and thirdly, a summary of the general characteristics of each estuary type.

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Introduction

This paper presents a broad geographical and geomorphological description of Western Australian estuaries lying between Kalbarri and Esperance (Fig. 1). Environmental conditions of the region are as follows.

Prevailing weather conditions are largely determined by a belt of anticyclonic, high pressure systems which exhibit seasonal displacement, alternating between latitudes 35^{o} to 45^{o}S in summer, and 26^{o} to 34^{o} in winter (Gentilli, 1971). This system is periodically disrupted by tropical and mid-latitude cyclonic depressions, and is locally modified by sea-breeze activity. In summer the prevailing winds are easterlies and northeasterlies. Near the coast these are countered by very strong sea breezes which normally reach velocities of 25 km/hr at least, and have a frequency occurrence of 20 days per summer month (Hounam, 1945). Seabreezes vary between alongshore southerlies in the northern portion of the region, to obliquely onshore southwesterlies in the central portion, to southeasterlies in the southern region. In winter prevailing winds are north easterlies and NW to westerlies along the west coast, and NW to westerly along the south coast.

The region is characterised by winter rainfall and dry summers with marked north to south, and west to east gradients in temperature and rainfall (Fig. 1). Rainfall is highly seasonal (see e.g. fig. 2.2 in Hodgkin, 1978). The evaporation rate is also highly seasonal and may exceed rainfall in parts of the river catchments. Summer thunderstorms may be significant in providing non-seasonal riverine influx.

Prevailing ocean swell arrives from the southwest. A highly variable wind wave regime is superimposed upon this. The latter is dominated by NW storm waves and S to SW (west coast) and S to SE (south coast) seabreeze generated waves. Wave energy is variable; in general the west coast experiences lower wave energy compared to the south coast (Davies, 1980, fig. 25). The actual wave energy received at the shoreline varies significantly and locally according to the presence or absence of offshore reefs, andshoreline orientation. Alongshore littoral currents may be strong and exhibit both seasonal and local (short term storm generated) reversals in trend (Hydrographer of the Navy, 1972, 1973). Tides are mirco-tidal, being mixed on the west coast, and diurnal on the south coast (Hodgkin and Di Lollo, 1957; Davies, 1980). Spring tides range from 0.8 to 0.9 m (Aust. Nat. Tide Tables, 1980).

Geologically and physiographically the near-coastal region may be subdivided into five broad regions. The west coast province extends from Kalbarri to Pt. d'Entrecasteaux, excluding the Naturaliste ridge region. This west coast province is dominated by a coastal plain, widening northwards, and comprising Cainozoic sands and limestones (Playford et al., 1976). The Naturaliste region extends from Cape Naturaliste to Cape Leeuwin. This region comprises a restricted Pleistocene limestone dune complex overlying Precambrian granulites and granite gneisses (Playford et al., 1976).

The south coast may be subdivided into three broad provinces (Hassell, 1962; Treloar, 1979). The Nornalup province extends from Pt. d'Entrecasteaux to Wilson Inlet and comprises a relatively narrow coastal plain. The basement geology consists of Precambrian plutonic and volcanic intrusions, and metamorphics, overlain by dissected remnants of Eocene sandstones, clays limestones and lignites (Hassell, 1962). The Barren Province extends from the eastern edge of Wilson Inlet to east Mt Barren. This province consists of three main types of parent material, namely, gneisses cut by dolerites, the siliceous Eocene beds, and of lesser importance, the quartzites and phyllites of the Mt Barren rocks (Hassell, 1962; Johnstone et al., 1973). The Esperance Province extends east of East Mt Barren (Treloar, 1979). The province consists of a wide coastal plain which broadens eastwards. Basement rocks consist of Precambrian gneisses, granites and metasediments, overlain by Tertiary sediments (Johnstone et al., 1973). A summary of the soils, vegetation and climate of these provinces may be found in Collins (1982).

Classification of W.A. Estuaries

In order to discuss the apparent geomorphological patterns in W.A. estuaries it is necessary to classify them. Observations indicate that drainage basin size, regional and local variations in rainfall receipt, and geological inheritance factors play a significant role in determining the morphology and evolutionary pattern of W.A. estuaries. I have thus arrived at the following working draft classification: Two major types are arbitrarily distinguished, Type 1, riverine estuaries, and Type 2, barrier estuaries.

Whilst estuaries are in general initiated due to the drowning of river valleysby a transgressing sea, I am here distinguishing between those estuaries which essentially retain their pre-Holocene Transgression, riverine or fluvial-channel dominated shape, and those in which more broad-scale flooding takes place forming estuarine basins behind dune barriers.

Two sub-types are distinguished within each type. Type 1a are relatively deep estuaries characterised by full tidal exchange ("drowned river valleys"; Roy, 1982) and Type 1b are shallow river valleys with limited tidal exchange. Type 2a comprises estuaries predominantly formed by flooding of inter-barrier depressions, and Type 2b those formed by flooding of river valleys/former estuarine basins. The general characteristics of each of these types are discussed below.

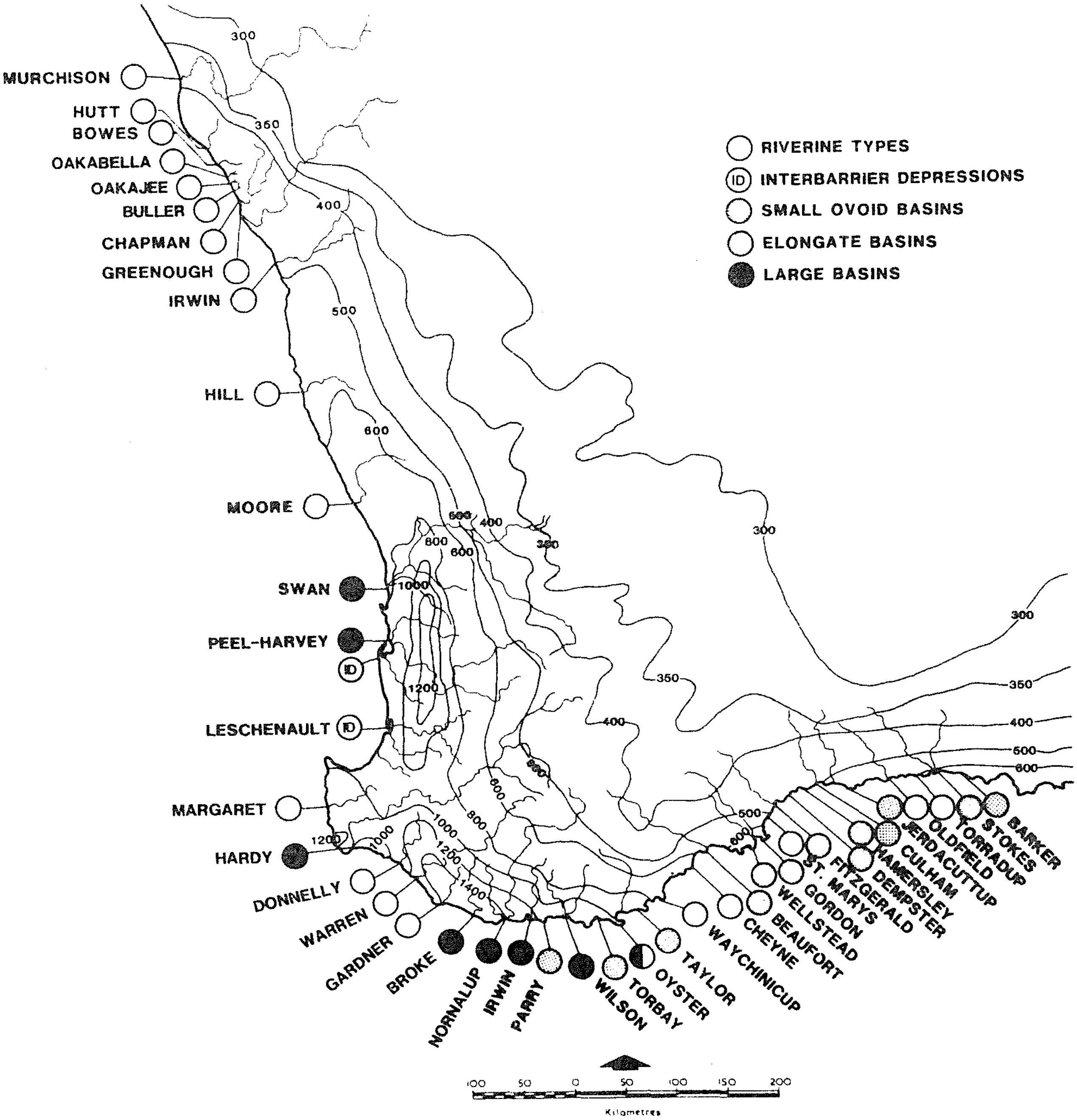

Figure 1:

Classification of Southwest Australian estuaries, and mean annual rainfall.

Type 1 Riverine Estuaries

Type 1 estuaries in W.A. appear to predominantly owe their shape to one or more of the following factors: either (a) geologic (boundary) control by either (i) parent rock or (ii) Quaternary dune complexes and/or (b) limited valley development due to either (i) being situated within a low mean rainfall zone or (ii) having a limited catchment size (see Table 1).

A significant proportion of the riverine-type estuaries occur north of the Swan (fig. 1). Figure 1 also illustrates that mean annual rainfall receipt decreases northwards of Perth. In addition, a large easterly trend in declining rainfall receipt exists such that the larger portion of many of the catchments traverse semi-arid regions. For example, 85% of the Murchison River catchment (estuarine for 12-20 km) is classified as semi-arid (P.W.D., 1977). An unknown proportion of rainfall/ drainage may also be lost to groundwater sinks within the extensive near-coastal limestone sequences. Of the estuaries whose drainage basins are confined largely to the higher rainfall strip (e.g. Oakabella, Oakajee, Buller), many have small catchment areas and average discharge is low. The above conditions appear to determine the gross morphology and behaviour of the northern riverine estuaries.

The northern estuaries are dominated by inherited Pleistocene alluvial and aeolian sediments (fig. 2). The coastal topography in the vicinity of the rivermouths largely consists of Pleistocene, cemented, aeolian and marine limestones, occurring as subacqueous, nearshore reefs and subaerial dune barriers. Cementation of sediment has occurred to such an extent that in rare instances Pleistocene river mouth bars/flood tide deltas have been cemented in place (e.g. the Murchison). Holocene nearshore, beach and dune sands partially overlie the Pleistocene units, but are, in general, limited in extent and volume.

Pleistocene alluvial sediments formed in aggradational phases during the Pleistocene (Wyrwoll, 1983) fill the valleys to various extents, producing a distinctive box-shaped valley form (e.g. Oakabella, Oakajee). The alluvium dominates the smaller valleys draining the Northampton block, forming an extensive valley fill/terrace unit which extends to the river mouths. The Pleistocene alluvium also occurs as lateral elongate deposits adjacent to the rivermouths. In the larger rivers (e.g. Greenough) the alluvium forms extensive plains filling interbarrier depressions/river valleys (e.g. the Greenough flats).

The smaller 'northern' estuaries (e.g. the Oakabella, Oakajee, Buller, Urwin and Hill) are characterised by very small (10 - 100's m) estuarine areas near their mouths. Average depths range from 0.5 m or less, to 2 - 3 m adjacent to the lee slope of the bar or berm. Sediments are predominatly fine to medium sands, and are polymodal, comprising reworked Pleistocene and Holocene alluvial, reef, dune and beach sands. In the immediate mouth or entrance region, berm/bar overwash sands and alluvial channel fill sands are inter-mixed. Landward of this region, the dominant

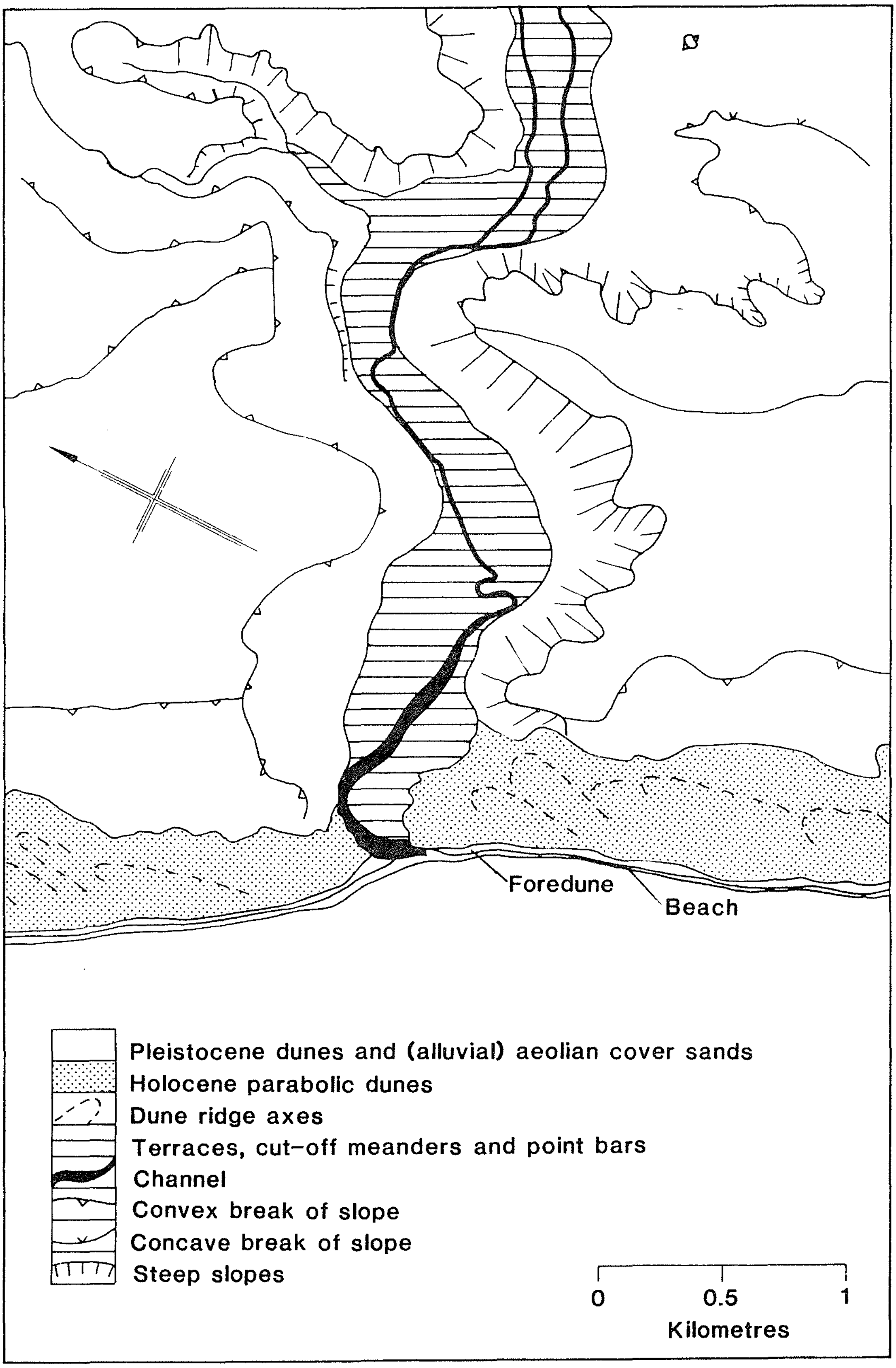

Figure 2:

Morphology of the Bowes River, a type lb riverine estuary, dominated by alluvial point bars and terraces, and surrounded by a high Pleistocene dune ridge. Drawn from aerial photo W.A. 1756(c), No. 5126.

process is deposition of modern sandy alluvium in point bar, levee and terrace formations. The Holocene sediments in general, are finer, particularly in the bed load fraction than the Pleistocene sediments.

The larger 'northern' estuaries (e.g. Moore, Greenough, Hutt and Murchison) are more characteristically estuarine. They are infilled to various degrees. The Murchison for example, is characterised by shallow pool and elongate bar sequences. Some of the latter occur as thin veneers over cemented Pleistocene bars. The deepest portions generally occur immediately behind the flood tide delta's/estuary mouth bars as narrow, restricted mud basins. In general, levee banks, overbank deposits and point bars characterise the adjacent shorelines of the estuaries. Rare, sand/silt source-bordering dunes may occur on the larger points bars (e.g. Murchison).

The estuaries north of the Swan are seasonally closed types. That is they open about once a year (Hodgkin and Lenanton, 1981). All are characterised by a 'flashy' discharge regime, where channel processes vary between low frequency, intense flood events and high frequency ephemeral flow with occasional complete dessication. For example, a high discharge event recorded in the Buller River on the 14/3/79 from rainfall (75 mm in 5 hrs), associated with the passing of a tropical cyclone, had an instantaneous discharge of 28.56 m^3/sec. The Institute of Engineers (1977) estimate an event of this magnitude has a recurrence interval of 20 years.

Riverine Estuaries South of the Swan

The riverine estuaries which occur south of the Swan estuary are scattered across the southwest (fig. 1). They appear to owe their shape to either small catchment area (e.g. Gardner, Torradup), bedrock control (e.g. Margaret River), or Quaternary dune control (e.g. Warren and Donnelly; fig. 3).

All these riverine estuaries are narrow (range = 25-500 m wide maximum), and the extent of estuarine water body is generally limited. They are classified by Hodgkin and Lenanton (1981) as varying between seasonally closed (open one or more times per year) to normally closed (open only after heavy rains). Essentially bar opening occurs after winter rains in the higher rainfall areas (e.g. Margaret River, Warren, Donnelly), and after excessive (sometimes non-seasonal) rain in the lower rainfall areas (see e.g. Collins and Barrett, 1980).

The estuaries are long and sinuous. Some have small, elongate mud basins, but many are dominated by shallow, sandy channels. Fluvial deltas are often difficult to distinguish as they tend to extend in a linear fashion into the estuaries. Marginal shoreline development is chiefly restricted to prograding lateral bars and beaches. Flood tide deltas are limited and ebb tide deltas are absent.

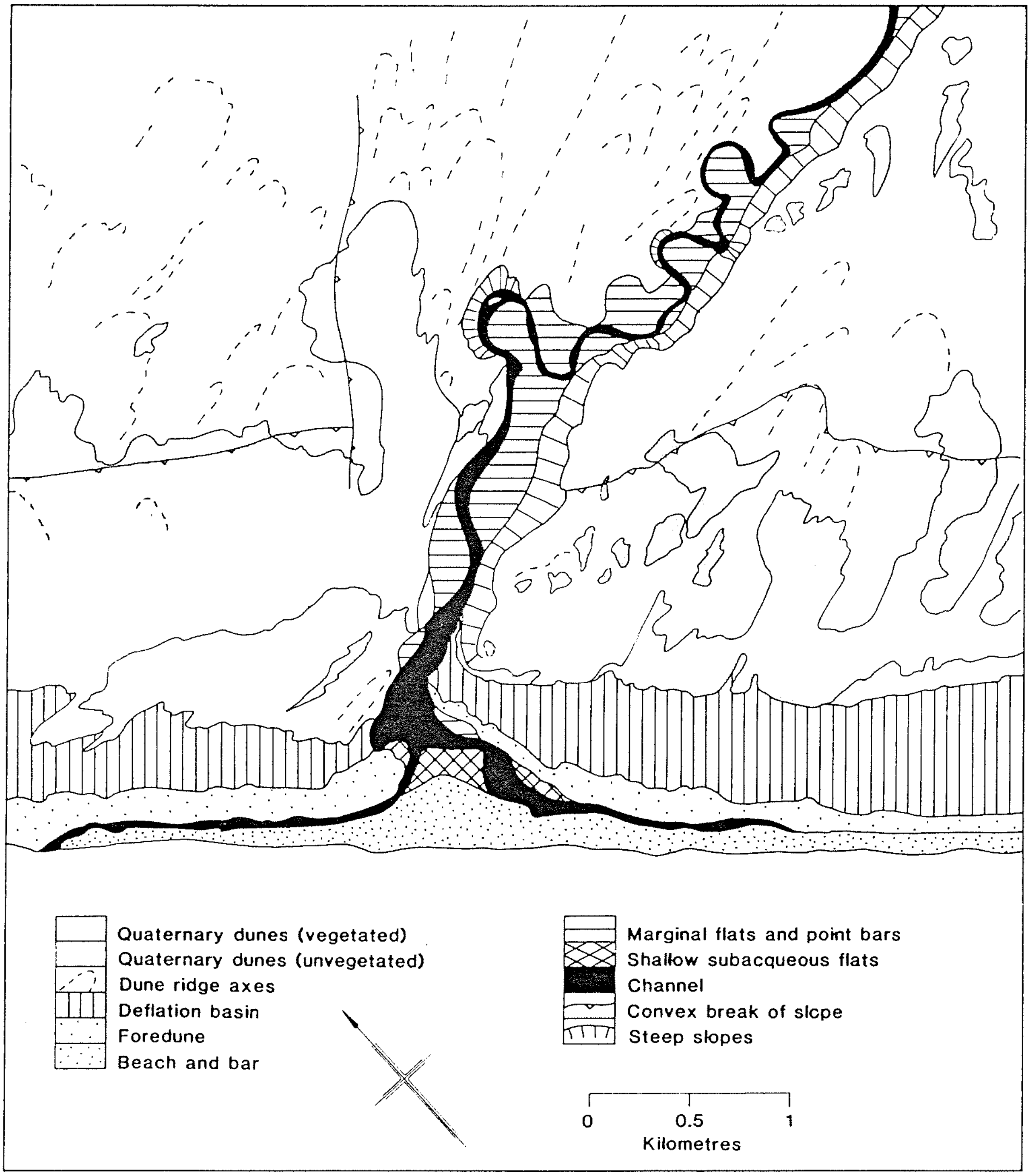

Figure 3:

Morphology of the Warren River, a Type 1b riverine estuary, characterised by laterally restricted point bars and surrounded by high, massive transgressive dune sheets and parabolic dunes. Drawn from aerial photo W.A. 1695(c), No. 5186.

TABLE 1: MORPHOMETRICS AND CHARACTERISTICS OF SOUTHWESTERN AUSTRALIAN ESTUARIES

Estuary	Type	Approx. catchment area (km²) [1]	River length (km) [2]	Estuary area (ha) [2]	Mean ann. precipn. range (mm) [3]	Bar open/ closing [4]
Murchison	1b	82 300	820	430	200-400	PO
Hutt	1b		55-60	Lagoon 2440 Inlet 20	450	NC(?)
Bowes	1b		40	20	450	SC
Oakajee	1b				450	NC(?)
Oakabella	1b				450	NC(?)
Buller	1b	34			450	NC(?)
Chapman	1b	484	105	20-24	450	SC
Greenough	1b	12 800	330	70-80	300-400	SC
Irwin	1b	4 480	135		300-500	SC
Arrowsmith	1b	878	-		500	SC
Hill	1b	692	55		500	SC
Moore	1b	13 000	195		350-600	SC
Capel	1b		55		800-1000	SC
Wonnerup	1b		11	290	800-1000	SC
Vasse	1b		28	320	800-1000	SC
Margaret	1b	450	58		1100-1250	SC
Torradup	1b	105	14		350-500	NC
Oldfield	1b	2 645	75-80	95	350-500	NC
St Mary	1b	115	16	40	400-500	NC
Cheyne	1b	50			400-600	SC
Waychinicup	1a	185	21		600-800	PO
Gardner	1b	607	35	38	1200-1400	SC
Warren	1b	4 360	95	36	600-1400	SC
Donnelly	1b	1 690	85	43	900-1300	SC
Harvey	2a	1 460		56 km^2	500-1000	PO
Leschenault	2a	4 780	Collie 105	2600	600-1000	PO
Barker	2bi			175	400-600	NC
Culham	2bi	2 500	Philips 70 Steer 25-30	1145	350-500	PC

TABLE 1 (cont'd)

Estuary	Type	Approx. catchment area (km²) [1]	River length (km) [2]	Estuary area (ha) [2]	Mean ann. precipn. range (mm) [3]	Bar open/ closing [4]
Taylor	2bi			52	600-1000	SC
Torbay	2bi			735	800-1000	SC
Parry	2bi	170	10	140	800-1200	SC
Oyster	2bi	6 370	Kalgan 105 King 18	1730	800-1000	PO
Gordon	2bii	3 050	110	295	400-600	NC
Beaufort	2bii	4 775	165	475	400-600	NC
Stokes	2bii	5 325	Lort 125 Young 100	1150	350-600	NC
Hammersley	2bii	900	40	260	350-500	NC
Wellstead	2bii	695	70	290	400-600	NC
Demster	2bii	300		265	350-500	NC
Fitzgerald	2bii	1 625	65-70	765	350-500	NC
Swan	2biii	123 500	Swan 80 Canning 70	3390	350-1000	
Peel	2biii	11 800		75 km^2	500-1000	PO
Hardy	2biii	22 550	300	925	400-1200	PO
Broke	2biii	840	60	4360	800-1400	SC
Nornalup	2biii	7 420	Deep 60 Walpole 20	1140	600-1400	PO
Irwin	2biii	2 380	Kent 135 Bow 14	1060	600-1200	SC
Wilson	2biii	2 500	Hay 50 Denmark 55	4830	600-1000	SC

[1] Source: PWD

[2] Source: PWD, Courtesy R. Lenanton, Fisheries & Wildlife

[3] Source: Met. Bur.

[4] Source: Hodgkin and Lenanton, 1981.

PO - permanently open, SC - seasonally closed,
NC - normally open, PC - permanently closed.

Type 2 Barrier Estuaries

Barrier estuaries were sub-divided above into two types, namely, thoseformed by flooding of interbarrier depressions (2a) and those formed by flooding of river valleys/former estuarine basins (2b).

Type 2a Barrier Estuaries

The estuaries which occupy inter-barrier depressions all occur within the west coast high rainfall zone (fig. 1; table 1). In this region Pleistocene and Holocene barriers form discrete linear ridges trending slightly west of north-south, separated by inter-barrier depressions. Two of these depressions may have been former estuaries at the close of the Holocene Transgression but now contain freshwater to saline lagoons (i.e. Lakes Clifton and Preston).

The Type 2a estuaries (e.g. Harvey; Leschenault) are typically shallow (~ 2-3 m max. depth), elongate basins (Harvey is 20 km long, Leschenault 14 km long). Maximum depths are associated with channels and range up to 6 m in Leschenault (Meagher and Le Provost, 1975). Marginal sediments comprise sand and mud subaerial flats, with salt marsh species, and sandy storm ridges, swash bars and storm ridge/foredunes. The former tend to occur on the more protected eastern shorelines, and the latter on the more exposed western shorelines, especially on Leschenault Inlet. Storm ridges are present on both sides of Harvey estuary, although they are more extensive on the western side. Extensive shell beds dominated by Katylesia spp. may be found under the storm ridges. They are also extensive along the shorelines of Lakes Clifton and Preston.

Marginal subaqueous sand flats are extensive around Leschenault and less so around Harvey. They are commonly 0.3 to 0.5 m deep, but may be exposed in summer (Semeniuk and Meagher 1981; Hodgkin et al., 1980). Basin sediments are primarily black, organic sandy muds. Spit segmentation is a major process in all these elongate, narrow lagoons and estuaries (see e.g. Bird, 1971). Fluvial deltas are largely unmodified (Harvey), to slightly modified by wave reworking, due to limited fetch and low exposure.

Both type 2a estuaries are permanently (artificially) open, and as Semeniuk and Meagher (1981) note, are far less brackish than they used to be prior to artificially imposed inlet channel maintenance. Even so circulation studies in Harvey indicate that flushing times may vary from 12 weeks (max,) in summer to 2 weeks (min.) in winter (Hodgkin et al., 1980). Salinities vary seasonally being higher in summer with increased evaporation, and lower than seawater in winter (e.g. Leschenault; Meagher and Le Provost, 1975).

Type 2b Barrier Estuaries

The type 2b barrier estuaries may be broadly sub-divided into three basic morphologic types. These sub-types comprise: (i) small, ovoid basins; (ii) elongate basins (perpendicular to the coast) and (iii) large basins. In suggesting these extremely simple sub-types I recognise the rather arbitrary nature of the classification. However, at this time it provides a broad framework within which most barrier estuaries can be placed, and their geomorphological processes discussed.

Figure 1 illustrates the location of the barrier estuary subtypes, and table 1 lists some general characteristics. The large basin estuaries all occur within the high rainfall belt on the south coast. The elongate estuaries principally occur in the medium to low rainfall band extending from Albany to Esperance, whilst the small basins are scattered in between.

(i) Small, ovoid basins

The small ovoid estuaries are commonly less than 3 km across, lying both parallel and perpendicular to the coast (fig. 1). Catchment size varies from small to moderate (table 1). Basins are shallow, and inlet channels are generally short or non-existent except for two cases (Torbay and Parry).

An example will serve to illustrate the general geomorphology of these estuaries. Culham inlet (fig. 4) is now strictly a saline lagoon since it is closed at the seaward margin by a high foredune. However it has been estuarine in recent times.

Clarke and Talton Phillipps (1953, p.80) note that "in April, 1849, A.C. Gregory recorded that after heavy rains the water in Culham Inlet had risen 7ft above its 'usual level' when it broke through the bar, and for three days the outflow was too strong for his horses to cross the mouth by swimming". At other times, the water level in Culham is notably lower than that of the adjacent sea level (Clarke and Tarlton Phillipps, 1953). These rather unusual conditions actually typify several of the south coast estuaries, especially the ones located in the lower rainfall zones.

Field observations in Culham inlet indicate that the Holocene Transgression flooded an almost intact Pleistocene estuary. Marginal sub-acqueous terraces are predominantly cemented, fossil-ferous Pleistocene sands with a thin veneer of Holocene sediment. Known extinct Pleistocene fauna are present in the cemented sediments and absent in the Holocene alluvial and estuarine sediments. One or two Holocene storm ridges are present around the margins of the estuary. The estuary itself is very shallow and is filled with a veneer of Holocene sands, silts and clays (fig. 4).

The small ovoid barrier estuaries are permanently closed to normally closed estuaries (Hodgkin and Lenanton, 1981). Flood tide deltas are consequently limited in size, and ebb tide

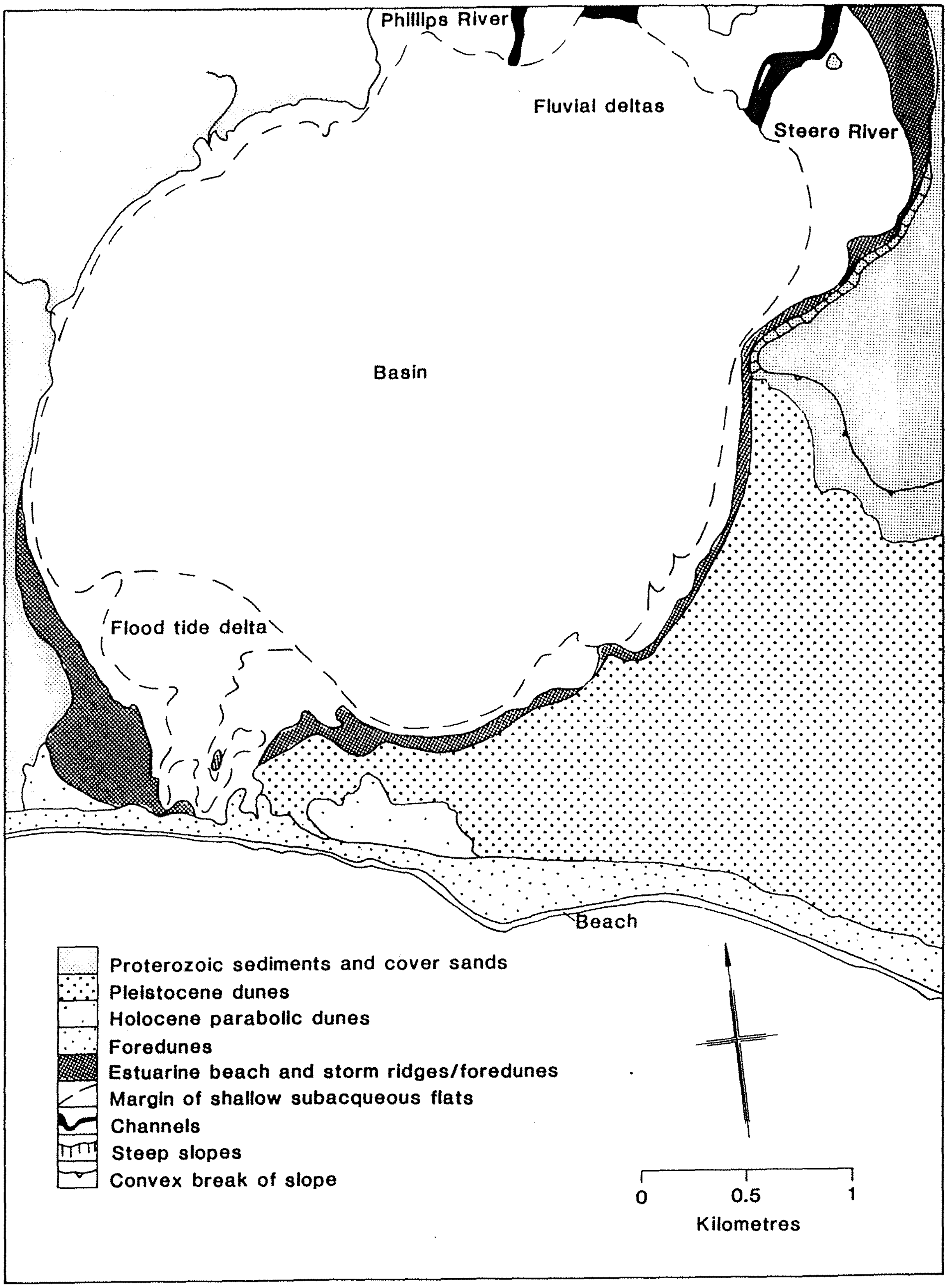

Figure 4:

Morphology of Culham Inlet, the largest of the ovoid, Type 2b barrier estuaries, characterised by restricted marginal shoreline development and a shallow basin. Drawn from aerial photo W.A. 1695(c), No. 5495.

deltas are only present for short periods following flood events. Tidal and wind wave processes appear to be limited due to the low rate of bar opening, shallow bathymetry and restricted fetch. The small fluvial deltas are consequently largely unmodified. Marginal shorelines developed in the Holocene appear to be limited in size, and are characterised by a few arcuate storm and foredune ridges. All estuaries of this type are at least partly filled, and some (e.g. Culham) are almost completely filled in the evolutionary stages of Roy et al.,(1980).

(ii) Elongate Estuaries

The type 2b estuaries (Gordon, Stokes, Hamersley, Wellstead, Dempster and Fitzgerald) are elongate perpendicular to the coast, receiving influx from one river system which enters at the extreme landward end. The estuaries receive medium to low rainfall, all being located within a region receiving less than 600 mm annually. Catchment size is also moderate (table 1).

These estuaries are normally closed in the terminology of Hodgkin and Lenanton (1981). That is, they open only following unusually heavy rains. They all display flood tide deltas, which are in general larger than the deltas of the ovoid barrier estuaries. Inlet channels are both short and relatively wide (200-300 m), and narrow, long and sinuous (100 m wide, 2000 m long). Those estuaries, with Holocene and Pleistocene barriers which are either limited in volume or landward extent, display short inlet channels. In these, flood tide deltas form symmetric fan-shaped lobes (e.g. Gordon). Those estuaries bounded by extensive dune barriers, display long deep channels with longer, parabolic-shaped flood tide deltas.

Fluvial deltaic deposition dominates the elongate estuaries. Two (Gordon, Wellstead) are characterised by long, thin subacqueous and subaerial jetties flanking long, sinuous fluvial channels which extend well into the estuary basin (fig. 5). Three more appear to have passed this evolutionary stage and are characterised by wide, shallow subacqueous (but occasionally subaerial during low stage) sand flats (e.g. Hamersley, Dempster, Stokes). One (Fitzgerald) is dominated by an extensive fluvial delta in which widely time-separated storm ridge-building events has lead to the formation of cut-off lagoons. The estuary with the largest and most exposed fetch (Stokes), displays a storm ridge/foredune plain adjacent to the fluvial delta. In general, it seems that the wider the estuary, the greater the potential wind fetch, and the greater the degree of fluvial delta reworking. Of note is the fact that since the estuaries may almost completely dessicate in some years, aeolian processes may be significant. Most wave-built, marginal swash bars and storm ridges display aeolian sand cappings to various extents.

The elongate estuaries are also dominated by a Pleistocene landform inheritance. For example, the eastern shoreline of

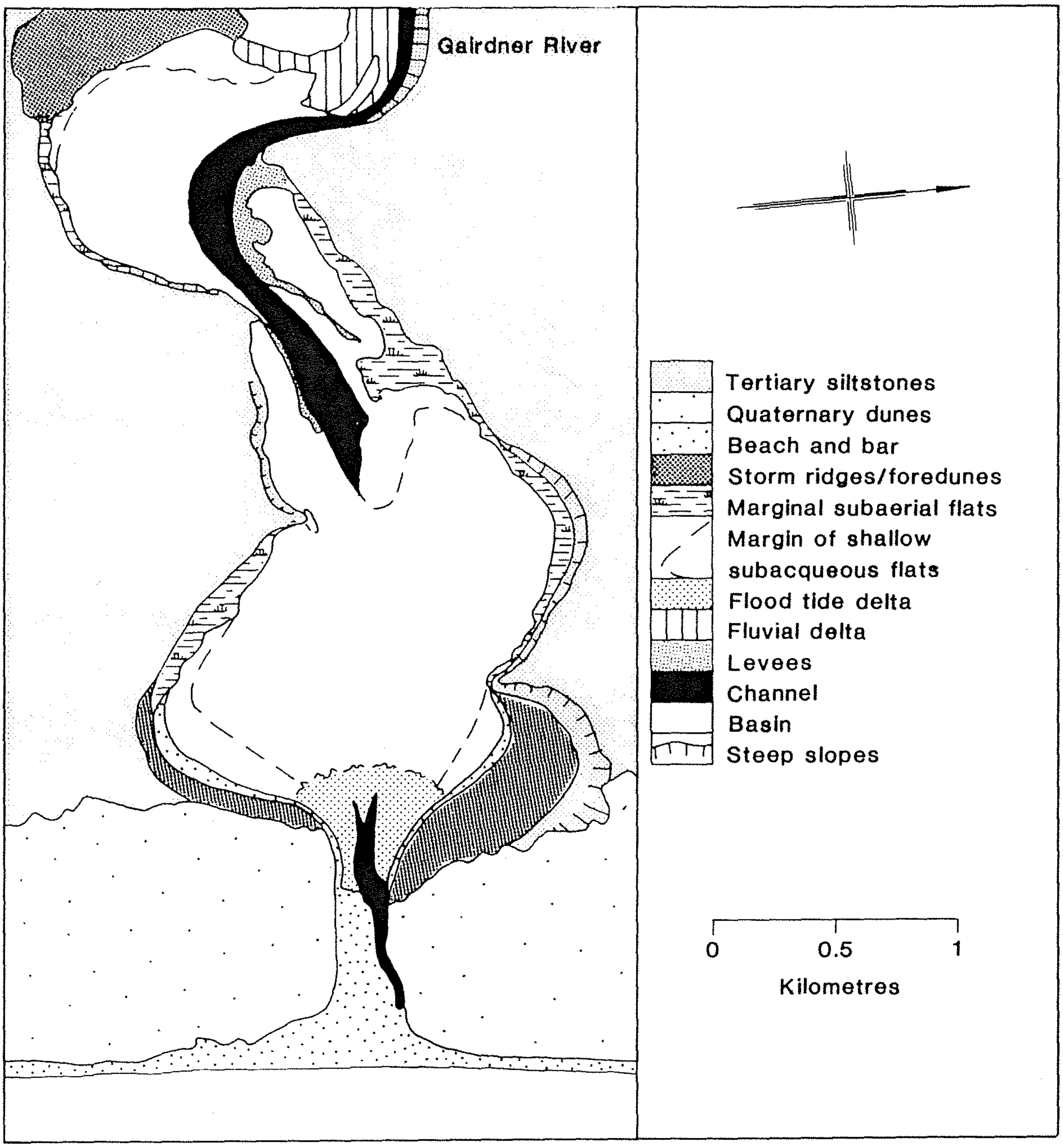

Figure 5:

Morphology of Gordon Inlet, an elongate Type 2b estuary characterised by fluvial deltaic levees, cut-off bays and shallow basin. Drawn from aerial photo W.A. 1695(c), No. 5461.

Hamersley Inlet has sand ridges containing abundant Pleistocene fossil fauna. In addition, marginal flats consist of a thin veneer of Holocene sands and muds over highly fossiliferous Pleistocene cemented sands.

Most of the elongate estuaries lie between the 'partly filled' to 'complete filled'evolutionary stage of Roy et al.(1980). Basins are very shallow and several appear to be at wind wave base, since sand veneers dominate fluvial channel margins as levee and overbank deposits. Cut-off bays develop where levees cross the basin linking adjacent shorelines. The bays remain as lagoons gradually filling with flood silts and organic sediments. In one case, Dempster Inlet, flow is so irregular that, even though the basin is completely filled, a defined fluvial channel is not maintained.

In general, the elongate estuaries are the most advanced in an evolutionary continuum. This appears to be a function primarily of the irregularity of flow, coupled with the presence of extensive estuary mouth bars/beach berms, and a significant Pleistocene landform inheritance. During moderate flood events water levels may reach significant heights (up to 3 m above normal) without bar breaking, and if the bar breaks it may not stay open for long. There would thus appear to be far less flushing of silts and muds in these estuaries than in others in which bar breaking is more regular. This condition would lead to greater rates of silt and mud sedimentation. In addition, it appears that portions of these estuaries may have remained relatively intact during glacial low sea level phases, and consequently the degree of sedimentation required to fill the basins was less than that of those estuaries lying within the higher rainfall areas.

(iii) Large Estuaries

The largest estuaries occur within the two high rainfall regions (fig. 1; e.g. Swan, Blackwood, Broke, Nornalup, Irwin, Wilson). All receive influx from two or more river systems, a condition which has been significant in producing large basins relative to the elongate estuaries. All the estuaries are bounded by extensive sandy limestone barriers formed in either progradational sequences (e.g. Swan, Blackwood) or in place (e.g. Broke Wilson) throughout the Pleistocene and Holocene (e.g. see Quilty, 1977). Hodgkin and Lenanton (1981) classify these estuaries as seasonally closed to permanently open. The former refers to a condition in which the estuary is open one or more times per winter (see e.g. Collins and Fowlie, 1981). Flood tide deltas are accordingly extensive, and tidal currents assume some importance in circulation processes. The estuaries are characterised by extensive alluvial deltaic plains, storm ridge and foredune complexes, wide, subacqueous marginal terraces and active spits (see e.g. Hodgkin, 1978; Hodgkin et al., 1979). Wind fetches are large, and exposure to the southwest generally high, so that wind waves are significant and coupled with set-up, (e.g. 1.18 m variation recorded in Peel-Harvey during Cyclone Alby, April 1978; Wallace, 1978) act to produce considerable reworking of fluvial delta sands.

Estuarine basins may be relatively deep (channels range from 20 m in the Swan, to 5 m in Wilson and Nornalup), and are dominated by organic silts, fine carbonate sands and faecal pellets. The typical sedimentary sequence from shallow marginal flat to basin is similar to that recorded elsewhere (e.g. Roy & Peat, 1974), in that the shallow flats are dominated by sands and muddy sands, basin margins by sandy muds, and basins by muds.

The detailed study of Walpole and Nornalup Inlets by Hassell (1962) provides further insight into the dynamics of a large estuary (fig. 6). In terms of hydrology, Hassell (1962) found a salt wedge present in the inlet channel, and extending across the deepest part of the inlet during a May, 1960 survey. A mixed water body overlay the wedge (chlorinity 18-19‰). The majority of the inlet proper contained a mixed layer of chlorinities of 17-18‰, above which occured a surface layer of 16-17‰. The latter water layer was also present at the mouths of the Deep and Frankland Rivers. Tidal currents were strong only in the inlet channel, and were negligable in the majority of the inlet. A strong correlation between bathymetry and grain size and sorting was found in the estuary (cf. Shepherd, 1970; Roy and Peat, 1974). Most sand sized particles were distributed close to rivermouths and on marginal flats, whereas silts and clays were carried in suspension into the basin beyond wave base (1.8 - 3.0 m; Hassell, 1962). See editorial note.

The large estuaries are all 'partly filled' types in Roy et al's. (1980) evolutionary scheme. Broke Inlet appears to be the furtherest removed from the 'unfilled' type, as it is very shallow (about 2m), and the 'basin' is primarily sand dominated. Peel is also very shallow, but retains a mud basin around 2 m deep (Hodgkin et al., 1980).

Discussion and Conclusion

Table 2 summarises the factors which appear to play a role in the development and present morphology and hydrology of each of the barrier and riverine estuaries. The barrier estuaries constitute the largest proportion of the estuary types, and these vary from being permanently open to permanently closed. The small estuaries display the greatest variability. The extent of tidal and wave action in each is largely based on supposition, although observations of faunal populations indicates some validity to the classification (e.g. Chalmer et al., 1976; Lenanton, this symposium; Hodgkin and Kendrick, this symposium; unpub. surveys, Kendrick and Hesp).

The description of estuarine types suggests that the geomorphological evolution of southwest Australian estuaries is primarily a function of regional variation in rainfall, drainage basin size, and the degree of Pleistocene inheritance. That is, these factors have largely determined the morphology and evolutionary paths of the estuaries. In addition, I would suggest that the estuarine types outlined above, do not, in general, represent an evolutionary continuum but rather constitute separate evolutionary types. Whilst many of the estuaries appear to have experienced similar hydrological conditions at the close of the Holocene Transgression around 6-7 000 years B.P. (Thom and Chappell, 1975) as evidenced by Hodgkin and Kendrick (this symposium), those

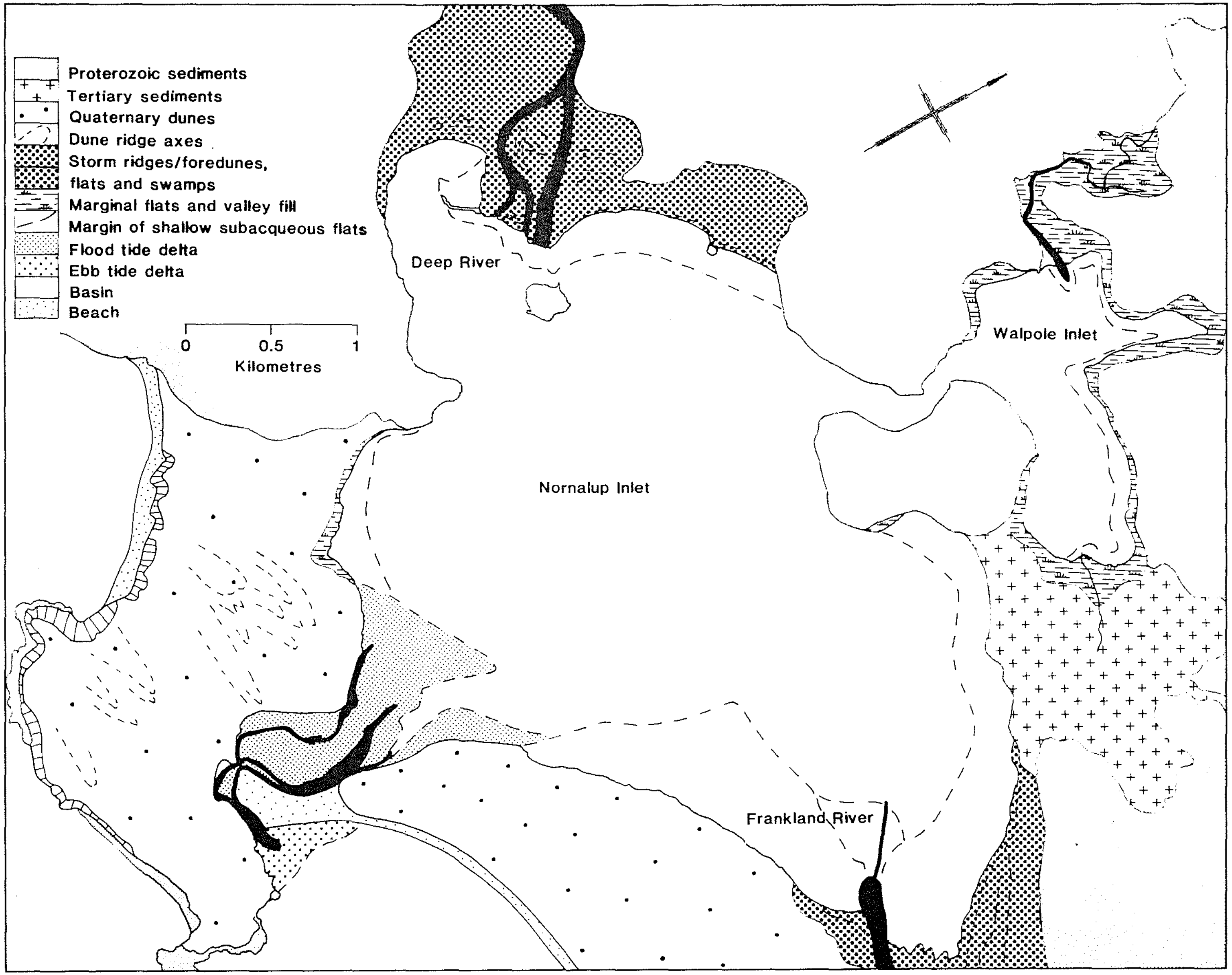

Figure 6. Morphology of Nornalup and Walpole Inlets, a large type 2b barrier estuary, characterised by an extensive flood tide delta, extensive storm ridge/foredune plains and wide subaqueous flats. Drawn from aerial photo WA 1694 (c), No.5245.

TABLE 2: CLASSIFICATION AND CHARACTERISTICS OF W.A. ESTUARIES

	RIVERINE ESTUARIES		BARRIER ESTUARIES			
TYPE	1A: DEEP	1B: SHALLOW	2A: INTERBARRIER DEPRESSION	2B: SMALL OVOID	ELONGATE	LARGE
EXAMPLES	WAYCHINICUP	GREENOUGH	HARVEY LESCHENAULT	CULHAM PARRY	FITZGERALD GORDON	NORNALUP WILSON
ENVIRON. FACTORS	DROWNED VALLEY	LOW RAINFALL LIM. CATCHMENT GEOL. CONTROL	HIGH RAINFALL	SMALL CATCHMENT LOW RAINFALL 1 OR 2 RIVERS	MOD. CATCH. MED.-LOW RAINFALL 1 RIVER INFLUX	LARGE CATCHMENT HIGH RAINFALL 2 OR MORE RIVERS
PLEISTOCENE ESTU. LANDFORM INHERITANCE	NONE(?)	HIGH	HIGH	MODERATE-HIGH	MODERATE-HIGH	LOW
MARINE BAR OPENING	OPEN	SEASONALLY OPEN	PERMANENTLY OPEN	PERM. CLOSED TO NORMALLY CLOSED TO SEASONALLY OPEN	NORMALLY CLOSED	SEASONALLY OPEN TO PERM. OPEN
TIDAL AND WAVE ACTION	HIGH	LIMITED	MODERATE	LOW	LOW-MODERATE	HIGH
ESTUARINE FAUNA	OPEN	RESTRICTED	MODERATE	FRESHWATER TO MODERATE ESTUARINE	RESTRICTED TO MODERATE (VARIABLE)	MODERATE-RICH
GEOMORPHOLOGY	DEEP, STEEP WALLED OPEN ESTUARY	SHALLOW, NARROW ESTUARY - POOL & BARS - OVERBANK & LEVEE DEPS.	ELONGATE, SHALLOW BASIN, NARROW MARGINAL SHORE; FEW RIDGES; SPIT SEGMENTATION.	OVOID, SHALLOW BASIN; LIM. FLUV. DELTA; VERY LIM. MAR. DELTA; SMALL MUD BASIN; FEW LATERAL STORM RIDGES.	ELONGATE EST; EXTEN. FLUV. DELTA; MOD. MAR. DELTA; MOD. TERMINAL STORM RIDGES/FOREDUNES.	LARGE BASIN; SMALL EBB TIDE DELTA; MOD. FLUV. DELTA; EXTEN. FLOOD DELTA; EXTEN. SUBACQ. TERR.; EXTEN. STORM RIDGES/FOREDUNES.

hydrological conditions must have changed fairly rapidly to become quite diverse between estuary types. Two points are relevant here: The first is that there is marked variation in fluvial input, evaporation, ocean exchange (bar opening/closing) and mixing between the estuary types, and it is these factors which determine hydrologic condition. Secondly, modern observations of flood tide delta formation at, for example, 'The Cut' an artificial inlet channel constructed on Leschenault Inlet, show that deltas are formed very rapidly following entrance flooding.

Evidence supporting these contentions may be seen in comparing the elongate and large barrier estuaries. The elongate estuaries are more advanced in evolutionary stage (or maturity; see Roy, 1982) than the large estuaries. I suggest that they have filled more rapidly due to a combination of factors, namely less erosion during low sea levels compared to the higher, more regular discharge of the large estuaries, and less tidal and fluvial-induced flushing due to longer-term bar closure, and less reworking of sediments due to restricted fetches. These conditions result in greater rates of flocculation of silt, clay and organic sediments within the elongate estuaries. This occurs for example in the Peel-Harvey system also, where Harvey, with less circulation and flushing has a higher percent organic carbon and clay content than Peel (Hodgkin et al., 1980). In addition, the modes by which the estuaries have evolved also vary between types. Thus, for example, elongate barrier estuaries trend towards riverine morphologies by sand levee and spit formation, and silt bay development over shallow mud basins, whilst the large estuaries trend towards a riverine morphology by marginal constriction. The latter is characterised by subacqueous terrace and subaerial ridge formations over deep mud basins.

In terms of estuarine management, the apparent inherent differences between the estuary types outlined above, suggests that while all types have similar sensitivities to man-induced changes, the magnitude of these sensitivities would vary between types. Thus, the northern riverine and southern elongate barrier estuaries would intuitively cope less well with, for example effluent disposal, than the large estuaries and some of the seasonally to permanently open ovoid estuaries. Similarly, the marked variations in water level experienced by the elongate and some ovoid and riverine estuaries would make shoreline or near-shoreline development hazardous compared to the large estuaries. Such variations in behaviour between estuarine types should be considered in developing management strategies.

In conclusion, a comparison between this paper (given all the omissions) and that of Peter Roy's, indicates the lack of geological, geomorphological and hydrological data available on West Australian estuaries. Note, for example, that the only stratigraphic evidence on hydrologic and sedimentologic change available at present comes from one estuary type, the large estuaries (e.g. Swan, Peel, Blackwood; see Hodgkin and Kendrick, this symposium). As Roy (1982) notes, "the rate and direction of natural change in an estuary provides a yardstick to assess impacts induced by man". With continuing and increasing recreational, urbanisational and industrial pressures on West Australian estuaries, it is critical that studies on the rates and directions of change of all estuarine types by continued and expanded.

Acknowledgements

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Editorial note

Data from CSIRO Division of Fisheries Oceanographical Station Lists 8 and 9, and other sources, confirm that Nornalup Inlet is often strongly stratified, with bottom chlorinities in excess of 16‰ persisting throughout the year despite surface chlorinities as low as 5‰ in winter. The two rivers are also often stratified, except during strong river flow.

THE CHANGING AQUATIC ENVIRONMENT 7000BP TO 1983 IN THE ESTUARIES OF SOUTH WESTERN AUSTRALIA

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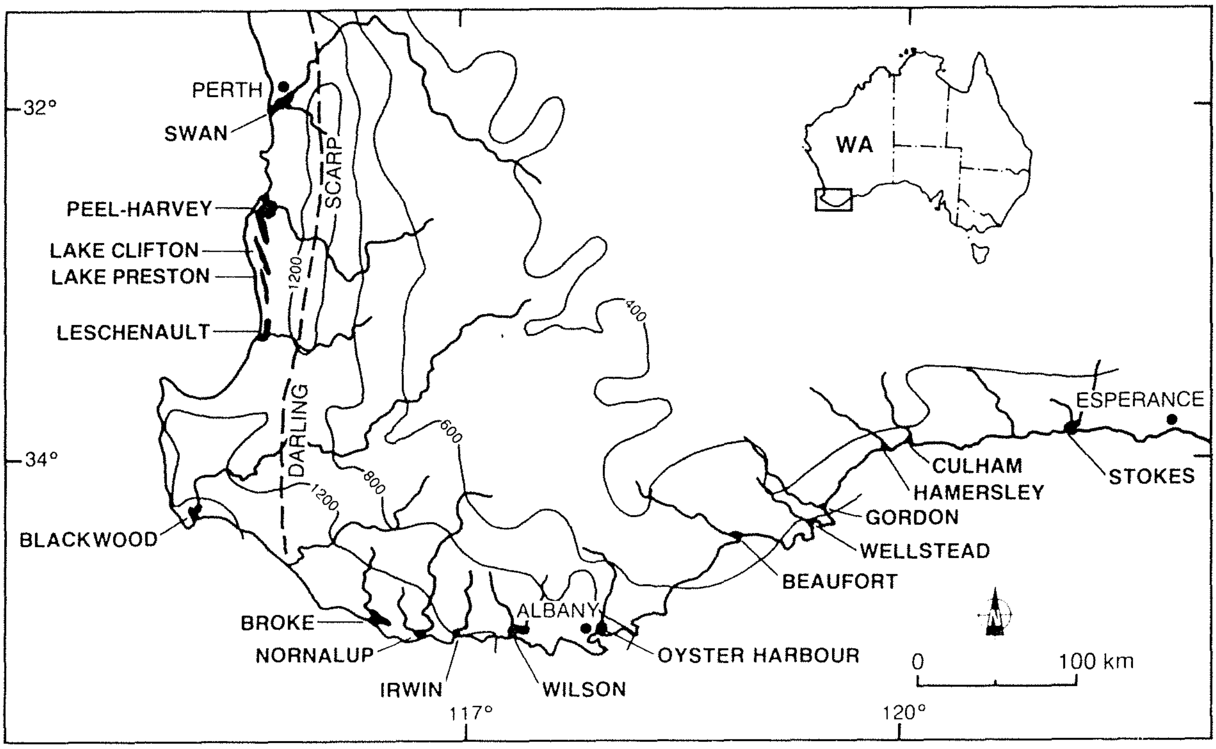
Abstract

The geomorphological changes experienced by our estuaries during the Holocene have greatly altered their hydrodynamic characteristics. The free exchange between ocean and estuary that existed following the post-glacial rise of sea level 7000 years ago permitted establish -ment of a diverse fauna characteristic of sheltered marine embayments. In south western Australia, where tidal amplitude is small, ocean bar formation has restricted exchange and hydrological conditions have become progressively less marine. Poor tidal flushing, together with the extreme seasonality of river flow, result in a great seasonal salinity range, often from fresh in winter to marine or hypersaline in summer. The estuaries now have a restricted resident fauna most or all species of which are confined to estuaries.

The geomorphological processes that have caused these changes are still active. They can be accelerated or reversed by man's activities, with effects on the biota that should be predictable from the anticipated hydrology.



Estuaries and coastal lagoons of south-western Australia. Isohyets in mm

There is no such thing as a typical estuary, nevertheless there is a commonly perceived picture of what constitutes an estuarine ecosystem and in particular the composition of the fauna and faunal communities (e.g. as described by Sanders *et al.*, 1965). This is a sequence in which a stenohaline marine fauna (animals confined to near marine salinities), similar to that of sheltered marine embayments, is dominant near the mouth and is progressively replaced as salinity decreases up the estuary, first by more euryhaline marine species (species which tolerate a greater range of salinity), then by 'true-estuarine' species (euryhaline species which are confined to estuaries) and finally by freshwater species of varying euryhalinity. In this sequence the diversity of species (species number) also decreases along the salinity gradient, at least until fresh water ($<3^{o}/oo$) is reached.

This sequence is illustrated in Remane's well-known diagram (Remane, 1971) or perhaps more appropriately to Australian estuaries by Day's (1981) modification of this (Fig. 1). Day *et al.*, (1952) give a detailed account of such a faunal sequence in the Knysna estuary of South Africa where 310 species of benthic animals were found. The large Gippsland Lakes system of Victoria has a similar faunal sequence (Poore, 1982) associated with a relatively stable salinity gradient from marine to fresh water. The less diverse fauna there is presumably attributable to the restricted tidal exchange.

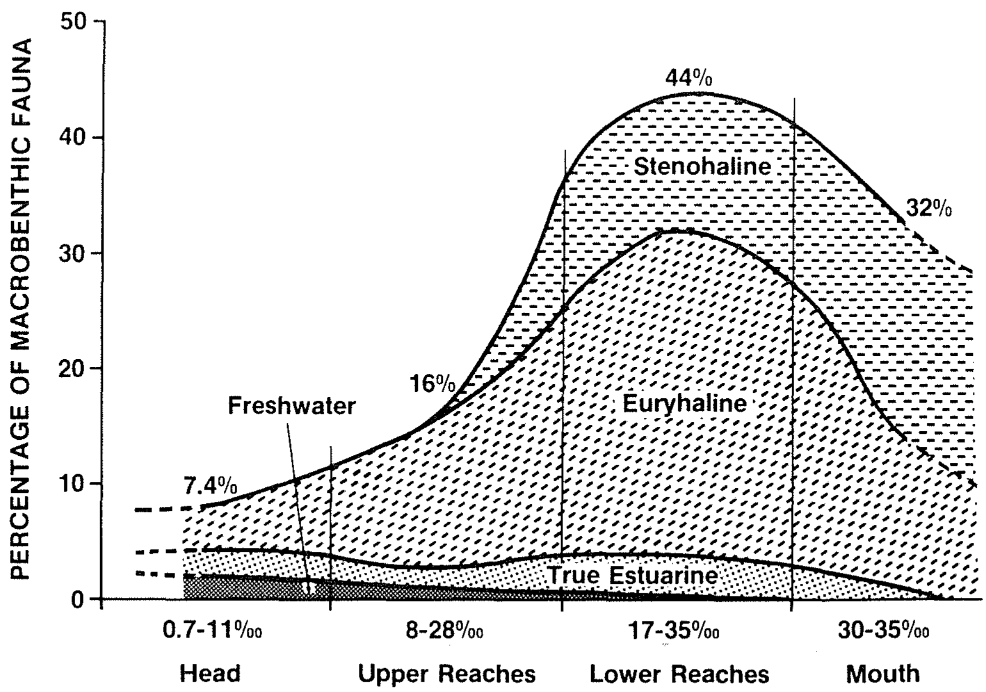


Figure 1. Distribution of faunistic components and percentages of total macrobenthos in the four reaches of an estuary. Redrawn from Day, 1981.

Salinity is certainly not the only factor determining the diversity and character of the estuarine fauna. Bottom type, for example, is also very important and many of the 82 molluscs found in the Kynsna estuary were rocky shore marine species. Nevertheless, in our view, salinity is the 'ecological master factor' (Kinne, 1964) which determines the character of the fauna in our estuarine environments.

While the salinity regime affects all the fauna, and the flora, it is pertinent here to consider only the resident fauna, animals which do not come and go in response to changing salinity, and in this brief review we propose to concentrate on the shelled Mollusca. Most molluscs are poor osmoregulators and, having calcareous shells, they leave an easily read fossil record and hence facilitate comparison between past and present faunas and environments.

THE ESTUARINE FAUNA TODAY

In south-western W.A. today, a faunal sequence of the type described above is only seen in the few permanently open estuaries and there in much modified form. In a survey of the Swan River estuary we (Chalmer *et al.*, 1976) found 97 species of molluscs, but only 23 of these lived permanently in the most marine part, the 'lower estuary', and in the estuarine basin there were only 10, the 7 most abundant of which are true estuarine species (Fig.2

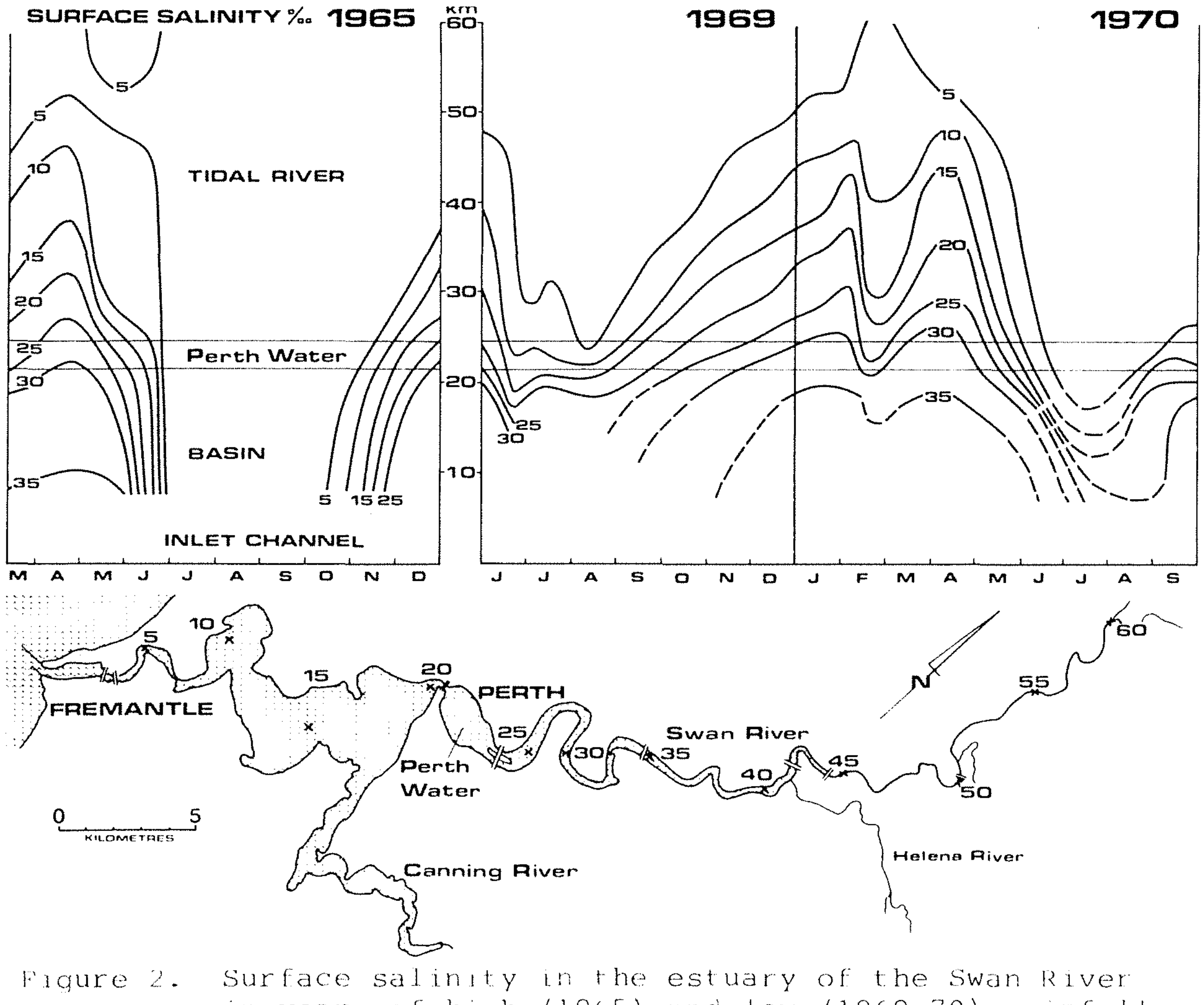


Figure 2. Surface salinity in the estuary of the Swan River in years of high (1965) and low (1969-70) rainfall.

This paucity of species and dominance by a few very euryhaline species reflects the peculiar hydrological regime experienced, where in summer there is a gradient of salinity from marine in the basin to nearly fresh in the upper reaches and for some months in winter the estuary is often too fresh for all but the most euryhaline species to survive (Fig. 2). This condition results from our Mediterranean-type climate, the small tidal range, and the restricted exchange with the ocean.

Similar, or more extreme, hydrological changes are experienced in all the permanently open estuaries of the south west, with the exception of Oyster Harbour (Fig. 3) where salinity is seldom less than $27^{o}/oo$ (McKenzie, 1964), except in the immediate vicinity of the King and Kalgan rivers, both of which are estuarine for some 5km. About 110 species of mollusc have been identified from Oyster Harbour and the fauna is similar in composition to that of the totally marine Princess Royal Harbour close by (Wells & Roberts, 1980). However it is dominated by a dozen species (Wells & Threlfall, 1980) and here again diversity decreases away from the mouth and is much reduced in the vicinity of the King and Kalgan rivers where *Katelysia*, the dominant mollusc near the mouth, is present only as small and deformed shells.

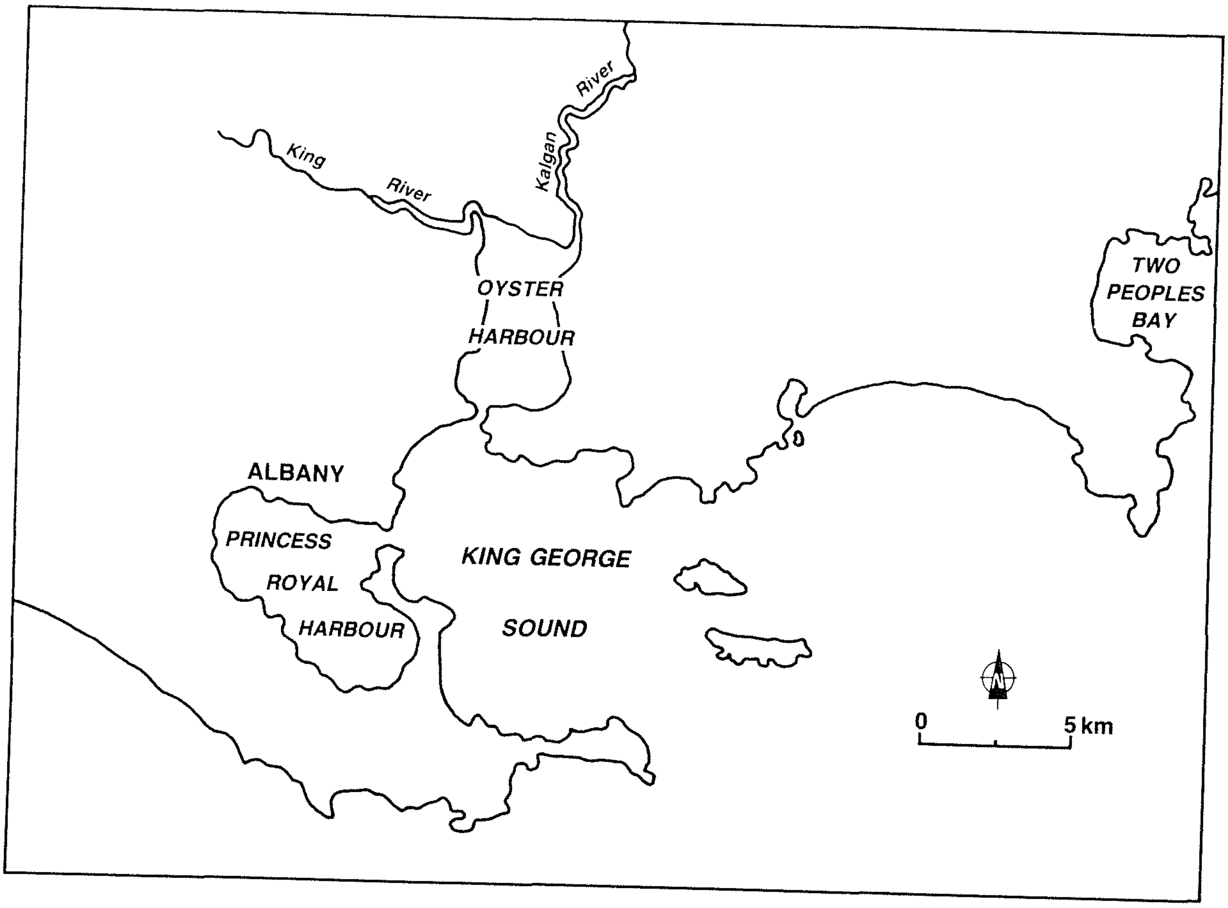


Figure 3. Oyster Harbour and Princess Royal Harbour.

Some of these species are of particular interest for what they can tell us about both the present and former conditions in our estuaries. Three sympatric species of the venerid bivalve *Katelysia* form half the biomass on the shallow marginal sand-flats of Oyster Harbour (Wells & Threlfall, 1980) and Princess Royal Harbour (Wells & Roberts, 1980) and their shells dominate the extensive Quaternary shell deposits of estuarine and former lagoonal environments along our coast from Esperance to north of Geraldton (Fig. 4).

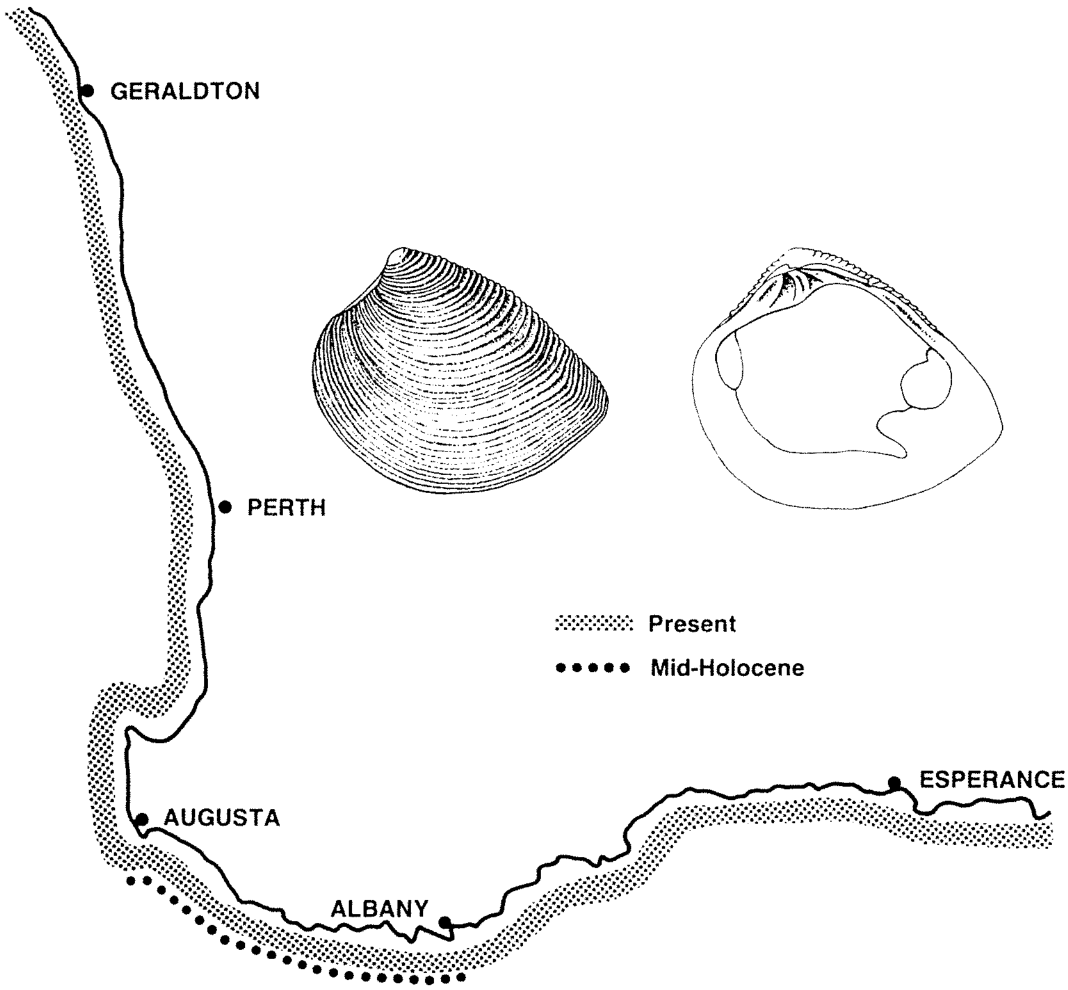


Figure 4. The present and Mid-Holocene range of *Katelysia scalarina* in south-western Australia. Shell drawings by Val Ryland.

Elsewhere in W.A. *Katelysia* is now confined to the proximity of the mouth in some estuaries of the south coast from Albany westwards, both permanently open estuaries (Blackwood & Nornalup) and the 'seasonally open' estuaries where the bars close for some months each year (Broke, Irwin & Wilson), but where salinity is only briefly less than $10^{o}/oo$ and does not exceed $35^{o}/oo$. These estuaries have a moderate diversity of species, by our standards, e.g. at least 29 molluscs in Nornalup Inlet and 14 in Wilson Inlet (Hodgkin, 1977) including *Katelysia* and a number of other euryhaline marine species.

In most of the estuaries east of Albany, the 'normally closed' estuaries where the bars often stay closed for several years at a time, and where the water is often hypersaline to sea water for prolonged periods, there is only a very restricted fauna of about 6 species of true estuarine molluscs. In some even this fauna is sparse and the salt lake gastropods *Coxiella* spp. may be abundant.

We have found *Katelysia* and a number of other euryhaline marine species alive, transiently, in Wellstead & Gordon Inlets following breaching of the bars. In Wellstead some have persisted for a year or more while the bar remained open. On one occasion they were killed by flood water, but on another there was no specific event to account for their disappearance. In Hamersley Inlet, the shell fauna suggests that euryhaline marine species such as *Katelysia*, *Ostrea* and a number of others have been able to establish themselves and persist for several years quite recently, although the bar now only opens briefly every few years and the estuary may dry out.

On the west coast, the Peel-Harvey estuary now stays open continuously, though tidal exchange is restricted and the bar used to close every few years before construction of training walls at the mouth. Salinity varies from near fresh to about $50^{o}/oo$. Only 13 species have been found in Peel Inlet (Wells & Threlfall, 1980) and, of these, five true estuarine species dominate the molluscan fauna. A few euryhaline marine species also occur in the most marine environment near the mouth.

THE HOLOCENE FAUNA

That, all too briefly, summarises what we know of the molluscan fauna of our different estuarine ecosystems at the present time and how this relates to the hydrological conditions. The data we have from the fossil record are admittedly still scanty and probably therefore interpretable in a number of different ways. Nevertheless it is worth while to try to interpret the sequence of events which has produced the present ecosystems on the evidence we have. We need to know how stable these systems are, what play of forces maintain them in their present condition and for how long and in what direction they are changing. Then in the light of this information we can better assess how subject they are to interference by man.

Hesp (this Symposium) has discussed the geomorphology of our estuaries and the processes by which the various types we see today have been transformed from whatever was their Pleistocene inheritance. Our concern is to try to trace the ecological history of the estuaries to see what this tells us about the changes they have experienced since they were flooded by the rising sea level 6-7000 years ago. For this purpose the extensive shell beds are a most useful source of information. They are 'time capsules' which, if interpreted on the basis of an understanding of the ecology of living species and communities, can tell us a lot about the ecological history of the estuaries, especially with respect to past hydrological conditions.

While concentrating on the geologically brief Holocene period, it is well to remember that the estuaries and their biota did not suddenly appear 7000 years ago, but that they had a degree of continuity over a vastly longer period during the many rises and falls of Pleistocene sea level, even though they must have changed greatly both in location and character. In fact, to judge from the fossil record, the estuaries of 6000BP were more like those of about 125,000BP than those of 1983.

Extensive middle Holocene shell beds in the basin of the estuary of the Swan River contain at least 90 species of molluscs (35 bivalves and 56 gastropods), a diversity similar to that of Princess Royal Harbour at the present time. There are of course differences in the composition of the fauna in these situations and there is a notable absence of a number of species that now live in the estuary. However, *Katelysia* was abundant in the basin and so too was the sub-littoral mud oyster *Ostrea angasi*. These shell beds have been radiocarbon dated 6000 to 4500yrsBP (Kendrick, 1977) and at Guildford, 40km upstream from the mouth, Kendrick has found shell beds with 31 species, predominantly of marine affinity, dated 6600yrsBP. (Except where otherwise indicated all dates quoted are uncorrected.)

Shell deposits of similar age (5250 to 4500yrsBP) occur in the estuarine basin of Peel Inlet and from these some 40 species of mainly marine and euryhaline--marine molluscs have been identified (Brown *et al*, 1980). There is an abrupt change in the upper part of these deposits from this suite of species to the present true estuarine fauna and an accompanying change in the nature of the sediments. This cannot be dated accurately because of bioturbation of the sediments, but is thought to follow shortly after the 4500BP date. Closer to the coast (at Mandurah) there are extensive shell beds, dominated by *Katelysia* and a number of small gastropods which appear to represent a more impoverished, largely shallow water, marine fauna. These shells have been dated at 4460yrsBP (corrected date, Kendrick unpublished). There are similar shell beds on the shores of the coastal lakes, Lake Clifton and Lake Preston, which must have been coastal lagoons open to the sea at about the same time.

On the south coast of W.A. there are at least 10 estuaries west of Esperance with extensive shell beds, some above present sea level and with paired bivalve shells indicating that they represent an *in situ* intertidal to shallow sublittoral environment. Unfortunately as yet the only dated material is from the Blackwood River estuary, where a limited intrusion of marine fauna in the lower sediments of the estuarine basin was dated 4475 to 3380yrsBP (Hodgkin, 1978). Nevertheless, two other examples are relevant.

Wellstead Estuary has extensive Holocene shell beds close to the mouth. While these have yet to be examined in detail, a preliminary examination shows a progressive change in the fauna from some 70 species, including a few rocky shore marine species, to 29 species in the upper levels but still including a high proportion of marine species. This is compatible with a progressive restriction of the mouth and change to a less favourable environment; also possibly with a higher sea level because the upper layers are about 1.5m above present sea level.

There are also shell beds of more limited extent along the riverine part of Wellstead Estuary up to 7km from the mouth, with 17 mollusc species at 4km and *Katelysia* again dominant. Clearly there was substantial exchange between ocean and estuary and near marine salinities when these beds were formed, unlike the present condition where the bar is more often closed than open and salinity varies from fresh to hypersaline, a catastrophic environment for marine species.

Further east still, Culham Inlet has extensive shell beds dominated by *Katelysia* and, near the bar, masses of *Ostrea* shells which appear to be very recent in origin. However the Inlet is now a closed shallow lagoon, cut off from the sea by a high well-vegetated dune barrier that is not known to have broken in the last 100 years. It is grossly hypersaline or dry in summer.

CONCLUSIONS

How then should we interpret the Holocene history of our estuarine ecoystems? We suggest that if the fossil record is examined in the light of what is known of the biology of the present day fauna we can draw the following tentative conclusions.

1. When first flooded by the rising sea level some 7000yrsBP all, or most of our estuaries, and many non-estuarine coastal lagoons, had a free connection with the sea so that there were near-marine salinities in the estuarine basins and in some cases also for a considerable distance into the present riverine reaches.

2. The estuaries must then have been gradient-type systems, just as our open systems are now in summer, dominated by a stenohaline marine fauna near the mouth and replaced by a less diverse, more euryhaline fauna up-estuary for varying distances depending on volume of river flow and other factors.

3. This condition persisted, at least in the large west coast estuaries until about 4000 BP after which there appears to have been a fairly abrupt change in the estuarine environments as evidenced by the subsequent reduced faunal diversity and disappearance of a number of dominant marine species and their replacement with an impoverished, predominantly true estuarine fauna. This clearly implies reduced exchange with the ocean and a considerable increase in the salinity extremes experienced.

4. Just what caused this change in hydrological conditions we can only speculate, but if as appears to have been the case the change was general throughout the south west then the cause or causes must also have been general, affecting the whole regional coastal environment. Such changes could have been : a retreat of relative sea level from a mid-Holocene high up to 2m above the present, as is indicated by a number of recent studies; a change in sea water temperature, as suggested by the retreat northwards to Shark Bay of a number of species; geomorphic change unfavourable to *Katelysia* and a number of other calm-water species (loss of sheltered marine embayments on the west coast); or a climatic change affecting the pattern of rainfall as suggested by Kendrick (1977) on the basis of the Guildford shell deposits; or of course a combination of these.

5. There is as yet little evidence from the fossil fauna as to the history of the estuaries since 4000BP and changes experienced must have proceeded at different rates in the various systems in order to produce the different estuarine types we see today with their restricted tidal exchange, often extreme range of salinity, and very low faunal diversity. These changes would, we suggest, have been caused by the geomorphic processes discussed by Hesp, principally those affecting exchange with the ocean and in consequence the energy in the systems: the development of tidal deltas and growth of the bars. Infilling and shallowing of the estuarine basins with sediment to the point at which annual evaporation is as great as or greater than the depth of water in them also tends to produce stressful hydrological conditions.

MAN'S IMPACT ON THE ESTUARINE ENVIRONMENT

It is these late Holocene changes, physical and biological, which are most important in the context of man's activities and the effect they may have on the estuarine ecosystems. The estuaries are a valuable natural heritage which can be maintained as healthy ecosystems that will be used and enjoyed for many years to come or they can thoughtlessly be destroyed through ignorance of the processes involved in their maintenance, as has happened to many in other parts of the world.

The geomorphic processes which have shaped them are still active today and can be reversed or accelerated, intentionally and in an informed manner or inadvertently through lack of understanding of their nature and the effects they produce on the integrity of the ecosystems.

As an example, construction of Fremantle Harbour in the 1890s, and removal of the old Fremantle railway bridge in 1968-69, have increased tidal exchange between the Swan estuary and the ocean, presumably resulting in a less extreme salinity range than when the mouth was obstructed by a rock bar and a massive tidal delta, and has also facilitated discharge of flood water. On the other hand the Irwin River (near Geraldton) estuary has ceased to exist, having been filled with sand as the result of clearing in the catchment.

Changes of a less spectacular character can also have an impact on estuarine ecosystems, the long-term effects of which are difficult to predict. Recently a number of euryhaline mollusc species not recorded in Holocene fossil assemblages have appeared and become abundant in our estuaries. Examples include the bivalve *Spisula trigonella* which was first observed as recently as 1964 and now forms a large part of the molluscan biomass in many estuaries of the south west. The edible mussel *Mytilus edulis planulatus* and the snail *Velacumantus australis* appear also to be newcomers with large populations in some estuaries. All three are common in eastern Australia from where, one suspects, they have come possibly by natural processes but more probably imported by man. Their introduction has radically altered the composition of the molluscan fauna of several estuaries.

The deliberate introduction of the marsh grass *Spartina* to Victoria (Bird & Boston, 1968) and Tasmania (Phillips, 1975) has the potential to produce great changes both to the geomorphology and the ecology of estuaries, as in fact it has already done in Anderson Inlet in eastern Victoria. The wisdom of such introductions needs to be carefully examined in view of experience elsewhere. For example, Hedgepeth (1978) speaks of *Spartina* "crowding out the native salt marsh vegetation" when introduced to Oregon estuaries.

In conclusion, we suggest that it is important to continue and extend study of the Holocene shell deposits, especially those of south coast estuaries, in conjunction with studies of the biology of molluscs such as *Katelysia* which characterise the present ecosystems and the ecology of the communities to which they belong, as well as the geomorphological processes at work. This is not merely an academic exercise, but one which is essential for interpreting the Holocene history of the estuaries and hence also as the basis for rational management decisions in the situation where the estuaries are under increasing pressure.

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PLANT BIOMASS AND PRODUCTIVITY IN SOUTH-WESTERN AUSTRALIAN ESTUARIES

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Abstract

The main types of vegetation in southwestern Australian estuaries are fringing marshes (characterised by the prominence of *Juncus* and *Sarcocornia*, and the absence of the otherwise cosmopolitan *Phragmites* and *Spartina*), the benthic macrophytes (angiosperms, especially *Ruppia* and *Halophila*, and macroalgae), and microscopic plants (on the sediments and as phytoplankton). Using limited local and relevant overseas data, it is shown that the fringing marsh typically contains most of the plant biomass and nutrients, and microscopic plants the least. Nevertheless microscopic plants account for a disproportionately high fraction of total estuarine productivity. Although more data are needed, it appears that the marsh contributes little productivity to the open water, but provides a buffer which traps and recycles nutrients. Seagrasses and microscopic plants are grazed and contribute detritus to food chains; seagrasses also provide an important habitat for other organisms.

Man's activities often reduce marsh area and, through catchment alteration, increase nutrient loading. High nutrient levels may lead to unacceptable increases in plant biomass in the open water, especially phytoplankton and macroalgae.

Plants power the biological wheels of estuaries. They do this by trapping energy and elements such as carbon, nitrogen and phosphorus, converting them to organic compounds; these support various food webs which include, fish, birds and man.

In this paper I would like to direct your attention to the production of this plant organic material within the estuary itself, the 'autochthonous' sources. Some organic materials enter estuaries when rivers flow, providing an external or 'allochthonous' source. However, our rivers flow for a short period each year, and when they do flow much of the material which they contain may be transported to the ocean. One suspects therefore that their contribution is relatively small when compared to that of the prolific plant life of estuaries, though there are a few data available. In Port Hacking in New South Wales it has been estimated that the catchment provides an amount of dissolved organic carbon equivalent to about 15% of the amount of organic carbon produced by plants in the water body (Cuff et al., 1980).

The amount of plant material present, the 'biomass' or 'standing crop', is clearly important. This tells us the size of the power plant which constructs the organic material; this is what the grazer consumes; and aesthetically, this is what strikes the eye. In this paper we will express the biomass as grams of dried plant material per square metre, though for other purposes it may be important to use other measurements, such as amount of carbon, energy, nitrogen or phosphorus contained per square metre.

The term 'primary productivity' is also important. This is the rate of increase of organic material. The units we will use for comparative purposes are grams (dry weight) of plant material per square metre per year. Strictly speaking this is 'net primary productivity', since losses of organic material incurred by the respiration of the plants themselves have been taken into account. For other purposes it may be important to express productivity as, for example, rate of carbon fixation or energy incorporation.

In the following paper I will review the main kinds of plants which occur in our southwestern estuaries, and assess their general levels of biomass and productivity, in some cases using data available for southwestern Australia, and in others information derived from the literature. Attention will be directed to the fringing marshes, to the benthic macrophytes (larger algae and seagrasses) and to microscopic plants in the water column and on the sediment surface.

Major Plant Formations

1. Fringing marshes

The most characteristic species in the marshes of southwestern Australia is the rush, *Juncus kraussii*, a widely distributed species, closely related to other rushes throughout the world. It builds up dense stands which may cover large areas, and which may be invaded by swamp paper bark trees of the genus *Melaleuca*.

It is worth mentioning the absence from southwestern estuaries of two notable, otherwise cosmopolitan genera. The first is *Spartina*, a genus of marsh grasses widely distributed in the world, very prominent in the United Kingdom and America, and introduced to the eastern states of Australia. *Spartina* invades further into the water than does the *Juncus* which fringes our marshes.

The other notable absence is the reed *Phragmites*, a genus of stout grasses, usually regarded as cosmopolitan. *Phragmites* occurs naturally in the eastern states of Australia, and has been collected as an introduced plant near Albany in Western Australia. There is also a species of more restricted distribution in the north of the State.

Another characteristic group of marsh plants is the samphires, *Sarcocornia* and it's allies, dicotyledonous shrubs which are locally abundant in our marshes.

Table 1 presents biomass data for Juncus in the Blackwood River Estuary. The data are from a particularly dense stand of Juncus, and some 50% of the above ground material is living. Our results are comparable with those for marsh plants in other countries, such as Spartina in the United States (up to 1600 g m^{-2}; 1200 in the United Kingdom), and Juncus roemerianus in the United States (approximately 800). Baumea juncea, another monocotyledon prominent in the Blackwood River Estuary, has a biomass of approximately 1,000 g m^{-2} (Congdon and McComb 1980). Sarcocornia, the samphire, reaches a biomass of around 800 in the Blackwood River Estuary, and 2800 in the Peel Harvey System (Rose and McComb 1981). Bearing in mind that not all of the marsh has stands reaching these figures, for comparative purposes a biomass of 1,000 g m^{-2} has been chosen as typifying the fringing marsh.

2. Submerged macrophytes

In this group there are, firstly, the true flowering plants rooted in the sediments. There are several species, but two are particularly prominent - Halophila ovalis, a widely distributed true seagrass which is very common in our estuaries, for example in the Swan/Canning Estuary. Then there is Ruppia, a genus not usually placed among the true seagrasses as it does not occur in the open ocean, and as it produces flowers which are not totally submerged like those of the true seagrasses. Nevertheless it is convenient to include Ruppia here; for example, Ruppia megacarpa is very prominent in Wilson Inlet.

Larger algae (macroalgae) may occur anchored onto rocks, attached as epiphytes to seagrasses, or as loose-lying masses on the sediments. These macroalgae are typically oceanic species; 20 have been recorded for the Blackwood River Estuary (Congdon and McComb 1981), and 65 in the Swan/Canning Estuary (Allender 1981). Although locally the biomass of macroalgae may be relatively high, in most of our estuaries their distribution is restricted; an exception in Peel Inlet, where marked eutrophication has occurred.

Some biomass figures for these plants are given in Table 2. The figure for Ruppia megacarpa in Wilson Inlet is particularly high; elsewhere in the Inlet the biomass of Ruppia, where it does occur, is 400 g m^{-2} or less. A large bed of the alga Cladophora may reach 1000 g m^{-2} in restricted areas in the Peel/Harvey system, but the levels are usually well below 50. It should also be emphasised that beds of seagrasses are typically patchy, especially in deeper water where biomass falls steeply. For comparative purposes, a figure for above-ground biomass of 50 g m^{-2} has been selected for further calculations.

3. Microscopic plants

The most prominent of these is the phytoplankton, microscopic plant cells or colonies suspended in the water column. The most commonly encountered of these are diatoms, with blue-greens occasionally forming dense, undesirable blooms. Other microscopic plants such as diatoms and various flagellates occur on the sediment surface.

Table 1. Examples of the biomass of prominent plants in south-western Australian estuaries[1]

Component	Biomass ($g\ m^{-2}$)		
	Juncus kraussii[2]	Halophila ovalis[3]	Ruppia megacarpa[4]
Above ground live	1400	70	2152
Above ground dead	1400		
Below ground	2400	50	37
Total	5200	120	2189

[1]Each example is from a dense, uniform plant stand.
[2]Blackwood River Estuary, Congdon and McComb (1980)
[3]Swan River Estuary, K. Hillman, pers. comm.
[4]Wilson Inlet, R.J. Lukatelich, pers. comm.

Table 2. Estimates of the biomass of phytoplankton[1]

Chlorophyll concentration ($\mu g\ l^{-1}$)	Biomass (dry weight: $g\ m^{-2}$)
2	0.2
8	0.8
100	10.0

[1]Assumes water depth of 2 m, and dry wt:chlorophyll ratio of 50:1 (Whittle, 1977).

The biomass of phytoplankton is usually measured as concentration in the water of the photosynthetic pigment, chlorophyll *a*, and the levels of chlorophyll fluctuate greatly in time and space, as the phytoplankton may grow rapidly and be transported about in the water. Nevertheless it is useful to derive figures which we can compare on the same basis with the other plants we have discussed. If we assume a water depth of 2 m, and a ratio of dry weight to chlorophyll of 50/1 calculated from the literature, we can see that the amount of biomass represented by different levels of chlorophyll is in fact very low (Table 2). Even enormous blooms of blue-greens, which may transiently reach 1000 $\mu g\ l^{-1}$ in restricted areas, for example in small patches in the Harvey Estuary at the height of an early summer bloom, the dry weight would reach only a 100 g m^{-2}. The yearly average for the Swan River is 8 $\mu g\ l^{-1}$ (Hillman, K. pers. comm.) It seems appropriate to use a figure of 1g m^{-2}, for comparative purposes, and assume this includes both benthic microalgae and phytoplankton, noting that in shallow water the benthic contribution becomes larger, and that of the phytoplankton less, because of the changing water depth.

Comparison of biomass

Table 3 presents a comparison of the standing crops of the three major groups of plants described above, and it is easy to see where maximum above-ground biomass will always be found when expressed per unit area. Of course the total amount of plant material in an estuary will depend on the areas occupied by these different communities.

Table 3. The biomass and productivities of estuarine plant components[1]

	Standing crop ($g\ m^{-2}$)	Productivity ($g\ m^{-2}\ yr^{-1}$)
Fringing marsh	1000	800
Submerged macrophytes	50	500
Microscopic plants	1	500

[1] Data are expressed per unit area of typical examples of plant communities, based on the assumptions in the text.

The Areas Occupied by Different Plant Formations

Woodwell et al. (1973) worked out for the United States the ratio between the total area of estuaries (leaving aside Chesapeake Bay) and the total length of coast line, and applied the ratio to other countries, so deriving a figure for the worlds estuaries. The estimate does not pretend to be accurate - for example Australia has 9.7% of the world's coastline, but no doubt very much less than about 10% of the world's estuarine areas (see Lenanton, this volume). However of particular interest here is the ratio between open water and fringing marsh, which is 77% and 23% respectively. Table 4 compares some data for estuaries in southwestern Australia; it

Table 4. Estimations of areas of marsh, open water and seagrasses.

(a) Estuarine areas

Estuary	Open water (km^2)	Marsh (km^2)	Total (km^2)	% Distribution Water	Marsh
World[1]	943,300	278,700	1,222,000	77	23
Blackwood[2]	10.2	6.0	16.2	63	37
Peel/Harvey[3]	115	13	128	90	10

[1]Woodwell *et al*. (1973)
[2]Congdon and McComb (1981)
[3]Rose and McComb (1981)

(b) Area of open water with seagrasses

Estuary	Seagrass	Area of open water with seagrass (%)
Harvey	*Halophila*	5
Swan[4]	*Halophila*	20
Blackwood[5]	*Ruppia*	42
Peel Inlet[6]	*Ruppia* and *Halophila*	50

[4]K. Hillman, pers. comm.
[5]Congdon and McComb (1979)
[6]Carstairs *et al*. (1979)

seems reasonable to use the 77/23 ratio in the absence of further information, for a generalized calculation. The proportion of fringing marsh will presumably be less as one moves further away from the southwestern, high rainfall region of the state.

An approximation is also needed for the area of open water which carries benthic macrophytes. Relevant data are also included in Table 4, and the figure of 30% is used for subsequent estimations.

The data summarized in Table 5 were obtained by calculating the generalized biomass figures on a proportional basis. It is quite clear where, on average, most plant biomass is located. Because of the relationship between dry weight and nutrients such as N and P, it is also clear that it is the fringing marshes which typically contain the greatest plant reserves of these elements.

Productivity of Plant Communities

We now have some feel for the amounts of plant material which produce organic matter, but this does not tell us how efficiently the plants work. In the *Juncus kraussii* marshes of the Blackwood River Estuary, a dense stand will lock up some 1300g m^{-2} yr^{-1} (Congdon and McComb, 1980). This rate is comparable with moderately productive *Spartina* marshes in the United States and other regions of the world. Of course the density of the *Juncus* marsh varies from one part of a marsh to another, and in some areas where *Juncus* is thin and productivity low, the swamp paper bark *Malaleuca* was found to be dropping some 430 g m^{-2} of dry leaf material each year (Congdon, 1979). There is of course additional productivity which goes into woody material in these trees. As we have seen there are other kinds of marsh plants. *Baumea* has a similar biomass to *Juncus*, and probably a similar productivity. The samphire (*Sarcocornia*), according to some overseas data, has a productivity probably comparable to that of *Spartina* (Christie, 1981). Overall, I suggest a reasonable average productivity for the marshes would be round 800 g m^{-2} yr^{-1}.

For benthic macrophytes, *Ruppia* was found to produce up to 500g m^{-2} yr^{-1} (Congdon and McComb, 1979); while *Hapophila* in the shallows of the Swan is remarkably productive, producing up to 1800g m^{-2} yr^{-1} (Hillman, K., per. comm.). As a general figure, therefore, 500 would seem appropriate.

Is is even more difficult to estimate an average productivity for the microscopic algae (phytoplankton and benthic microscopic plants), because of the technical difficulties in making the appropriate observations, and the paucity of relevant information. However, perusal of appropriate papers (*eg* Axelrad et al., 1981; Cuff et al., 1980; Fisher et al., 1982; Newell and Field, 1983; Pomeroy et al., 1981; Whittle, 1977; Woodwell et al., 1973) suggests that about 500 g m^{-2} yr^{-1} would not be an unreasonable estimate.

These data are summarized in Table 3 on a unit area basis, and then transferred to a generalized estuary in Table 5. some more specific information is given for two estuaries in Table 6. It is clear that although the maximum biomass is often found in the fringing marsh, the benthic and planktonic microscopic algae have a productivity which is disproportionately high compared to their low biomass. This is, of course, because of

Table 5. The proportions of estuarine biomass and productivity contributed by different plant components in a hypothetical estuary[1]

	Area occupied	Biomass (%)	Productivity (%)
Fringing marsh	23% of whole	94.9	27
Submerged macrophytes	30% of open water	4.8	17
Microscopic plants	77% of whole	0.3	56

[1]The assumptions are as given in Tables 3 and 4. For marsh and submerged macrophytes, only above-ground biomass and productivity are presented.

Table 6. Proportions of estuarine productivity contributed by different plant components in particular estuaries.

Component	Proportion (%)	
	Blackwood River Estuary	Swan River Estuary
Fringing marsh	40[1]	-
Submerged macrophytes	18[2]	30[3]
Microscopic plants	42[3]	70[4]

[1]Derived from Congdon and McComb (1980)

[2]Congdon and McComb (1981)

[3]K. Hillman (unpublished)

[4]Estimate only, based on assumptions in text

the high 'turnover' rate of these small plants, the populations of which expand rapidly, but are continually depleted by sinking and decay, and grazing by small animals.

The Fate of Organic Material

So far we have considered the size of the organic machines and how rapidly they work, but we now must address briefly the question of what happens to their products.

The fringing marsh grows and decays rapidly, but does not extend rapidly into the open water. The marsh provides an enormous buffer between the landscape and the water, trapping and recycling nutrients. Much has been written about the importance of productive fringing marshes to the ecology of open water, but the situation is far from universally clear. In *Spartina* marshes the plants grow within the water, into which they collapse and decay, and even the higher marshes are regularly inundated by the tide. Our *Juncus* marsh, on the contrary, is rarely inundated because of the small tidal range in our southern estuaries, and so most decay occurs *in situ*, within the marsh. What flooding of the marsh does occur tends to be in winter, when river transport tends to remove material out of the estuary. Occasionally one does see wracks of *Juncus* material deposited in the marsh, but this is unusual. Further, despite its quite high productivity, very little grazing occurs of the *Juncus* marsh. Overall one cannot visualize much of the productivity of the marshes being in fact contributed to the open water, although I would be the first to say that more data are needed.

Phytoplankton may be grazed by small animals (zooplankton), which may in turn be eaten by other animals, and so on, forming a food chain. The diatoms appear to be readily grazed, the blue-greens less so.

Seagrasses growing in shallows are grazed extensively by weed eating birds, which may take large amounts of *Ruppia* and *Halophila*. For example in a small lagoon in the Blackwood River Estuary, it was estimated that more than 20% of the maximum standing crop of *Ruppia* was probably taken by swans (Congdon and McComb, 1979). Even so, relatively little of the biomass appears to be well digested, much of the consumed material returning to decay in the water. Seagrasses are grazed by certain fish, but the extent of grazing is probably not large. In Port Hacking, Kirkman and Reid (1979) estimated that about 3% of the carbon assimilated by seagrasses was removed by fish.

However, direct grazing is only part of the story, as the 'detrital' pathway is of great importance. The detritus in the estuary derives from sedimenting phytoplankton, from animal material (especially faecal pellets), senescing seagrass and perhaps marsh material. Particles of this decomposing matter, rich in microorganisms, are consumed by a variety of animals, so supporting food chains.

Seagrasses not only provide rapidly-decomposing packages of nutrient-rich material, they are an important habitat for a diversity of other plants and animals, including juvenile fish.

Ultimately, the carbon trapped by the plants is lost in the respiratory activity of microorganisms and animals in the food chains, lost to the oceans, or in trivial part incorporated into the sediments. On average, the amount of organic material produced in the estuary each year is balanced by these processes.

Factors Affecting the Amount of Plant Biomass

The extent of the marshes is primarily a result of geological accident - the interplay between sediment deposition, plant growth and water movement. A common activity of man is to 'reclaim' the marshes - for real estate, boat harbours, roads, and so on; so removing in some cases a sizeable proportion of the total biomass and productivity of an estuary. If we are correct in suggesting that most of the organic material formed in the marshes is recycled there, this loss in productivity may not greatly affect the ecological functioning of the open water. However, we have noted that marshes are a nutrient buffer between landscape and water, and it would seem that there is room for a more quantitative study of the transfer of nutrients and organic material through our marshes to the open water beyond.

Turning to the benthic macrophytes, we can immediately conclude that light penetration is of critical importance to determining the lower limits at which these plants can survive, and also in controlling their productivity (McComb et al., 1981). In the clear oceanic waters off Cape Naturaliste, seagrasses will grow down to 45 m or so. In the turbid waters of an estuary, survival may be limited to less than 2 m. Any factor which reduces the light available to seagrasses will inevitably affect their contribution to estuarine productivity. Fig 1 shows the growth of Ruppia in the Blackwood River estuary, where the dependence of growth on water turbidity is clearly implied; an increase in the turbidity of the water would bring about a reduction in productivity. The importance of light for growth of seagrass is also emphasised by the work of Bulthuis (1983). You will appreciate that deepening water by dredging may also preclude seagrasses.

Fig 2 shows an example of the seasonal growth rate of the alga Cladophora, also controlled very largely by light availability. Even a short distance below the surface of a bed of this alga, there is a significant reduction in growth because of self-shading. Where a bed of algae is 10 cm or so deep, clearly light is of critical importance to production.

If things were this simple - if light were the only critical controlling factor for benthic macrophyte growth and hence plant biomass - we might expect that the addition of nutrients to water would be essentially without effect on the amount of this plant material. It is a difficult matter to experimentally add fertilizers to estuaries, but it happens that man's activities have inadvertently provided some valuable 'experimental' information. In the Peel Inlet massive accumulations of plant material have occurred, washing onto beaches which had, until the mid 1960's, been generally sandy and subject to only occasional depositions of seagrass material. The quite unacceptable accumulations of macroalgae have been attributed to the increased use of phosphatic fertilizers in the catchments (Hodgkin et al., 1980; McComb, 1982). Although in general the productivity of the algae may be limited by light in the estuary, the addition of nutrients has allowed the accumulation of very large biomasses of these plants.

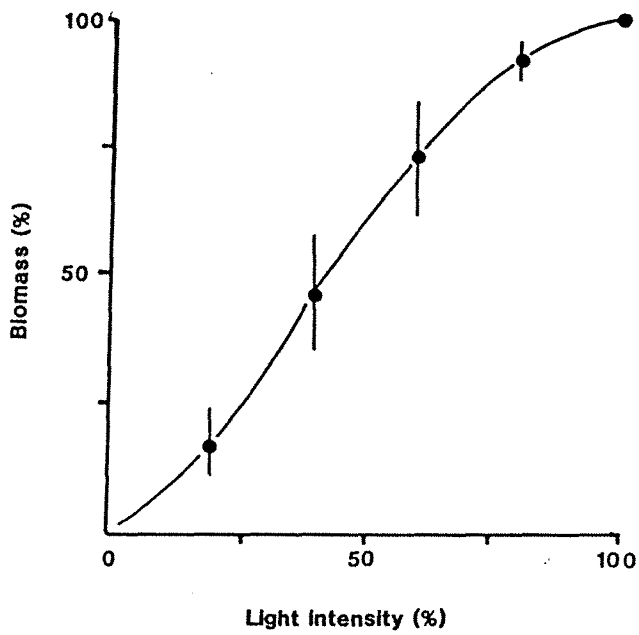

Figure 1. The percentage biomass of Ruppia produced at different levels of light. Full sunlight = 100%. Data were obtained in the field using shadecloth; vertical bars indicate standard errors. Redrawn from Congdon and McComb (1979).

Algal accumulations will cover and eliminate seagrasses in estuaries, but there is an even more subtle interation between seagrasses and algae - the algae which grow as epiphytes on the surfaces of seagrass leaves can so shade those leaves that seagrass photosynthesis is significantly reduced, and survival of the seagrass is placed in jeopardy. In the marine embayment Cockburn Sound, the additional growth in epiphytes of nutrient-enriched waters has resulted in the elimination of large areas of seagrass (Cambridge, 1979).

And what of phytoplankton? These respond particularly rapidly to increases in nutrient levels in the water, the nutrients being derived from rivers entering the system, or by recycling of nutrients from the floor of the estuary. Artificial nutrient enrichment, especially with phosphorus, leads to very high levels of phytoplankton such as the massive bloom of the blue-green Nodularia which occur in early summer in the Harvey Estuary. In Fig. 3, the magnitude of the Nodularia bloom is plotted against the amount of phosphorus brought down by the river in the previous winter, in each case some two-three months before the bloom actually occurred.

It should be emphasised that the effect of man in increasing plant biomass in both Peel Inlet and Harvey Estuary has not been directly exercised on the estuary itself, but on the catchments of the rivers which drain into the estuary; and the primary effect of man has not been so much to remove

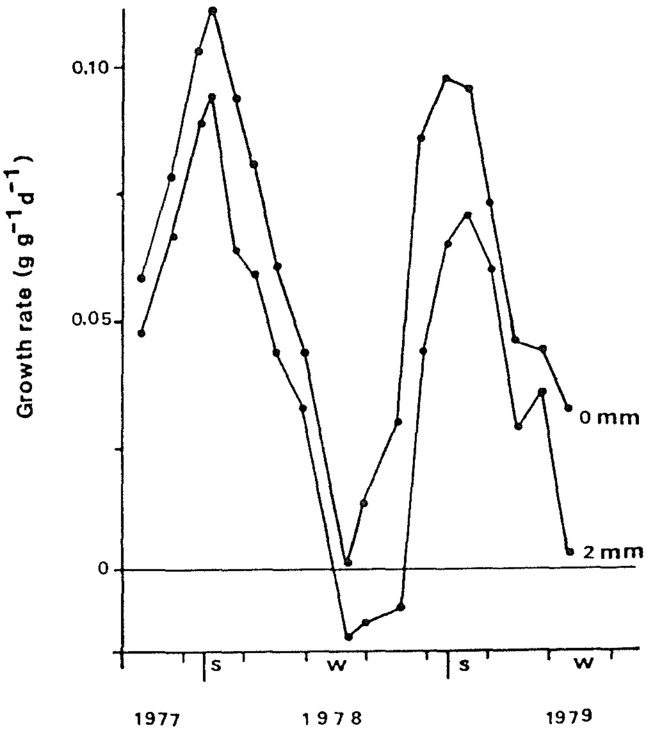

Figure 2. Effect of environmental factors on the growth of Cladophora. Simulated responses using laboratory responses of photosynthesis and growth rates to light, nutrients, temperature and salinity, and field measurements of these environmental factors. The curves are for algal filaments at the surface of a submerged bed of algae, and 2 mm below the surface. Redrawn from Gordon et al. (1981).

primary producers from the ecosystem, but rather to cause the plants to build up to massive, unacceptable populations.

Conclusions

Although this paper has been based upon a limited amount of direct information about our estuaries, several important points can be made.

1. The fringing marsh typically contains most of the plant biomass of the estuary, and most of the nutrients contained by plant material.

2. Benthic macrophytes have a high biomass in shallow water; have high productivities in shallow water; and are reduced by reduced light intensity.

   Macroalgae build up to large populations when nutrients are available. Seagrasses are inhibited by macroalgal growth and growth of epiphytes, which are favoured in the presence of high water nutrients.

3. Microscopic algae have a trival biomass compared to the other estuarine plant components; have a high productivity; and are favoured by high water nutrients.

4. More information is needed about the contributions of phytoplankton and benthic microscopic algae to estuarine productivity, and about the interactions between marsh and the open water.

5. Care must be exercised in any alterations to catchments, which may increase the amount of nutrients reaching an estuary.

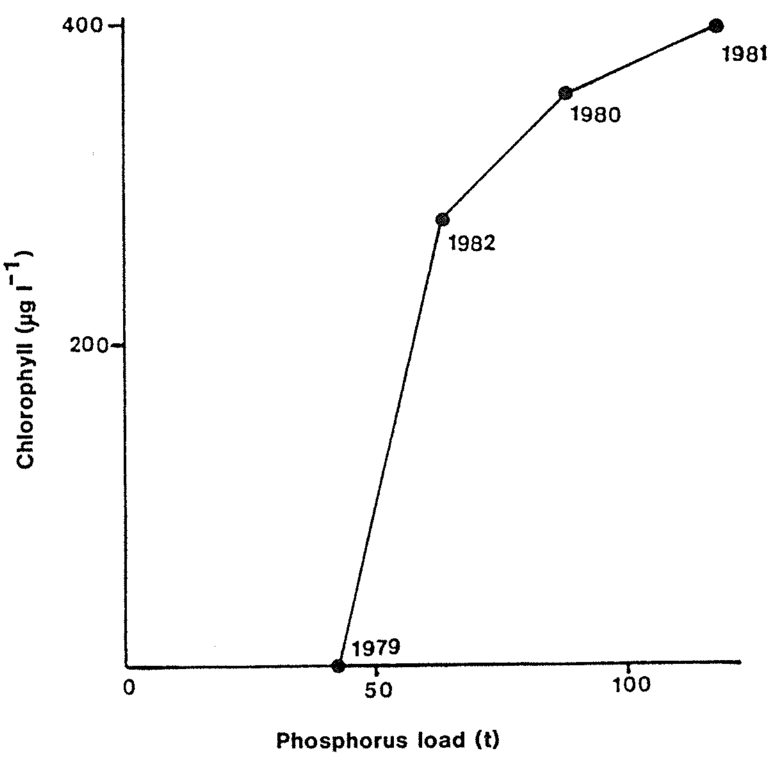

Figure 3. The relationship between peak chlorophyll a concentrations of Nodularia blooms in Harvey Estuary, and the amount of phosphorus brought into the estuary by the Harvey River. River flow is highly seasonal, and peak Nodularia blooms are reached 2-3 months after peak river loading. Unpublished data of R.J. Lukatelich (University of Western Australia) and P.B. Birch (Department of Conservation and Environment).

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AUSTRALIAN ESTUARIES AND THEIR DEPENDENT BIOTA AS SEEN FROM THE EAST COAST

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Abstract

Our estuaries are squeezed between the rivers and the sea, and between advancing river sediment and wandering coastal sand; they are also surrounded by man. Their nature is determined by the extent and pattern of river flow, tidal action and bathymetry. Mans activity is then superimposed. Within these constraints certain animals continue to live.

Man's impact is inevitable so we must decide, and apply present and future knowledge to engineer a satisfactory solution for each estuary.

The Estuary

An estuary is no sooner formed between a river and the sea than the processes of sedimentation start to fill it up. Eroded river sediment is washed steadily seaward and migrating coastal sand moves upstream forming a tidal delta. Fine muds accumulate either in the deeper mid-estuary or in the correspondingly quiet water below 60 metres on the continental shelf. The progressive bathymetric changes so produced alter both the water characteristics, and the biology of the estuary. Its nature is further governed by the extent of tidal exchange, and above all, by the extent and pattern of river flow.

The water may be deep or shallow, open to the sea or temporarily closed, subject to tidal flow or not; it may be mixed or layered, more or less saline than the sea, subject to summer rain or winter rain or, like New South Wales, it may have no reliable seasonal pattern, but be subject to variation by years. Any one estuary can vary its properties with time or at different places along its length.

Consensus between East and West Australia can only be achieved if an expanded practical estuary definition is adopted:-

"It usually lies between a river and the sea, but it may sometimes by isolated from the sea, and it may also become more saline than the sea. It is potentially tidal."

Biota

A biota is on hand to cope with whatever environmental extremes the climate dictates. It is less diverse than that of the ocean.

·Migrants

Most prawns and commercial fishes take the precaution of breeding at sea and returning to use the estuary as a nursery though one prawn, Metapenaeus bennettae can breed without going to sea, and hence persists when lagoons are cut off from the sea for protracted periods. Recent work indicates that the larval fishes recruit to the estuaries from a very narrow onshore band less than 50 metres deep.

Australian fresh-water fishes are mostly of recent marine origin and marine dependence is still present in the requirement of many of them to go either to sea like eels or at least to the head of the estuary to breed.

Beside the fish and prawns, wading birds are conspicuous among estuarine migrants. These are totally dependent on coastal shallows for food during their wide-ranging and internationally sanctioned migrations. Estuaries are indeed habitats or passages to a wide range of species.

·Seagrasses

The most conspicuous estuarine plants are the sea grasses, Zostera and Ruppia, with the deeper Posidonia being important in the clearer waters of the tidal deltas. The rise and fall of Zostera populations is inadequately understood for lack of reliable records, but there are indications that the extent of its colonisation has been considerably reduced in the Sydney area. In semi-enclosed lagoons Zostera and Ruppia exchange dominance over periods of several years in association with periods of dry and wet weather respectively.

·Notospisula

This small white clam which is an important fish food, is perhaps the most universal of Australian estuarine animals. Within wide ranges it is indifferent to temperature and salinity. While its dead shells are found everywhere it is often hard to find live specimens, but when they are found they are usually in very large numbers. This annual species relies on high fecundity and rapid growth for its survival and it is able to use offshore muds as a refuge. It may be a recent introduction to Western Australia as it is absent from the older sediments.

·Jellyfish

Coastal survey indicates that the abundance of the large common jellyfish Catostylus depends on bathymetry. It is abundant only in estuaries where there is a substantial volume of water which minimises the proportion of the population which is flushed out to sea.

·Ocean Mimics

In some senses deep estuarine basins mimic conditions in deeper water on the continental shelf so species like the worm, Maldane sarsi, are found in both habitats. While currents, sediment and light intensity may be similar at 10 and 100 metres in these respective situations, the ten metre estuary is also subject to periodic catastrophies when flooding lowers the salinity or so stratifies the water that the bottom deoxygenates.

·Mussels

In the eastern estuaries the mussels include the tough slow-growing "climax" species Trichomya hirsuta, the hairy mussel, which can tolerate deoxygenation for over a month, but is unable to tolerate low salinity, and the fast-growing, cold-water, "weed" species Mytilus edulis, the blue mussel which can tolerate less than half sea water, but is intolerant of deoxygenation. The upper estuary is dominated by the little brown mussel, a fast-growing annual species called Xenostrobus securis, which avoids full sea water but tolerates high turbidity and extremely low salinity.

·Oysters

The mangrove oyster Saccostrea commercialis uses the seaward half of the estuary. It develops extensively where there is a significant rise and fall of tide for its strength lies in its capacity to tolerate extreme exposure which is fatal to its competitors and predators. In seaward areas larval settlement is excessively successful leading to extreme crowding and slow growth. Adults are also vulnerable in these seaward areas to a disease known as "winter mortality" which regularly and severely reduces the population. In the middle estuary oyster settlement is sparse, growth is rapid and winter mortality is absent. Within these constraints the oyster farmer seeks to maximise his yield.

Constraints

The natural constraints of an estuary are too severe for all but a few species. The fact that man has elected to establish ports and cities round the sheltered waters of estuaries, has filled their watersheds with agricultural and pastoral development, and finally has made tourist resorts out of those estuaries which were not previously considered useful, has not helped the life of the estuarine biota. In some instances it has become severely constrained.

·Dams

Dams, weirs, road crossings and similar obstructions completely block many fresh-water fishes from the upstream habitat. They also cause downstream problems where freshwater is diverted, as in the Sydney region, passed through a city and returned to the river as treated sewage. Enrichment promotes phytoplankton growth at the expense of otherwise dominant sea grasses. Stabilisation of flow is also a disadvantage to species whose life cycles are dependent on episodic flooding. Australian bass need flooding to initiate the spawning run. Oysters can tolerate extreme flooding, but if a dam is managed to produce moderate flooding for a long period, the oysters will succumb to lowered salinity.

·Lethal Inputs

Addition of toxic or deoxygenating material or hot water can produce spectacular mass mortalities or chronic effects such as reduction in species numbers if not absolute numbers. It is worth noting in this context that although some polluted areas are highly modified they may also be highly productive. In Sydney, Cook's River can boast catastrophe, restricted fauna and extremely high production of a few species.

·Canals

Remote coastal land has become extremely desirable for tourist and holiday use as well as for city refugees in search of a retirement site. It has been possible to make large profits by buying very cheap coastal wetland and developing it into housing estates by a dredge and fill technique which gives each house its own canal frontage. Leaving aside the question of how much wetland should be converted, there is the spectre of long dead-end canals, without flushing or circulation, accumulating pollutants to such an extent that they become health hazards. Conservationists and planners have been troubled by these developments for some years.

Solutions

In the past solutions have been sought and found for these and other problems and in the future it will be essential to apply a great deal of effort towards their solution.

·Urban Development

While it is now possible to control major toxic discharges into finite water bodies, multiple minor inputs are a problem. The combined effects of surrounding a small lagoon like Lake Illawarra, N.S.W., with dense urban development will overpower the biota. Nature alone cannot cope and positive steps must be taken to intervene in the system. The public can be pleased if the malodourous black slop which ecologists call decomposing *Zostera* is separated from the beach by a navigable foreshore canal and a chain of small islands on which birds can be undisturbed by children and domestic pets. If a permanent entrance to the sea can be engineered general water quality can be assured.

·Ports

Where an estuary terminates in a large port like Botany Bay where toxic or dangerous materials are present, no amount of careful regulation will prevent accidents from happening. The waterway is always under threat. A solution in cases of this sort is to partition the estuary by isolating the port from the river which is then given a new mouth to the sea.

·Canals

Where these developments are sewered and inputs are restricted they can be healthy and full of marine life even without tidal flushing.

·Hot Water

Where estuarine water is used for industrial cooling such as cooling the condensers of steam driven power stations, very large volumes of warm water, some ten degrees above estuary temperature, are discharged. A common technique employed to lower the temperature is to dilute the discharge, but this implicates even more huge volumes of water. By contrast, New South Wales design discharges a shallow, half metre, layer of hot water which more rapidly exports heat to the atmosphere by radiation and evaporation. In this circumstance animals can avoid the heated layer by falling half a metre into water at ambient temperature. This peculiarity of local design has allowed large power stations in very small estuaries without significantly altering the local populations. Present investigations are considering the effects of raising the temperatures to thoroughly lethal levels, but implicating very much less water.

A Useful Concept

When one has to guess what will result from a given change to an estuary, or what is the current status of an estuary, the comparative approach is very useful. By this is meant the use of stored information about a diverse range of estuaries and their histories so that when a new estuary is under discussion it can instantly be compared with the range of "knowns", and an assessment can be made on its likely behaviour. By contrast, the most protracted and detailed study of one system in isolation can still leave one without predictive confidence.

The same approach is used when one looks at the local fauna and draws conclusions about the environment, or one places test organisms in a new environment to observe their responses. For example, if softwood blocks are not riddled with shipworm within two months of being placed in estuarine water of moderate salinity, the water is polluted beyond all reasonable doubt. If on the other hand scallops survive in the water it is of very good quality.

A Useless Concept

The virginity concept is widely used by the less thoughtful protestor, and it plagues much of ecological study and planning in estuaries. The only original condition of a system is that which prevailed at the time when a particular individual first observed the system. Massive changes have occurred in recent geological time, aboriginal man has introduced changes, agricultural and pastoral man has gone even further, and the grubby attitudes of city and industry, to say nothing of city refugees, have produced a number of very unattractive estuaries, but there was no original condition. We must take estuarine systems as we find them.

The Responsible Citizen

The citizen, and this includes those paid to be scientists, must observe the estuary as it is, decide how he wants it to be, and pay to have it so arranged.

This can mean anything from taking zero action, minimising public access and making it a national park, or deciding that it is overrun by man and needs help to the extent of excavating it, restructuring it and partitioning it for multiple urban use.

Once the citizen has made a decision, chosen a condition and provided public funds, engineering skill with some scientific help, using present and future knowledge can produce any desired result.

LIFE HISTORY STRATEGIES OF FISH IN SOME TEMPERATE AUSTRALIAN ESTUARIES

R.C.J. Lenanton *

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Abstract

Biological and physical data have been collected during various fish surveys and research projects conducted in the estuaries of temperate Western Australia over a relatively long period of time. The physical data have enabled the estuaries to be grouped according to the condition of their connection to the sea, i.e. permanently open, seasonally open, normally closed and permanently closed. The extent of this connection to a large degree dictates their hydrological status which, together with natural history data of fish species caught in these estuarine systems, promotes an understanding of the various strategies which the fish adopt in order to utilise these important environments. In regions of the coast where relatively large areas of estuarine environment are available. the resultant composition of the estuarine nekton enables substantial commercial and recreational fisheries to operate, as well as providing recruits to important fisheries in adjacent marine waters. However in regions of the coast where estuarine environments are not available, many of the species which are normally found in the estuaries utilise the inshore-marine environment as an alternative nursery area.

I INTRODUCTION

Estuaries provide abundant food and shelter which promote respectively fast growth rates and high rates of survival for a great many of the world's coastal fish species. Most numerous are those marine species which reproduce in the sea and are dependent on estuaries as nursery areas for their juvenile life history stages i.e. estuarine-dependent species (Cronin and Mausuiti 1971; Day et al. 1982; Chubb et al. 1981; Potter et al. 1983). Many of these estuarine-dependent species are of commercial and recreational importance. For example in the United States of America, 69% by weight of all the 1970 commercial landings consisted of estuarine-dependent species; while 62% by weight of the recreational fish catch (excluding invertebrates) was also of estuarine-dependent species (McHugh 1976). Similarly in the State of New South Wales, Australia, 66% by weight of the total commercial catch was composed of estuarine-dependent species (Pollard 1976, 1981) Although some selected estuarine and truly marine species do constitute important components of the fish fauna of some of the estuaries of temperate Western Australia, estuarine- dependent species dominate (Hodgkin and Lenanton 1981).

Between 15 and 20% of the State's annual fish catch is actually caught within the temperate estuaries (Figure 1. Australian Bureau of Statistics 1970-1982). However if the annual catch of

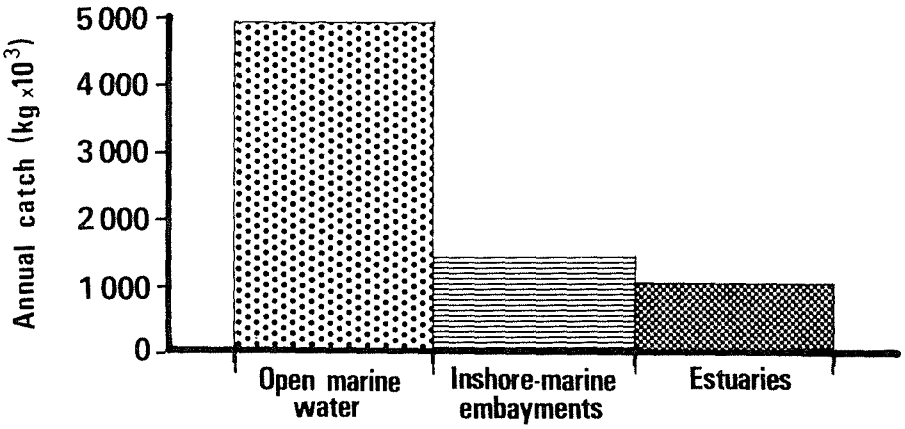

Figure 1. The source of commercial fish catches from temperate Western Australia.

each species is grouped according to the environment on which their juvenile stages depend, then approximately 70% by weight of these catches were composed of species, the juvenile stages of which were dependent on estuaries and inshore-marine embayments; 10% being of those species entirely dependent on estuaries, while the remaining 60% were of species dependent on both estuarine and marine embayment nursery areas (Figure 2). Thus, the composition of these catches is to a great extent a reflection of the composition of the available nekton, which in turn is governed by the ability of each nekton species to utilise a wide range of coastal habitats. In order to manage fisheries which exploit estuarine-dependent species, and more specifically to offer adequate protection to the nursery areas on which these species obviously depend, it is essential to have a thorough understanding of how these fish utilise the often extreme habitats encountered in the estuaries and inshore-marine environments of Western Australia.

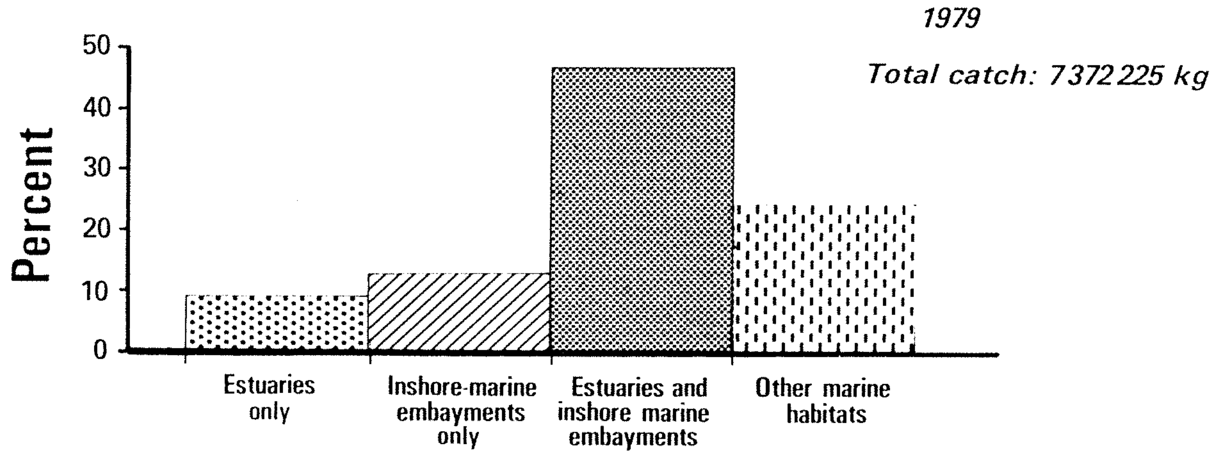

Figure 2. Commercial catches grouped according to environments on which the juvenile stages are dependent.

Using a long series of biological and physical records, an attempt has been made to describe how the more important estuarine-dependent commercial fish species utilise a wide and representative range of habitat types from coastal regions of Western Australia. These habitats include estuaries which are permanently open (Blackwood and Nornalup- Walpole), seasonally open (Broke and Wilson), and normally closed (Beaufort and Wellstead) (Hodgkin and Lenanton 1981) as well as coastal habitats from the central and lower west coast inshore-marine environments (Lenanton 1982; Lenanton et al. 1982) of temperate Western Australia.

II MATERIALS AND METHODS

1. General data acquisition

Historically, research staff at the Western Australian Marine Research Laboratories, have advised Government on matters relating to the management of estuarine fish and fisheries. This work has necessitated many field trips over many years, most of which have involved ad hoc sampling to determine the relative abundance and distribution of the fish fauna and the measurement of certain environmental characteristics of many of the State's temperate estuaries. All such biological and environmental records collected over the period 1971 to 1983 have been stored on a specially developed computerised data storage and retrieval system (Loneragan 1981). The results of some of these surveys undertaken during this period have been published (Lenanton 1974, 1977, 1982; Lenanton *et al*. 1982). However although many of the results remain unpublished, they are easily accessible and have been used extensively in this investigation.

2. Fish samples

Depending on the objective of the particular survey, and the type of habitat to be sampled, the appropriate unit of sampling equipment was chosen. Beach seines were used in shoreline habitats with haulable bottom topography. Gill nets were used both in deeper offshore habitats and shallow nearshore habitats with rough bottom topography. An otter trawl net was used to sample selected deeper areas. The beach seines varied in length from 41 to 210 m with areas swept ranging from 260 to 7000 m^2 respectively. All "bunts" or "pockets" were of standard design with a minimum mesh size of 9.5 mm, and the wings, which varied in length between two different nets were always constructed of 25.4 km stretched mesh. The mesh size of gill nets ranged from 38 mm to 102 mm. The otter trawl was 5 m long, with a 2.6 m mouth width, and wings constructed of 51 mm mesh. A more detailed description of the gear types used is presented by Lenanton (1974) (1977), Lenanton *et al*. (1982) and Potter *et al*. (1983).

The total length and weight of all fish caught was recorded to the nearest 1 mm and 0.1 g respectively. Gonads were sampled and weighed from representative samples of the most important species.

3. Environmental data

Environmental characteristics such as the date and time of sampling, surface and bottom salinity (‰), temperature (°C), dissolved oxygen (mg/l or % sat.), water depth (m), secchi depth (m), wind direction and strength, state of the tide and moon, and degree of cloud cover were recorded after the collection of each fish sample. However, only the surface and bottom salinity records from a single station in the lower estuary immediately upstream (<1 km) from the entrance channel to the ocean are referred to in this particular exercise. The surface area of both the estuaries and the 50 m wide shoreline strip of potential inshore-marine nursery area were determined from 1:250 000 Transverse Mercator Projection charts prepared by the Royal Australian Survey Corps of the Australian Military Forces with the aid of a Kolzunic compensating Planimeter (type KP-27). The lengths of shoreline were determined using a Minerva Opisometer.

Hydrological data collected from the Blackwood River estuary, Nornalup-Walpole estuary and Wilson Inlet over the period 1940-1945 were extracted from the CSIRO station lists (Spencer 1952).

The opening and closing times and duration of opening of all six estuaries being considered were simultaneously available only during the period 1964-1972.

III RESULTS AND DISCUSSION

1. Relative distribution of estuarine waters

Compared with other States of Australia, and other countries of the world, Western Australia has relatively few estuaries (Table 1). Most are located in the lower south-west corner of the State. In order to provide a worthwhile assessment of the fish nursery area role of these estuaries, an attempt has been made to determine the relative coastal distribution of the four habitat types.

REGION	SURFACE AREA (HA)	SOURCE OF INFORMATION
TEMPERATE W.A.	42,000	LENANTON (UNPUBLISHED)
GIPPSLAND LAKES (VIC)	37,500	BURDON (1973)
NATAL, SOUTH AFRICA	41,000	BEGG (1978)
U.S.A.	10,000,000	SAILA (1980)
MEXICO	1,500,000	YANEZ-ARANCIBIA (1981)

Table 1. The surface areas of estuarine waters from selected localities around the world.

Beginning at Cape Leeuwin, each of the west and south coasts were arbitrarily divided into 400 km zones. The combined surface areas of all permanently open, seasonally open, normally closed and permanently closed estuaries (Hodgkin and Lenanton 1981) in each of these zones was calculated and expressed as the surface area of habitat type per kilometre of coastline (Figure 3). It is clear from these data that the 400 km of coastline both immediately north and east of Cape Leeuwin contained the majority of permanently and seasonally open estuaries (44.2 ha of estuarine water per 1 km of coastline). However estuarine waters were much less numerous along the remaining temperate Western Australian coastline (4.4 ha of estuarine water per 1 km of coastline). The few estuaries located on the west coast north of the Swan-Avon estuary are mainly seasonally open. Virtually all estuaries east of Oyster Harbour on the south coast are either normally or permanently closed.

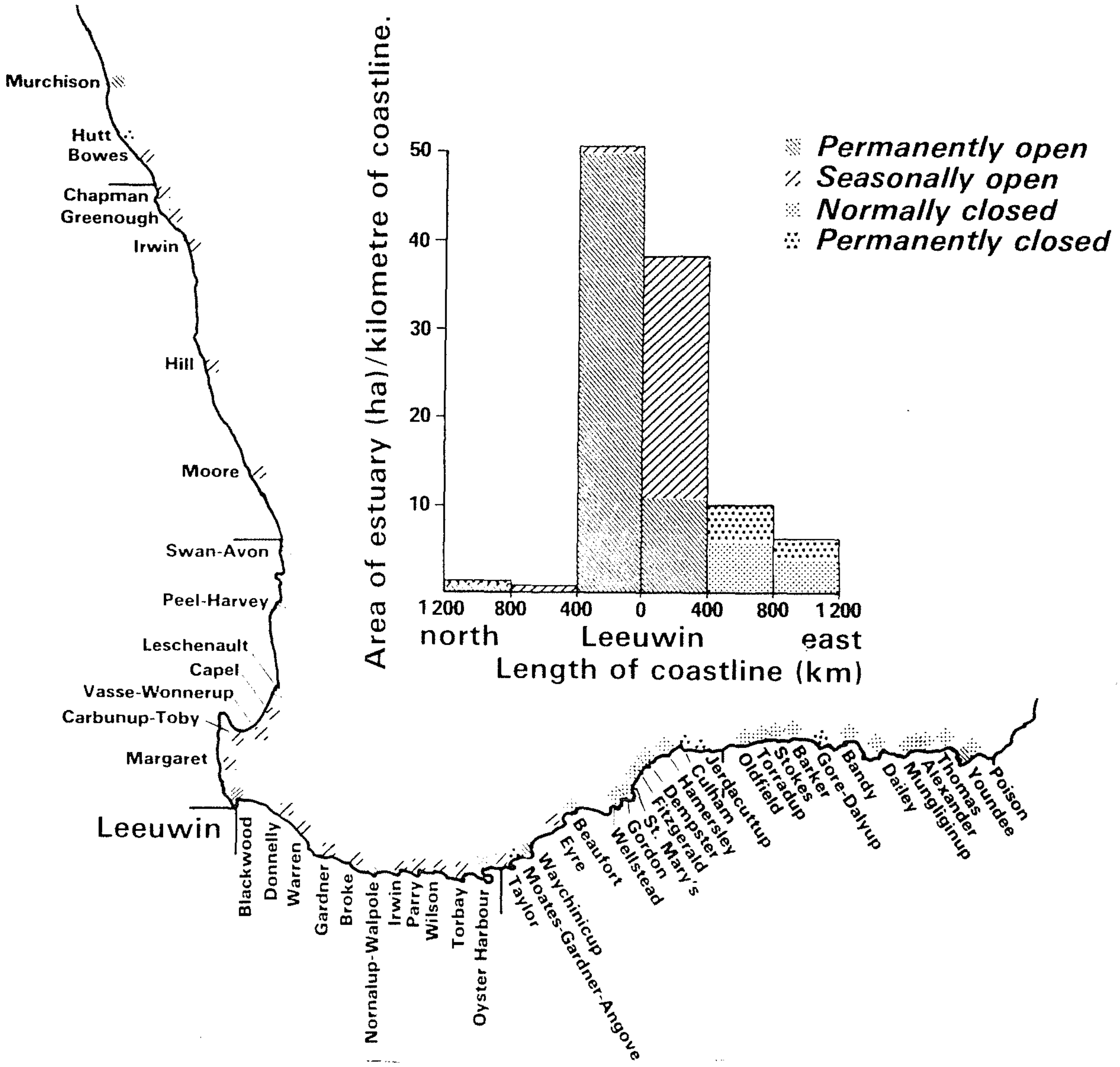

Figure 3. Estuaries of temperate Western Australia showing the surface area of estuary per kilometre of coastline of all permanently open, seasonally open, normally closed and permanently closed estuaries.

2. <u>Salinity regimes of representative habitats</u>

(a) The Estuarine Environment

Schematic representations of the salinity regimes in two permanently open (Blackwood and Nornalup-Walpole) estuaries and two seasonally open (Broke and Wilson) estuaries are given in Figure 4. Results from two normally closed (Beaufort and Wellstead) estuaries of the south coast are presented in Figure 5.

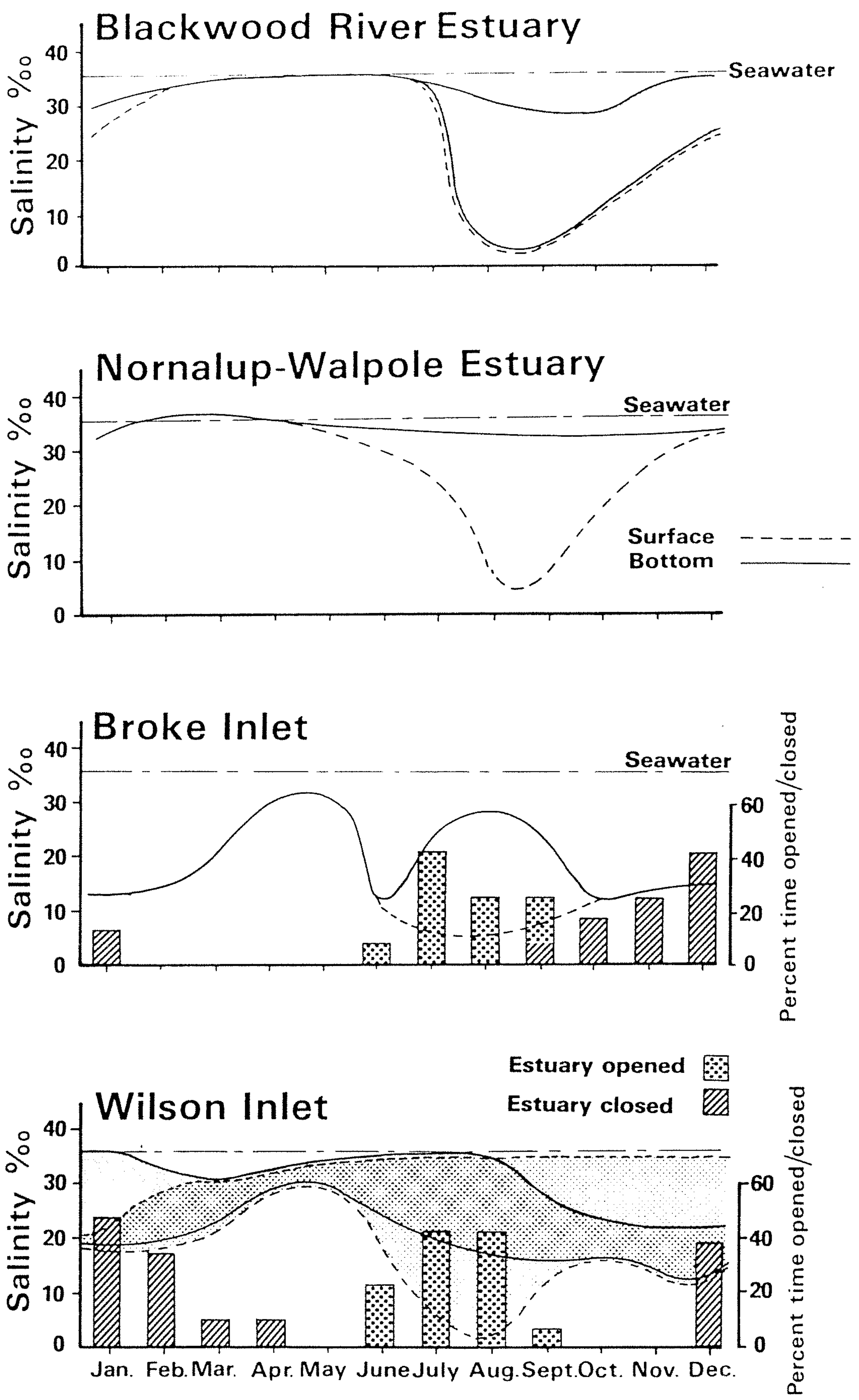

Figure 4. The hydrological status of two permanently open and seasonally open estuaries on the south coast of Western Australia. Showing over the 1964-72 period, the number times (expressed as a percentage) that both Broke and Wilson Inlet were opened or closed in a particular mont

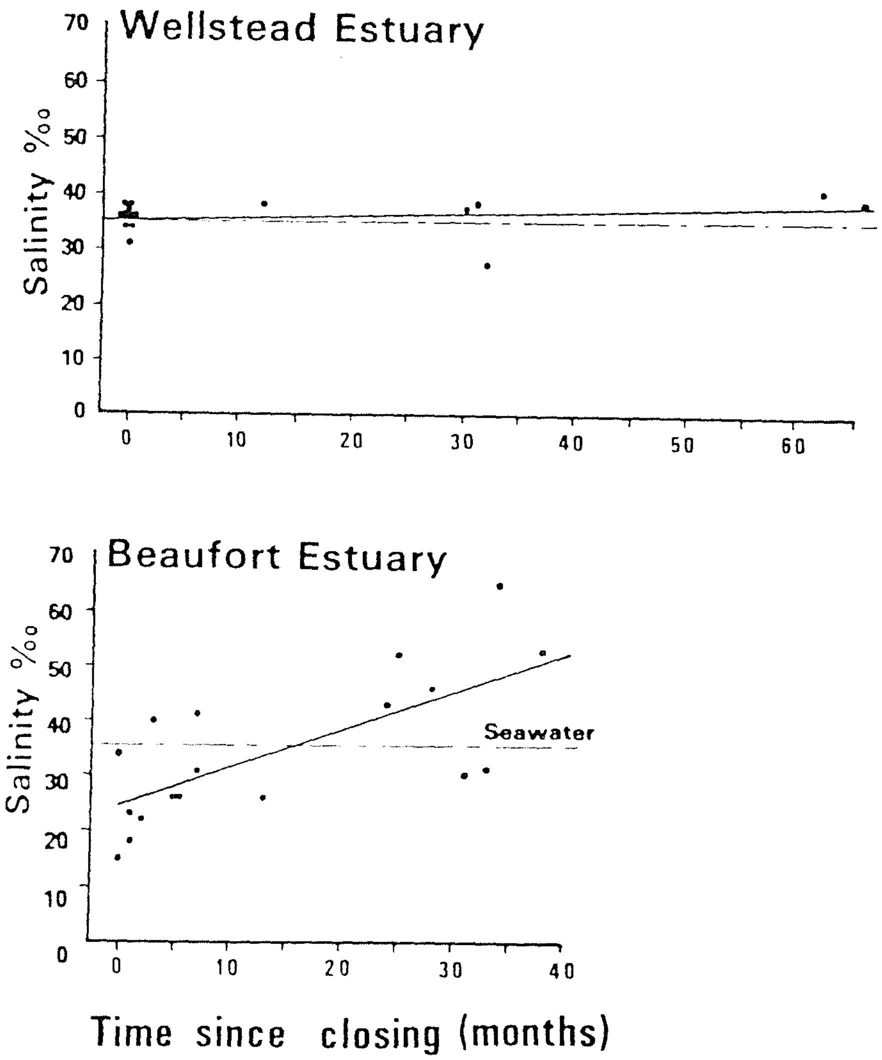

Figure 5. The hydrological status of two normally closed estuaries on the south coast of Western Australia.

Permanently open estuaries: The trends in surface salinity from both the Blackwood River and Nornalup-Walpole estuaries were similar. Both systems experienced a drop in surface salinity from approximately seawater strenth to almost fresh during the period of the winter freshwater flush. However, although bottom salinities of the Blackwood ranged between freshwater and seawater strength, those of Nornalup-Walpole remained at approximately seawater strength throughout the year. Thus although both systems were located in the western region of the south coast (Figure 3), and were both permanently open, they experienced very different winter salinity regimes. One of the reasons for this difference is that the Blackwood is a relatively narrow estuary with a potentially large riverine input, whereas Nornalup-Walpole is a larger estuary with potentially relatively less riverine input (Table 2). This means that during periods of heavy winter runoff the former is capable of being flushed top to bottom, a phenomenon which was never recorded in the Nornalup-Walpole system.

Seasonally open estuaries: Broke Inlet is a relatively large shallow estuary (Table 2) (much of the system is only 1-2 m deep) in which surface and bottom waters are usually well mixed (Figure 4). In late summer and autumn (March-April) when the entrance sand bar is closed, and when riverine input is at a minimum and evaporation rates are at their highest, surface and bottom salinities in the lower estuary tend to increase to almost seawater salinity. There is a marked reduction in salinity in May-June as a result of the first winter freshwater input. After the bar has broken, the lower estuary experiences a period of stratification, as a result of seawater moving into the estuary under the fresher surface water. By October-November when the estuary has either closed or is very near to closing, surface and bottom salinities are both once again about 15%.

ESTUARY		SURFACE AREA km^2	CATCHMENT AREA km^2
NAME	TYPE		
Blackwood	PO	9.0	23 000
Nornalup-Walpole	PO	12.6	6 500
Broke	SO	43.6	840
Wilson	SO	48.3	2 823
Beaufort	NC	4.8	4 775
Wellstead	NC	2.9	695

TABLE 2: THE SURFACE AREAS AND RIVERINE CATCHMENT AREAS OF REPRESENTATIVE PERMANENTLY OPEN (PO), SEASONALLY OPEN (SO) AND NORMALLY CLOSED (NC) ESTUARIES OF THE SOUTH COAST OF WESTERN AUSTRALIA.

Wilson Inlet is of similar surface area, but considerably deeper (mostly 5-6 m deep) and with a much larger catchment (Table 2). The lower estuary is more consistantly stratified than the comparable area of Broke Inlet (Figure 4). Both surface and bottom salinities vary over a much wider range. In general terms, the bottom salinities remain higher than those of Broke, while the minimum surface salinities are similar to those experienced in Broke Inlet. Both estuaries experienced their highest salinities during late autumn, while the lowest salinities occurred when the estuaries were open to the ocean during periods of intensive freshwater flushing.

Normally closed estuaries: Beaufort and Wellstead Inlets are both relatively small, shallow (1-2m in depth) estuaries (Table 2). Thus the surface and bottom waters are usually well mixed. In order to understand how prolonged closure affects the salinity of the lower estuary, surface salinity has been plotted against time since closure for the 10 year period covered by this survey. Two very different patterns emerged. With increasing time since closure, the salinities of lower Wellstead virtually did not increase above seawater salinity. By contrast, salinity of the lower Beaufort ranged from below to above seawater concentration with increasing time since closure (Figure 5). The Wellstead situation was unexpected and could possibly be the result of either frequent storm surge of marine water over the entrance bar, or a groundwater input of relatively fresh water into the lower estuary.

(b) The Inshore-Marine Environment

A comparison of the salinity regime of a number of inshore-marine habitats of south-Western Australia with salinities experienced in the lower Blackwood River estuary is presented in Figure 6. The surface and bottom waters of shallow shoreline marine habitats are always well mixed. At those sites which were located respectively near the entrance of the Blackwood River estuary (Flinders Bay) and the Carbunup River (E. Toby's Inlet) (Figure 3) there is evidence that winter riverine runoff depressed the normal seawater salinities (Figure 6). At sites away from the entrances to these systems, salinity was remarkably stable at around seawater concentration year-round. In contrast, the lower estuary sampling site in the Blackwood River estuary experienced winter salinities of 25‰ .

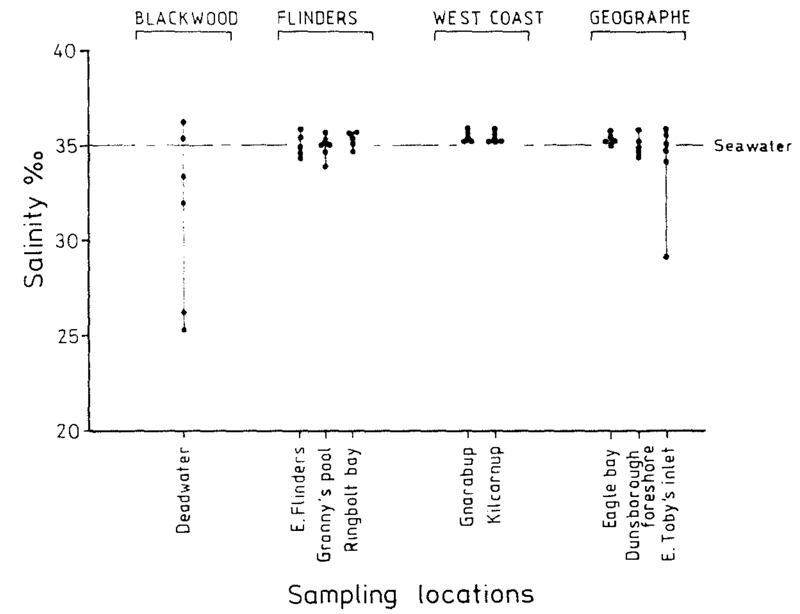

Figure 6. A comparison of the salinity regime of a number of inshore-marine habitats of south-Western Australia compared with salinity recorded in the lower Blackwood River estuary.

3. Utilisation of estuarine habitats by estuarine-dependent fish

(a) Permanently open estuaries

On the basis of the results of the research work of Lenanton (unpublished, 1977, 1978); Chubb et al (1979, 1981) and Potter et al. (1983), the various strategies fish adopt when utilising the permanently open estuaries of temperate Western Australia have been both summarised (Table 3), and represented schematically (Figure 7). The main contributors to the

ESTUARINE SPECIES

REPRODUCE AND LIVE WITHIN THE ESTUARY. (ADULTS OF SOME SPECIES DO MOVE TO THE SEA).

MARINE SPECIES

REPRODUCE IN THE SEA AND :

- USE ONLY THE ESTUARY AS A NURSERY AREA
- USE BOTH THE ESTUARY AND INSHORE-MARINE EMBAYMENTS AS A NURSERY AREA

REPRODUCE AND LIVE IN THE SEA (ADULTS OF SOME SPECIES DO ENTER ESTUARIES)

USE ONLY INSHORE-MARINE EMBAYMENTS AS A NURSERY AREA

USE OTHER MARINE ENVIRONMENTS AS A NURSERY AREA.

Table 3 Life history strategies of fish from the estuaries of temperate Western Australia.* Most of the important commercial species use these strategies.

commercial catch of temperate Western Australia are marine species which reproduce in the ocean and use both the estuaries and marine embayments as nursery areas. They include yellow-eye mullet (*Aldrichetta forsteri*), Australian salmon (*Arripis trutta esper*), King George whiting (*Sillaginodes punctatus*), and western sand whiting (*Sillago schomburgkii*). Sea mullet (*Mugil cephalus*) and tarwhine (silver bream) (*Rhabdosargus sarba*) reproduce in the sea and use only estuarine nursery areas. Black bream (*Acanthopagrus butcheri*) is the most important commercial species which lives and reproduces entirely within the estuarine environment. Cobbler (*Cnidoglanis macrocephalus*) can reproduce and live in both the estuarine and marine environments, while of the group of fish which have only marine breeding and nursery habitats, Australian herring (*Arripis georgianus*) is the one most commonly taken in estuaries.

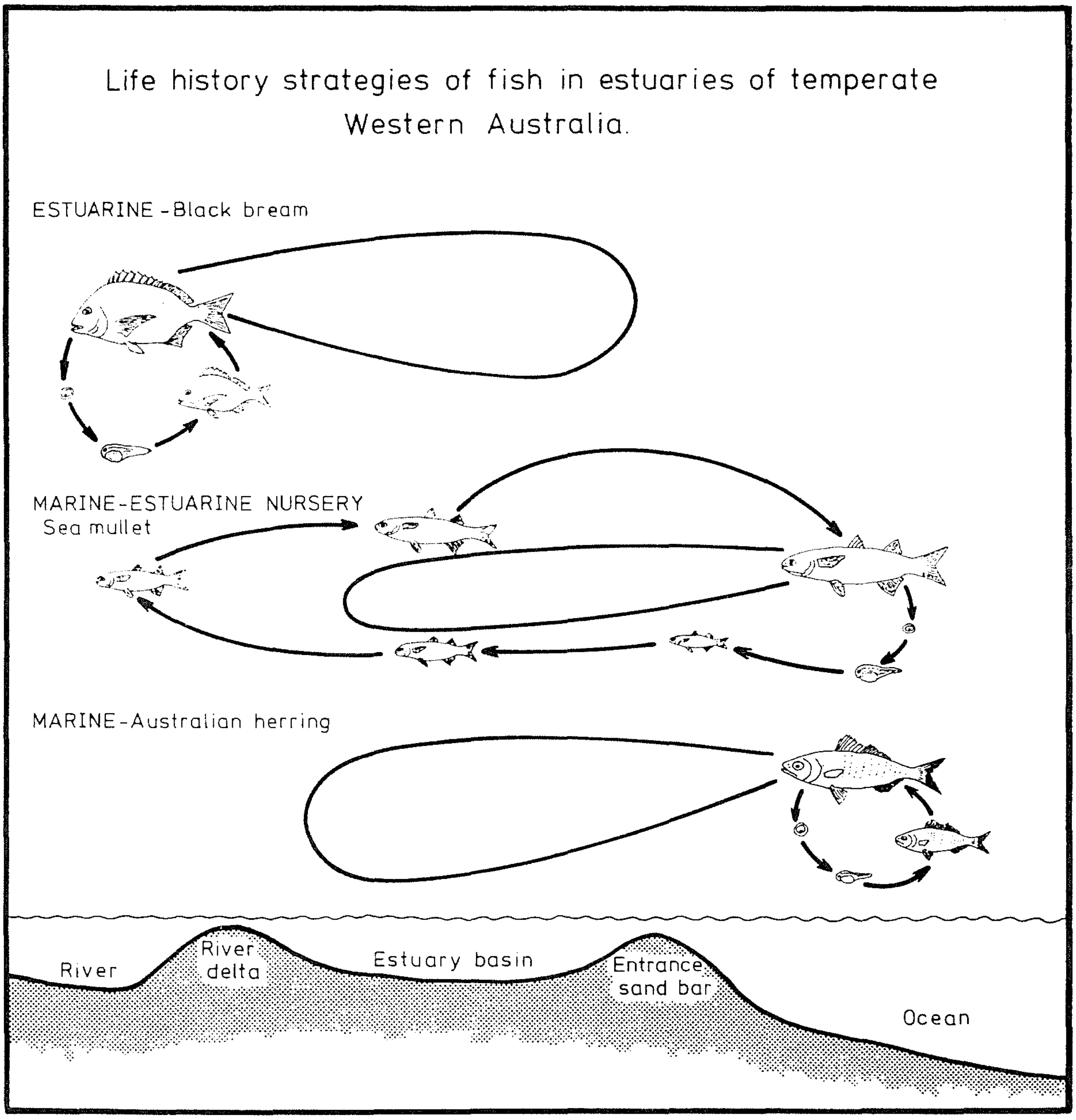

Figure 7. A schematic representation of the life history strategies of fish from the estuaries of temperate Western Australia.

(b) Barred estuaries

Any reduction in the extent of the free connection between the estuary and the ocean will directly affect the recruitment of fish into the estuary, and indirectly through resultant hydrological regimes, the distribution, abundance and ultimate survival of those fish once they have been recruited into the estuary. The times of recruitment of the various species were determined from the results of past work (Lenanton unpublished, 1977, 1982; Lenanton <u>et al</u>. 1982; Potter <u>et al</u>. 1983). The spawning period and the time when 0+ individuals were first recorded in the estuaries has been determined for eight of the most important commercial species listed

Section 3(a). For each year during the 1964-72 period, these data were compared to the time and duration of the free connection to the ocean for the six estuaries (see Materials and Methods) being considered in this paper (Figures 8 and 9). From these data, it is clear that all nominated species are well placed to be recruited into the permanently open systems of the Blackwood River estuary, and the Nornalup-Walpole estuary. However recruitment opportunity is restricted in both the seasonally open and normally closed systems. For example, during many years, both Broke and Wilson Inlet are closed before 0+ western sand whiting and tarwhine (silver bream), which both have restricted spawning seasons, are normally first recorded in the estuary as 0+ individuals. By comparison, sea and yellow-eye mullet, with their protracted winter spawning period are well placed to enter these seasonally open systems as small 0+ individuals. Although seasonally open systems do restrict recruitment opportunity, these estuaries do open regularly and for a comparabale period each year. The normally closed systems, however, open most irregularly and for widely variable periods of time. Thus, for example, for several consecutive years (1965-67) recruitment of sea and yellow-eye mullet into Wellstead estuary was possible; then for the following three years (1968-70), complete closure of the system prevented recruitment of these species into this estuary.

The extent of the free connection between the estuary and the ocean, together with the rates of freshwater runoff, mixing and evaporation are the main factors which determine the salinity regime of all temperate Western Australian estuaries. Examples of some of these regimes are provided in Section 2 of Results and Discussion. These data show clearly that compared with permanently open systems, barred estuaries have a relatively inconsistent seasonal salinity regime. They can also remain substantially fresher than the ocean (Broke Inlet, Figure 4); or as in the case of Beaufort Inlet, become significantly more salne than the ocean for relatively long periods of time (Figure 5). Thus for fish species to persist over a range of such hydrological environments, they need to be very euryhaline.

Possibly the best way to illustrate how both the reduction in the extent of free connection with the ocean and fluctuating salinity can affect the estuarine nekton, is to review the case history of the changes in relative abundance of the fish fauna in the Beaufort Inlet (Figure 3) both prior to and following the breaching of the entrance sand bar.

(c) Case History Study - Beaufort Inlet

The total number of fish species, together with the relative abundance of sea mullet, a marine species

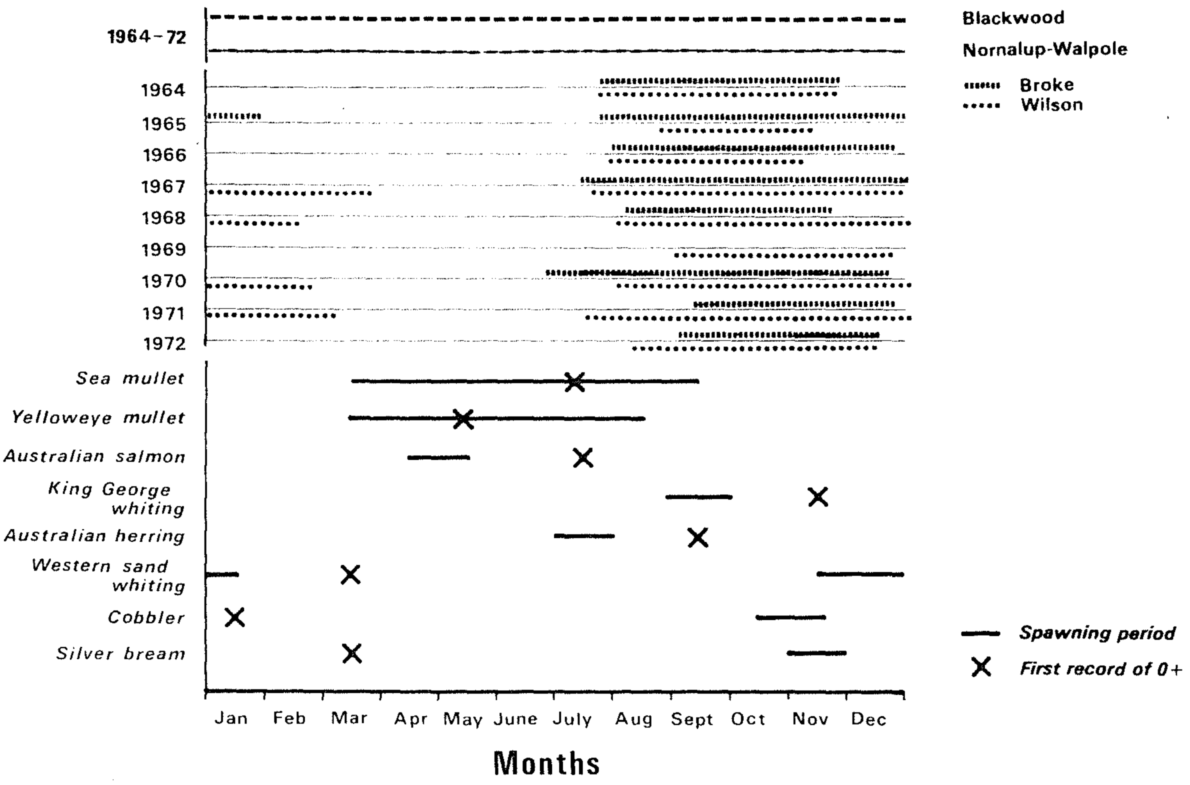

Figure 8. The time and extent of free connection between the estuary and the ocean for both permanently and seasonally open estuaries, compared with the duration of spawning and time at which 0+ individuals of a number of fish species were normally first recorded in the estuaries of temperate Western Australia. Hatching indicates the period when the estuaries were open to the ocean.

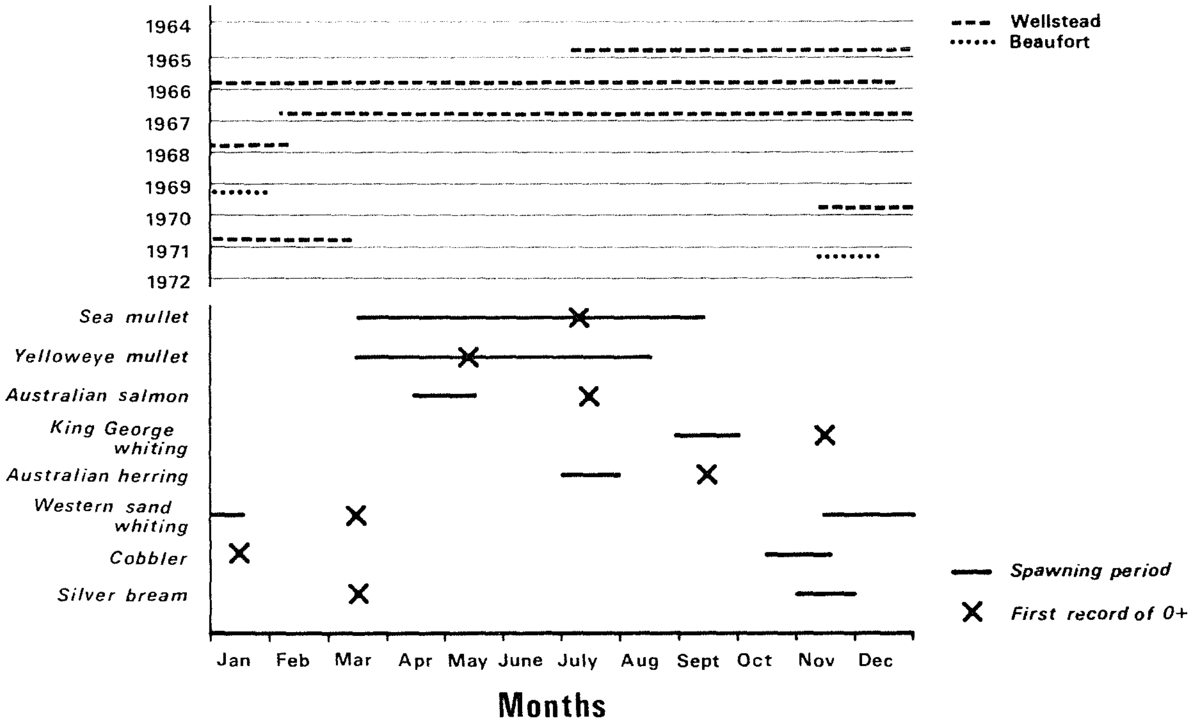

Figure 9. The time and extent of free connection between the estuary and the ocean for normally closed estuaries, compared with the duration of spawning and time at which o+ individuals of a number of fish species were normally first recorded in the estuaries of temperate Western Australia. Hatching indicates the period when the estuaries were open to the ocean.

that uses the estuary as a nursery area, and black bream, an estuarine species sensu stricto, were monitored both prior to and following the breaching of the sand bar at the mouth of the Beaufort Inlet (Figure 3). A small-meshed beach seine net was used to catch the 0+ individuals while gill nets were used to sample the larger (>0+) more mobile individuals (see Materials and Methods).

This estuary had been closed for approximately 48 months before it opened to the ocean in July 1978 (Figure 10). Sampling in the hypersaline lower estuary prior to the opening revealed only 6 species of fish Large (≈420 mm T.L.) sea mullet were the only commercially important species recorded. Although no black bream were taken in the lower estuary at this time, numbers were taken in the riverine region of this estuarine system where salinities were slightly lower (53 ‰) (Figure (10).

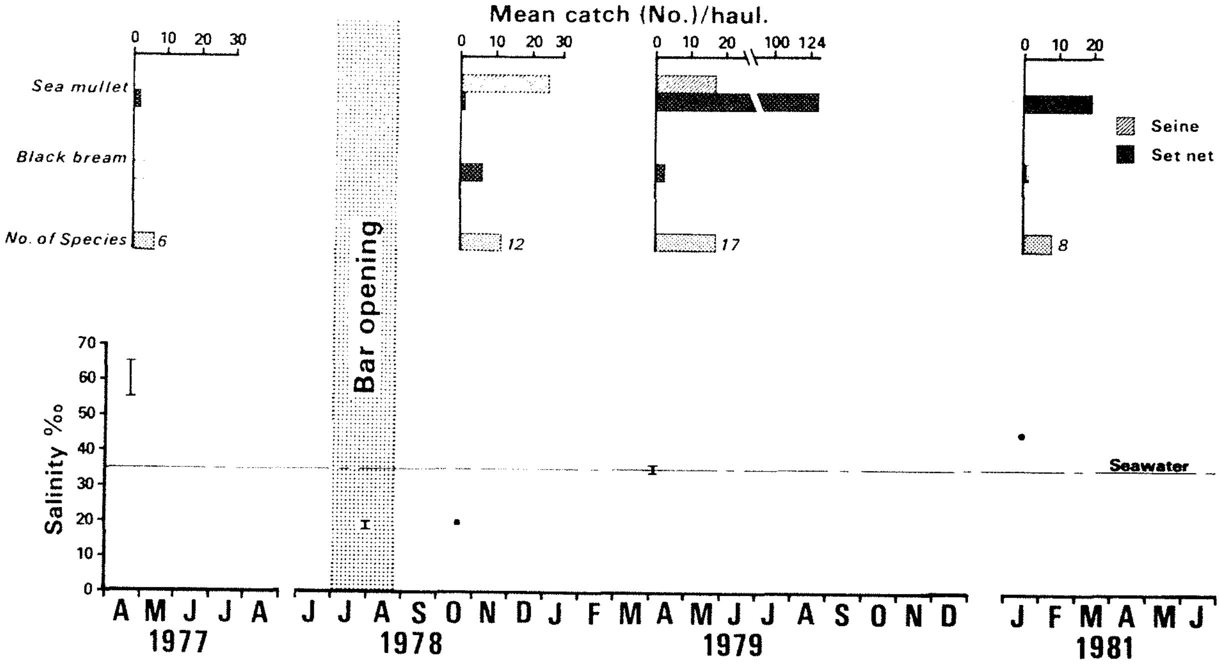

Figure 10. The relative abundance of selected fish species, together with the number of all recorded fish species and salinity of the lower Beaufort Inlet prior to and following the breeching of the entrance sand bar. The dashed bar histogramme shows the relative abundance of black bream in the riverine region of the estuary during April 1977.

The two month-long opening to the ocean resulted in a number of significant changes to the fish fauna.

(i) Large black bream were caught in the lower estuary soon after the bar had broken. As salinities increased during the months following sampling, numbers of black bream in the lower estuary decreased. There was no recruitment of small 0+ black bream to the lower estuary over this period.

(ii) There was a good recruitment of 0+ sea mullet from the ocean to the lower estuary. The fact that increased numbers of sea mullet taken in gill nets during the April 1979 sampling period demonstrates that this species grew rapidly once it had entered the estuarine system.

(iii) The total number of fish species caught in this estuarine system doubled immediately following the period of opening, and had almost trebled by the time the April 1979 sampling was completed. With the exception of black bream, the increase in the total number of speices consisted entirely of marine species which had been recruited into the system. Maximum numbers were not recorded until April 1979, because a number of the marine species which were normally distributed away from the shoreline took some months to grow large enough to be retained by the gill nets.

(iv) Once salinity rose substantially above that of seawater, fewer species were recorded. Allowing for the fact that durinq this month, sampling was restricted to gill netting only, it was still clear that the decline in numbers was at least in part due to the absence of some of the more stenohaline-marine species that had been taken by gill nets during the previous sampling period.

(d) Alternative Non-estuarine Nursery Habitats

A comparison of the relative abundance of juvenile fish in the Blackwood River estuary and the nearby marine habitat (Lenanton 1982) has shown that the juveniles of the commercial fish species yellow-eye mullet (*Aldrichetta forsteri*), small toothed flounder (*Pseudorhombus jenynsii*), Australian salmon (*Arripis trutta esper*), Australian herring (*Arripis georgianus*), western sand whiting (*Sillago schomburgkii*), King George whiting (*Sillaginodes punctatus*), sea garfish (*Hyporhamphus melanochir*), cobbler (*Cnidoglanis macrocephalus*) and blue sprat (*Spratelloides robustus*) use the shoreline marine waters of south-Western Australia as an alternative to estuaries as nursery areas. Subsequently Lenanton et al. (1982) have shown that it is the surf-zone accumulations of detached macrophytes in this nearshore marine habitat that provide the principal source of food (amphipods) and shelter for these fish.

0+ individuals of species that utilise these nearshore marine environments in this manner have two clear advantages over other individuals of these same species that utilise estuaries as nursery areas. Firstly, they do not have to negotiate restrictive and often barred estuarine entrance channels in order to reach their nursery habitats. Secondly they have a much more stable hydrological environment in which to feed and grow.

At this stage the absolute extent of the alternative nearshore-marine environment has yet to be determined. However, some preliminary estimates are available. Assuming the nursery habitat lies within 50 m of the shoreline, Lenanton (1982) has estimated that in the 166 km of coastline between the Vasse-Wonnerup estuary mouth and the Blackwood River estuary mouth (Figure 3) a minimum area of 40 km^2 (or 200 ha) is potentially available as a detached macrophyte based nursery area.

More recently, using measures of detached macrophytes in the surf-zone along a 50 km piece of coast near Perth as a guide, Robertson (unpublished), has estimated that there is, depending on the the time of year, between 24 and 600 ha of "high quality" nursery habitat available in the 1600 km section of coast between the Chapman River mouth, Cape Leeuwin and the Jerdacuttup River mouth (Figure 3).

In regions such as the lower west coast of Western Australia where there are relatively large areas of permanently open estuaries, the alternative inshore-marine areas do contribute additional nursery areas to those found in estuaries. However further north along the west coast and east along the south coast where the available estuarine nursery areas are considerably reduced (Figure 3), alternative inshore-marine areas are considered to be relatively much more important.

IV SUMMARY AND CONCLUSIONS

It has been widely reported in the literature that most juvenile marine fish which utilise estuaries, achieve fast growth rates and high rates of survival.

In temperate Western Australia, as in other parts of the world, many of these estuarine-dependent fish species contribute significantly to the total commercial fish catch of their respective regions. Many of the temperate Western Australian habitats utilised by estuarine dependent species are barred estuaries. It has been demonstrated, however, that barring reduces recruitment opportunity and through the influence of extreme hydrology can affect survival of estuarine fish. A practical example of the events preceding and following the opening of a barred estuary were given in Figure 10. This showed clearly how in the elevated salinities of the closed system, the relative abundance of fish was low and confined to a few tolerant species, especially black bream. Once the bar was breached, the number of species trebled and the quantity of some species, notably sea mullet greatly increased through recruitment from the ocean. The success of this process will depend on the time of availability of recruits relative to the bar opening. It has also been demonstrated that many of the estuarine-dependant species can also successfully utilise inshore-marine habitats as alternative nursery areas. Thus it is suggested that in regions of the coast where barred estuaries predominate juvenile marine fish are increasingly dependent on alternative inshore- marine nursery habitats.

V ACKNOWLEDGEMENTS

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SUMMING UP

A.E.F. Heydorn

Summary of impressions after a field trip to southern estuaries and symposium

It is important for all who are involved in the utilization or management of the coastal environment to appreciate that processes which have shaped the coast since the Pleistocene and Holocene and before are still active today. Human influence may have begun to play a role since the appearance of aboriginal man some 25 000 years ago, particularly through the clearing of vegetation in catchments. Artificially induced fires were probably important in this context. However, gross environmental change has only been brought about during the past 200 years through sharp increases in the overall human population, through modern man's demands upon his environment and his increasing technological ability. The effects are well known but can be summarized as follows:

- the clearing of forests, agricultural practices and intensive inland water usage has in many regions brought about profound changes in catchment and run-off characteristics;
- not only the volume of water but also the sediments and nutrients (e.g. dissolved and particulate organic matter) carried into estuaries by rivers, can be grossly changed by human activity. Silting up as a result of soil erosion, eutrophication as a result of excessive use of fertilizers in catchments or impoverishment due to impoundments acting as nutrient traps, are examples;
- chemical pollution by industrial developments or organic pollution by residential developments in the vicinity of estuarine environments can have obvious detrimental effects;
- the same applies to the manipulation of estuarine configurations, particularly if this affects tidal exchange mechanisms. Meso-tidal estuarine environments such as in South Africa are more vulnerable to such effects than micro-tidal estuarine environments such as those which occur in the south-west of Australia.

Obviously the equilibrium of estuaries both physically and biologically can be severely disrupted by human interference of the types enumerated above and by others which may not have been mentioned. This can severely reduce the food-producing potential of estuaries and their attractiveness in recreational and aesthetic terms. When this happens a decline in their economic potential is quick to follow. Where marine organisms utilize estuaries for feeding purposes or as nurseries, marine recreational or commercial fisheries can also suffer.

While the reasons for (and the consequences of) estuarine degradation are well-known, the scientists ability to forecast with precision and confidence what the long-term effects of man-induced change on estuaries will be, very often falls woefully short. Why?

- cohesive planning of land-use in catchments and around estuaries takes place in very few cases. Rather, developments are haphazard and unco-ordinated. The forecasting of long-term effects on estuarine environments is therefore not possible;

- in the vast majority of cases, the origin and reservoirs of unconsolidated sediments in estuarine and nearshore environments are not adequately understood. The same applies to the processes of sediment distribution and the interaction of the forces of wind and water. Thus much more attention needs to be given to the study of past and present dynamic processes in estuarine environments, including the role of estuarine and dune vegetation in these processes;

- similarly estuarine ecosystem analyses in biological terms (including interaction with the nearshore marine environment) need to be intensified if the effects of various forms of human activity are to be predicted with any degree of confidence;

- it must be appreciated that the differences between individual estuaries and their respective catchments are usually so great that guidelines in general terms may only be of limited value. Thus priorities as to which estuarine systems should be studied need to be set with great care if meaningful results of practical value are to be achieved.

If these criteria are accepted, does this affect the direction which estuarine research should take in future? In my opinion the answer is yes. In the past there has been a tendency by many scientists to work on individual and detailed facets of estuarine biology, chemistry, physics, sedimentology or geology, without being really concerned with contributing to the understanding of the functioning of overall estuarine ecosystems. While the need for such detailed fundamental research is fully acknowledged, inadequate attention to ecosystem functioning must restrict the scientist's ability to advise in matters of management. To maintain scientific integrity there has been in the case of many scientists, an unwillingness to venture opinion. Those who have ventured opinion are frequently slated by their peers as being superficial. But, environmental pressures are increasing so rapidly, that advice must be given now if total degradation of many systems is to be avoided. In terms of research this means that we must strive to reduce disciplinary compartementalization in our approach. It is emphasised again that it is of particular importance that we must improve our ability to interpret today's processes in estuarine environments in the light of past physical and biological events (at the very least those which have occurred during the Holocene). If we cannot achieve this, it will not be possible to predict with any degree of confidence the effects of modification (e.g. acceleration or reversal) of natural processes by modern human activity. To me this points to the need for a far greater level of communication between biologists, geologists/sedimentologists and palaeoentologists both in the planning and execution of estuarine research. The value of this was clearly demonstrated during the pre - ANZAAS field trip, in which workers from all these disciplines participated.

Finally it must be accepted that the scientist should be willing to communicate with those responsible for estuarine management (or for manipulation of the coastal environment through engineering or other works) in clear and understandable form at all times, whether his research has been completed or not. Coastal zone managers both in Australia and South Africa, need such interaction very urgently and the importance of drawing coastal engineers into this form of discussion cannot be over-emphasized.