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The Leschenault Inlet estuary: an overview

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Abstract

The Leschenault Inlet estuary is an elongate shore-parallel, shallow water estuarine lagoon with distinctive patterns of bathymetry and geomorphology, framed to the east by the Mandurah-Eaton Ridge, to the west by a dune barrier, and to the south by two deltas. The estuary is diurnally micro-tidal, wave dominated and wind current driven. Estuarine waters are close to marine salinity but annually poikilosaline. Four salinity fields are recognised, corresponding to the delta zone, the lower estuary, the mid estuary, and the upper estuary. Large scale stratigraphic relationships within the system are relatively simple, with estuarine sediments to the east onlapping a quartz sand ridge, and a dune barrier encroaching over estuarine sediments to the west. Sedimentary patterns are underpinned by geomorphology, linked to the nature of shorelines, reworking sources and hydrodynamics, with muddy sediments accumulating in deeper water basins and semi-sheltered environments, and sand accumulating on exposed platforms, dune margins, or in deltas. The dune barrier, underlain by fresh water, separates oceanic and estuarine waters, with a saline / freshwater interface on both sides. Freshwater discharges from the barrier form shore seepages, which are important for shore vegetation and faunal use.

Leschenault Inlet estuary is unique in south-western Australia for several reasons. Formed behind a shore-parallel dune barrier, and wholly Holocene in age, its estuarine geomorphology and hydrologic structure are different to other local estuaries such as the Swan River Estuary and the Peel-Harvey Estuary. The estuary does not represent a simple river-to-sea transition, but has rivers entering at one end of a long coastal lagoon formed by marine processes rather than fluvial erosion. Leschenault Inlet estuary also has had a complicated Holocene sea level history, resulting in complexity of its shores. The western shore is further complicated as parabolic dunes encroach into the estuary, producing a varied assemblage of shore types and stratigraphic / hydrologic situations. The complex of shores and wetland types peripheral to the estuary support five types of fringing vegetation. Consequently, Leschenault Inlet estuary is a classic area for studies of ecology of estuarine peripheral vegetation, and the system ranks as one of the most significant in southern and south-western Australia. Through its proximity to the Leeuwin Current, the estuary also supports the most southern occurrence in Western Australia of the mangrove *Avicennia marina*, and the array of landforms and vegetation in and around the estuary combine to create an important classroom for palynology.

With numerous low-tidal to subtidal benthic habitats in the estuary, there is a rich diversity of flora and fauna: 3 species of seagrass, 7 species of algae, 31 species of mollusc (6 common species), 21 species of small benthic crustaceans, several species of larger crustaceans including the Blue swimmer crab (*Portunus pelagicus*), 15 polychaete species, and a normally oceanic ophiuroid echinoderm. The foraminifera assemblages in the estuary also are unusually diverse. Forty two species of fish have been recorded from nearshore and shallow waters. The estuary also is important for waterbirds, and as a dry season refuge in mid spring and summer it ranks amongst the top wetlands in south-western Australia.

Land reclamation, dredging, harbour reconstruction and urbanisation have impacted the estuary in the past 60 years. The estuary currently also is mildly enriched in nutrients introduced during winter freshwater influx. Studies on the phosphorous content of mud, phytoplankton and aquatic macrophytes of the estuary, however, suggest that the impact of nutrients on the estuary to date has been small. The long-term effects of development impacts on the unique characteristics of the estuary, however, are currently unknown.

Keywords: Leschenault Inlet, estuary, sediments, vegetation, fauna, ecology, south-western Australia.

Introduction

Leschenault Inlet estuary is a shallow estuarine lagoon located along the coast in the southern part of the Swan Coastal Plain (Semeniuk & Meagher 1981a), in the Leschenault-Preston Sector of Searle & Semeniuk (1985). It is set in a subtropical subhumid climate, or Mediterranean climate (Gentilli 1972). It is the estuary of the Collie-Brunswick rivers and the Preston-Ferguson rivers (Fig 1). The estuarine lagoon is separated from the Indian Ocean and Rottnest Shelf by a barrier dune system, the Leschenault Peninsula (Semeniuk 1985).

This paper provides an overview of the Leschenault Inlet estuarine lagoon from several perspectives, mostly drawing from contributions in this Special Issue. Firstly,

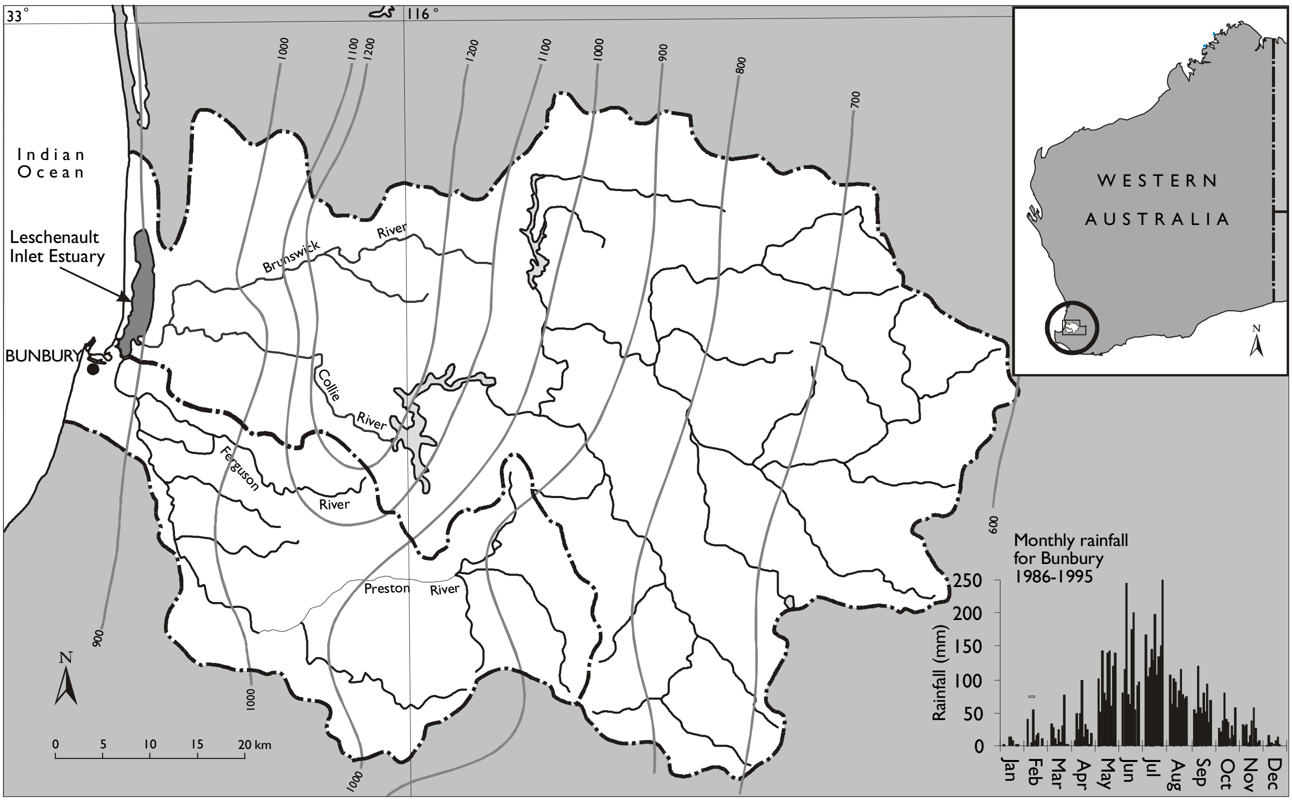

Figure 1. Location of Leschenault Inlet estuary showing setting within the extensive drainage basin of the Collie, Brunswick, Preston and Ferguson rivers, and rainfall isohyets in millimeters (data source Anon 1996). Rainfall graph for Bunbury shows monthly rainfall for 10 years (within each month, the vertical bars record monthly rainfall from left to right for each year from 1986 to 1995; data source Bureau of Meteorology, Perth)

its definition, geohistorical context and origin are described. A synthesis of its environmental aspects in terms of geomorphology, peripheral hydrology, water quality, estuarine hydrodynamics, sediments and habitats follows. Summaries of its biotic characteristics are presented *viz* its invertebrate fauna, fish, avifauna, and the population dynamics of selected groups, as well as subaquatic and peripheral vegetation. The paper concludes with a description of the range of human impacts on the estuary.

While the range of papers noted above deal with abiotic, biotic and ecologic aspects of the estuarine environment, small-scale and microscale habitats and their biota to date have not been considered in detail. These include the small-scale habitats contrasts of megaripples and sand waves and their intervening troughs, and microhabitats of *in situ* tree trunks, transported logs and other wood as benthic substrates, rock pebbles derived from locally eroding calcrete cliffs on the western shore or from eroded ferricrete on the eastern shore, isolated shells and shell pavements, cohesive mud cliffs along the saltmarsh shore, and limestone pavements. Such microhabitats provide the only localised hard substrate in the estuary; supporting localised populations of algae, diatoms, crustaceans, polychaetes, serpulid worms, ascidians, barnacles, mussels, bryozoa, and small rock crabs.

Leschenault Inlet estuary

Leschenault Inlet estuary encompasses an estuarine lagoon barred by a Holocene dune barrier. Some authors refer to the estuary simply as "Leschenault Inlet", or more recently, as "Leschenault Estuary". The term "Leschenault Inlet" once referred to the entire narrow water body comprising a barred estuarine lagoon and a river channel connecting it to the ocean (Fig 2). By definition, an inlet is "a short narrow waterway between islands, or connecting a bay, lagoon, or similar body of water with a larger body of water, such as a sea or lake" (Bates & Jackson 1997). The term "inlet" is not synonymous with "estuary".

Strictly, the name "Leschenault Inlet" should have been applied only to the narrow opening connecting the lagoon with the Ocean, and "Leschenault Lagoon" should have been applied to the larger water body, but the name "Leschenault Inlet" was applied to the lagoonal water body and to its narrow (tidal and fluvial) connection to the sea. Engineering modifications in southern parts of the former Leschenault Inlet severed the system into two. The Department of Marine & Harbours, the Leschenault Inlet Management Authority, and the Department of Land Administration then renamed the system: the original narrow connection was called "Leschenault Inlet", and the larger water body "Leschenault Estuary".

The definition of an estuary has been long debated in the literature, and has significantly progressed from its original hydrochemical concept, *viz* "a body of water where

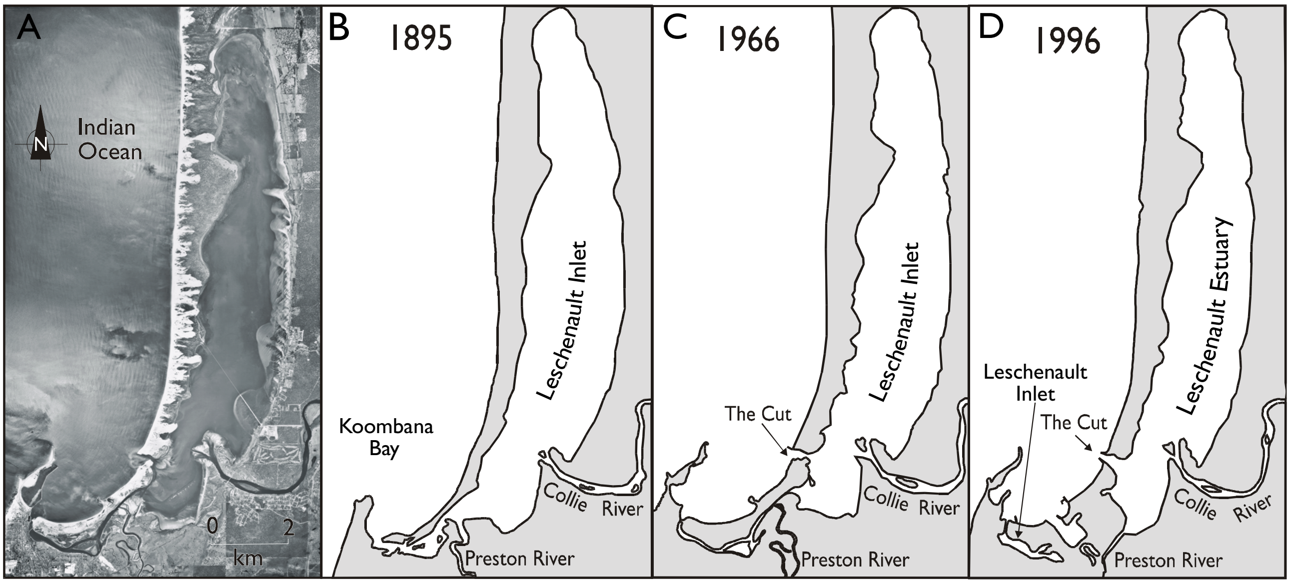

Figure 2. A: Aerial photograph of Leschenault Inlet estuary showing barrier dune separating the elongate lagoon from the Indian Ocean, and the Collie River delta to the southeast. **B:** Map of Leschenault Inlet in 1895 showing continuous waterway from the ocean inlet to the south to the elongate landlocked estuarine lagoon. **C:** Map of Leschenault Inlet in 1996 showing first impact on the system by an artificial breach in the dune barrier referred to as "The Cut". **D:** Map showing terrain modification severing Leschenault Inlet, and terminology of the Leschenault Inlet area during the 1980s and 1990s.

river water mixes with and measurably dilutes sea water" (Ketchum 1951). Perillo (1995) distilled 40 dictionaries, encyclopedia and specialist references to define an estuary as "a semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage, and can sustain euryhaline biological species for either part or the whole of their life cycle." This definition, the most comprehensive to date, encompassing geomorphic, hydrodynamic, hydrochemical and biological aspects of estuaries, expands on the long accepted definition of Pritchard (1967), and addresses the difficulties raised by Day (1981). The system devised by Digby *et al*. (1999), a national classification proposed for Australian estuaries, which through application captures coastal embayments such as Shark Bay and partly land-locked ocean-connected waterways such as Port Hedland Harbour as estuaries, is conceptually flawed and is not used here. That used by Dalrymple *et al*. (1992), an internationally proposed classification of estuaries based on wholly sedimentologic criteria essentially is a classification founded on what is considered to be useful geologically or palaeo-environmentally, and also is not used here.

Leschenault Inlet estuary accords with the definition of Perillo (1995). It is a semi-enclosed lagoon, with the Preston and Collie Rivers contributing freshwater and fluvial sediments, with marine water exchanges and tidal influences propagated through a narrow, artificial opening ("The Cut") in the dune barrier, and where euryhaline fauna are sustained for all or part of their life cycle. The full extent of the estuary encompasses the large lagoonal water body and the lower reaches of the Collie River to the limit of the tides and brackish water (Fig 3). The limit of the estuary into the lower reaches of the Preston River diversion channel is sharply delimited by engineering modifications and landfill.

Against this background, we term the large water body "Leschenault Inlet estuary", rather than "Leschenault Estuary", for several reasons. The name "Leschenault Inlet" has precedence, and the larger part of the water body should retain the original name. Moreover, since the larger water body is still estuarine (receiving freshwater from the Collie and Preston Rivers, albeit the latter discharges into the larger water body through a diversion channel), the term "Leschenault Inlet estuary" is apt. Ideally, the term "estuary" should be applied to the river-to-ocean transition, however, "Leschenault Inlet" is too entrenched as a name to supplant it with "the Collie-Preston River estuary". In technical terms, the system now is comprised of the Collie River Estuary, the Preston River Estuary, and the Leschenault Inlet estuarine lagoon. The smaller part of the severed water body, once the original oceanic opening to Leschenault Inlet and the outlet of the Preston River, and now essentially a tide-influenced marine inlet, is no longer estuarine. Here we retain the name "Leschenault Inlet".

The estuary earlier in the Holocene

The Leschenault Inlet estuary has had a history influenced by a retreating barrier, and a fluctuating sea level. Earlier in the Holocene, between 7 000 years and *ca* 2 500 years BP, the estuarine lagoon was longer and wider, as indicated by stratigraphic studies, radiometric dates and the erosional history along the Leschenault-Preston Barrier (Semeniuk & Meagher 1981a,b; Semeniuk & Searle 1986, 1987; Semeniuk 1985, 1995a,b). The original proto-estuarine lagoon originated 7 000 years BP, with the construction of a shore-parallel barrier dune. At that stage, the estuary extended as far as northern Lake Preston, and was at least three times as wide. Fossil molluscs and sediments indicate that estuarine conditions existed along

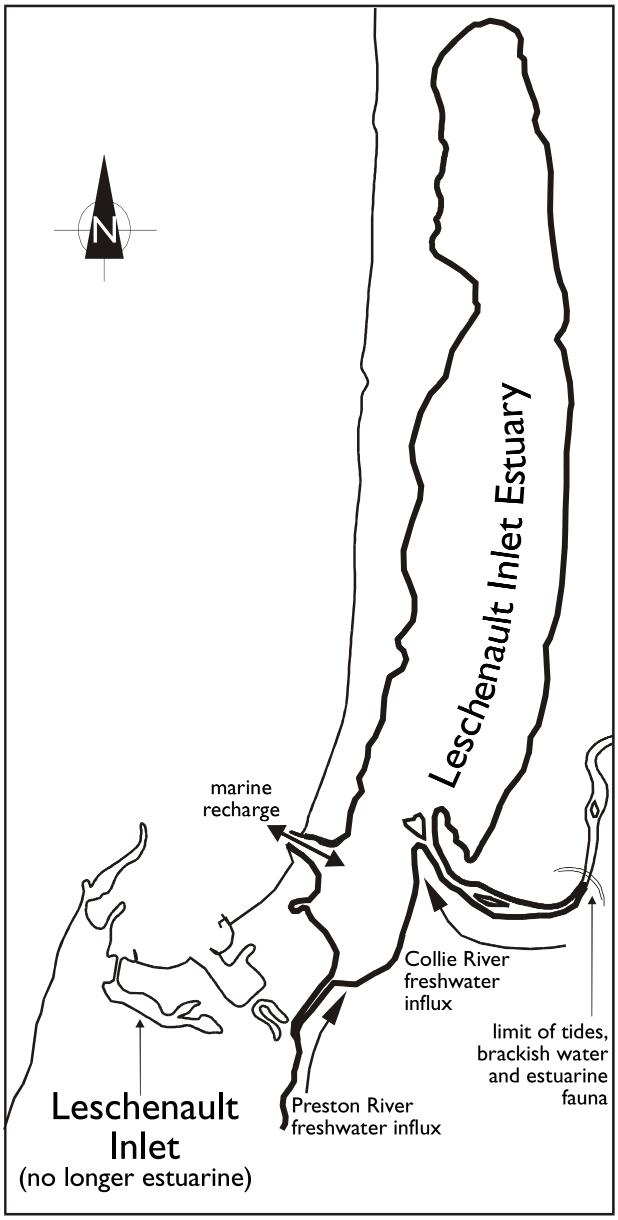

Figure 3. Terminology for the Leschenault Inlet estuary used in this paper, and extent of the Leschenault Inlet estuary.

the entire length of the lagoon, which resembled a system like The Coorong in South Australia.

With the eastward advance of parabolic dunes and the retreat of the barrier (Semeniuk 1985), the estuarine lagoon progressively became narrower, until a series of parabolic dunes *ca* 4 500 years BP crossed its narrowest part opposite a coastal limestone projection (a Pleistocene cuspate foreland; Semeniuk 1997) segmenting the proto-estuarine lagoon into a northern part (Lake Preston, now uninfluenced by river input, and hence no longer estuarine), and a southern part (the present estuary influenced by the Preston and Collie rivers). Sea level rising to 3-4 m above present *ca* 4 500 years BP flooded the lowlands marginal to the estuary, increasing its width. With falling sea level, the lagoon marginally became narrower. Ongoing parabolic dune encroachment has progressively narrowed the estuarine lagoon. The shape, length, and extent of the estuary during various stages of the Holocene is shown in Fig 4.

Estuarine geomorphology

The main landform and estuarine units that border and constitute the Leschenault Inlet estuary are (Fig 5):

- to the east, the Mandurah-Eaton Ridge, a moderately high ridge of Pleistocene quartz sand and limestone, and lowlands underlain by Pleistocene limestone referred to the Yalgorup Plain (Semeniuk 1995a, 1997);
- Leschenault Inlet estuary itself *i.e.* the elongate shore-parallel, shallow water estuarine lagoon;
- two deltas, the Collie River Delta and the Preston River Delta, that enter the estuarine lagoon from the south-east and south; and
- to the west, the Leschenault Peninsula, a moderately high quartz and carbonate sand Holocene dune barrier (Semeniuk 1985).

Based on its geomorphic setting, hydrodynamics, and morphology, the estuary can be classed as a microtidal barrier lagoon estuary (*cf* Hayes 1975). Hesp (1984) classes it as a barrier estuary, *i.e.* one that occupies an inter-barrier depression, and Perillo (1995) and Isla (1995) would class it as a "coastal lagoon" estuary.

The Leschenault Inlet estuary has distinctive patterns of bathymetry and geomorphology (Fig 5). The subtidal part is a flat-floored, elongate central basin, generally 1.2-2.0 m deep, flanked to east and west by shallow, shore-parallel platforms and ramps sloping from intertidal to 1 m depths. To the south, the central basin adjoins deltas, and to the north it grades into a shallow water flat, which further grades to extensive tidal and supratidal flats. High tidal to supratidal zones (saltmarsh flats) are developed along the eastern shore, in the middle to northern parts of the western shore, and to the north. Spits, and bar-and-lagoon complexes are developed locally along the southern to middle part of the western shore.

The stratigraphic framework is summarised in Fig 6. Estuarine mud, muddy sand and sand referred to the Leschenault Formation is Holocene in age, and < 7 000 yrs in age. This formation onlaps the Pleistocene ridge of sand (the Eaton Sand) and limestone to the east, overlies Pleistocene limestone (the Kooallup Limestone) at depth in the central and western parts of the system, and is itself overlain by a shoestring eastward retrograding body of Holocene dune sand (the Safety Bay Sand) to the west.

Salinity and hydrochemistry

Waters in the estuary are annually poikilosaline. In winter, the salinity generally decreases with the influx of fresh water from rivers, drains, run-off, and groundwater seepage (*e.g.* from dunes and deltas). In summer, evaporation (induced by increased temperatures and wind) and the continued exchange with the ocean influence the salinity, such that to the north, estuarine waters are often hypersaline. Wurm & Semeniuk (2000) divide the estuary into 4 salinity fields based on mean salinity and its variation throughout the year (Fig 7):

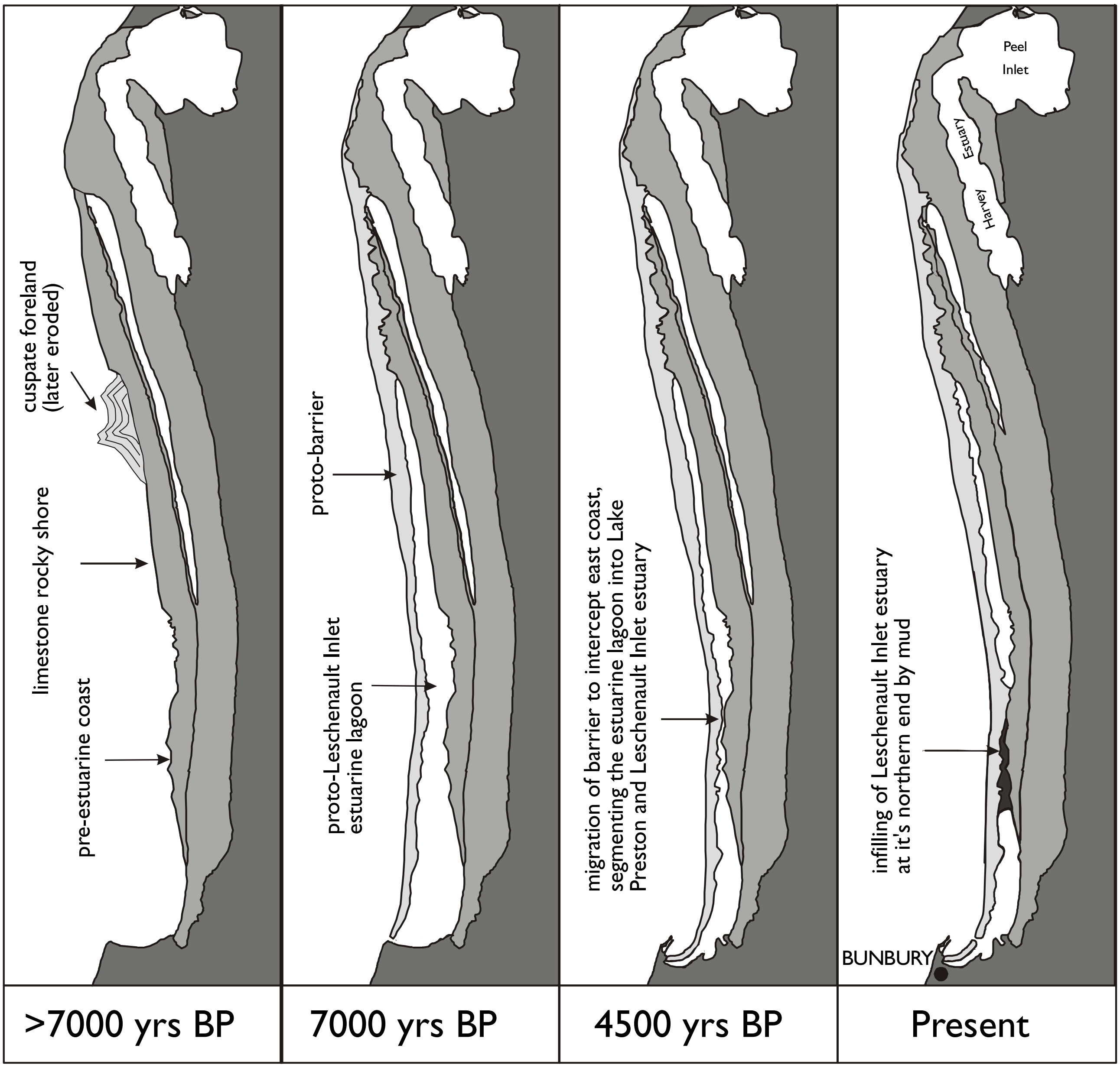

Figure 4. Evolution of the Leschenault Inlet estuarine lagoon during various stages of the Holocene. Before 7 000 yrs BP, the coast between Mandurah and Bunbury was an open limestone rocky shore, with a discrete cuspate foreland to the north. A dune barrier developed about 7 000 yrs BP forming a long barred estuarine lagoon that encompassed the present Leschenault Inlet system and Lake Preston. At *c* 4 500 yrs BP, the dune barrier impinged onto the eastern estuary shore segmenting the estuarine lagoon. The estuarine lagoon began to infill with mud in its northern portion.

- a deltaic field, where mean salinity influenced by river freshwater is slightly less than seawater but with a large variability about the mean (*e.g.* Collie River Delta area);
- a lower estuarine field, in which mean salinity is slightly greater than sea water, with a small variability about the mean within a mesosaline regime;
- a mid estuarine field, in which mean salinity is higher than sea water, with a large variability about the mean within a mesosaline regime; and
- an upper estuarine field, in which mean salinity is much greater than sea water, with a very large annual variability about the mean from hyposaline to hypersaline.

The classification of salinity used by Wurm & Semeniuk (2000) follows Hammer (1986), which encompasses salinities from fresh to hypersaline. Other workers at times use the Venice system (Anon 1959) to classify salinity of the brackish water spectrum of estuarine waters. A comparison between these classifications is shown in Table 1.

Table 1. Comparison of salinity between Hammer (1986) and the Venice System

Hammer	Salinity	Venice	Salinity
Fresh	< 0.5 ‰	Fresh	< 0.5 ‰
Subsaline	0.5-3 ‰	Oligohaline	0.5-5 ‰
Hyposaline	3-20 ‰	Mesohaline	5-18 ‰
Mesosaline	20-50 ‰	Polyhaline	18-30 ‰
		Euhaline	30-40 ‰
Hypersaline	> 50 ‰		

Salinity structure of the Leschenault Inlet estuary is complex as a result of the interplay of daily marine recharge through "The Cut", summer hypersalinity in northern parts of the lagoon, freshwater seepages from the adjoining uplands, and winter freshwater flooding from the Collie River. The estuary generally has no vertical stratification in salinity, but there is a south to north salinity gradient for most seasons. Short term and weak stratification exists during times of freshwater influx, and when there are water bodies of contrasting salinities, induced either by tidal recharge, or slugs of freshwater from the Collie River (Fig 7). Within the context of the elongate estuarine lagoon, overall, the estuary is well mixed in summer, and a positive estuary in winter along both the south to north lagoon transition, and the east to west Collie River to "The Cut" transition. The salinity dynamics along the east to west gradient from the middle reaches of the Collie River to "The Cut" have yet to be fully explored.

Water temperatures of the estuary are largely determined by air temperature and wind. Shallow water on the platforms, Collie delta and the northern flat have winter temperatures of *ca* 15 °C, and summer temperatures of *ca* 30 °C, with annual temperature fluctuations of *ca* 14 °C. Deeper water of the central basin has winter temperatures frequently below 15ºC and summer temperatures at or

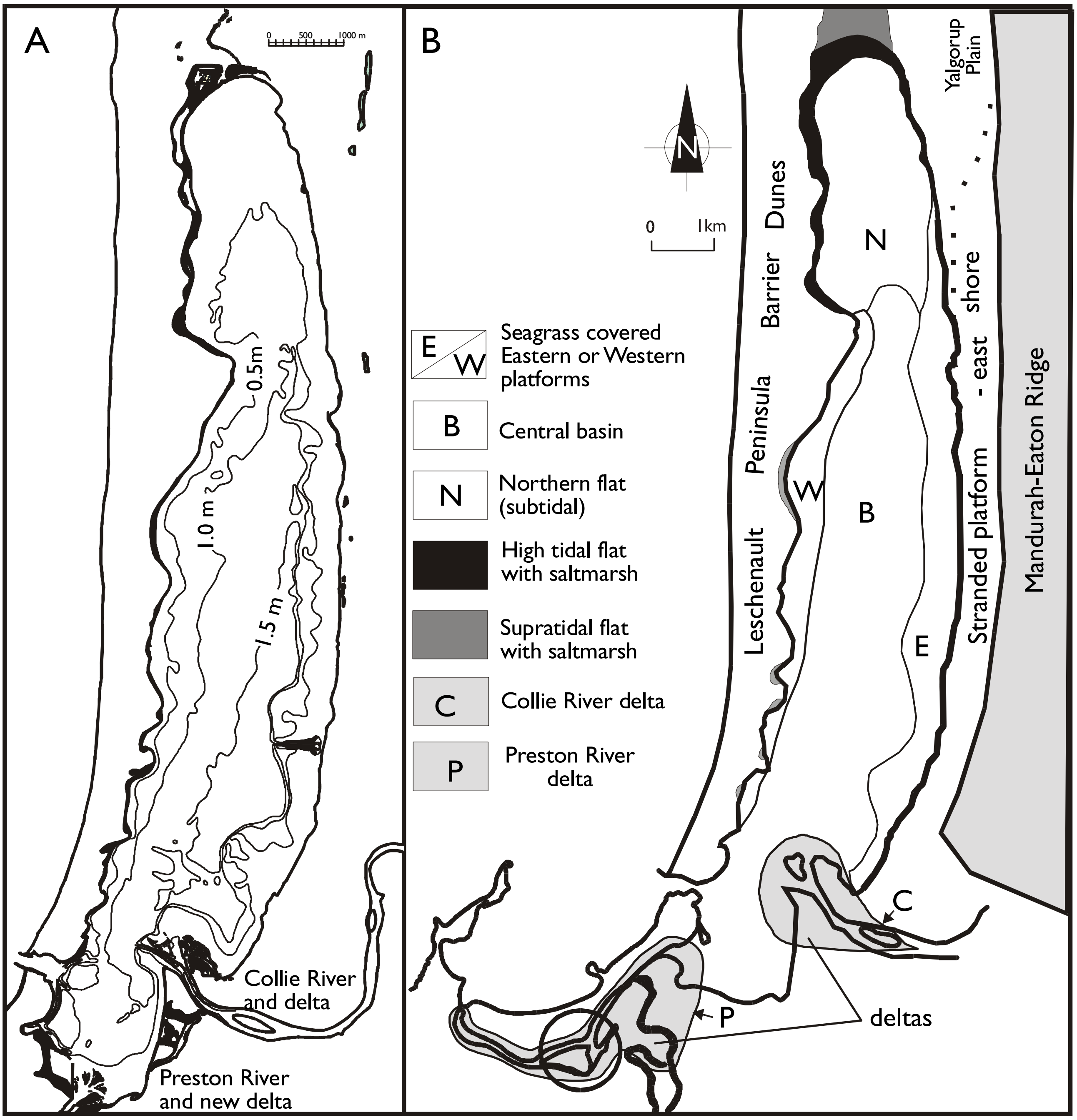

Figure 5. A: Bathymetry of the estuarine lagoon. **B:** Geomorphic units framing the estuarine lagoon, and geomorphic unit within the estuarine lagoon.

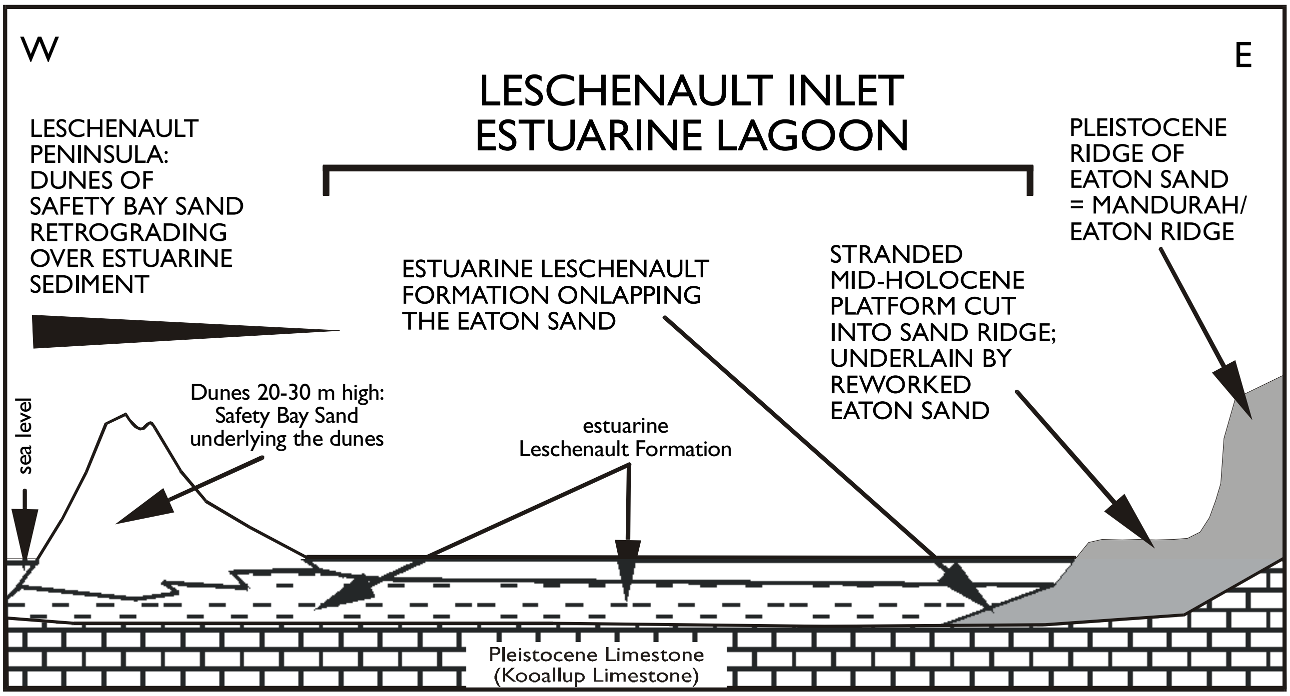

Figure 6. Stratigraphic framework of the Leschenault Inlet estuary (information from Semeniuk 1985, 1995a).

above 25 °C, with annual temperature fluctuations of *ca* 10 °C. The estuarine waters are well oxygenated throughout the year with dissolved oxygen concentrations, even in summer, generally > 5 mg L^{-1}. The highest oxygen values occur at shallow water vegetated sites.

Hydrodynamics

The estuary is wave dominated and wind current driven. Summer seabreezes and landbreezes generate short period waves. Winter storms deriving from the northwest generate larger period waves. Periodically, cyclones in the region, through low pressure and storm surge elevate water levels up to 2 m (*cf* Cyclone Alby in 1978; Semeniuk & Meagher 1981a,b). Tides are diurnal, micro-tidal, with a mean spring range of 0.5 m. Atmospheric pressure influences water level more than astronomical tides, with high pressure in summer contributing to low tides, and low pressure in winter resulting in a small general rise in mean sea level (Semeniuk & Meagher 1981a). Tidal exchange and wind shear generate currents, generally aligned south to north, with a net drift northwards, transporting suspended mud and algae and sea-wrack to northern parts of the system. More complicated patterns occur in the southern estuary because of interacting ocean exchanges, river flow, wind induced currents, and complex bathymetry and shorelines of deltas and prominences. As is typical of estuaries, Leschenault Inlet estuary commonly is turbid due to mud re-suspended by wave action.

Modeling the circulation under a variety of tidal, river flow and wind conditions *e.g.* typical summer or winter ebb and flood tide, and a typical summer with a sea breeze coinciding with flood tide (Charteris & Deeley 2000) shows significant attenuation of the ocean tidal range in the estuary, a 4 to 7 hour phase lag for high and low water between the ocean and estuary (due to hydraulic restriction by "The Cut"), and a similarity of circulation patterns for summer and winter conditions. Mean water level in the estuary also appears influenced by river flow and generally is high during winter when river flows are highest.

Sedimentology

At the largest scale, sedimentary patterns and Holocene stratigraphic relationships within the estuary are relatively simple (Fig 6). A shore-parallel wedge of sand reworked from eastern shore Pleistocene landforms is on-lapped by mud of the central estuarine lagoon. A shore-parallel dune barrier to the west bars and retreats over muddy sediments of this estuarine lagoon. Deltaic complexes invade the southern estuary, with the Collie delta recording a deltaic sand wedge capped by muddy sediment, and the Preston River delta recording a tidal-deltaic system of shifting shoals and mud. At finer scales, the west coast of the estuary (with its staggered dune encroachments) exhibits more complex stratigraphic relationships, and the deltas exhibit complexity of layered sand, muddy sand and mud in upper deltaic sequences, with shoestrings of sand (cheniers) interspersed with muddy sediments, and ribbons and shoestrings of mud.

Within the estuary, sedimentary patterns are underpinned by geomorphology (Fig 8; and Semeniuk 2000). The central basin and northern basin are underlain by bioturbated mud, the eastern platform is underlain by sand, the western platform is underlain by sand, muddy sand and mud (depending on the relationship of dune sand encroaching into the estuary), high-tidal platforms are underlain by root-structured mud, spits and bars-and-lagoons are underlain by sand, muddy sand, mud, and peat, pocket beaches are underlain by sand and shell grit, and the deltas are underlain by complexes of sand, muddy sand, mud and peat. The variety of sediment types and sedimen-

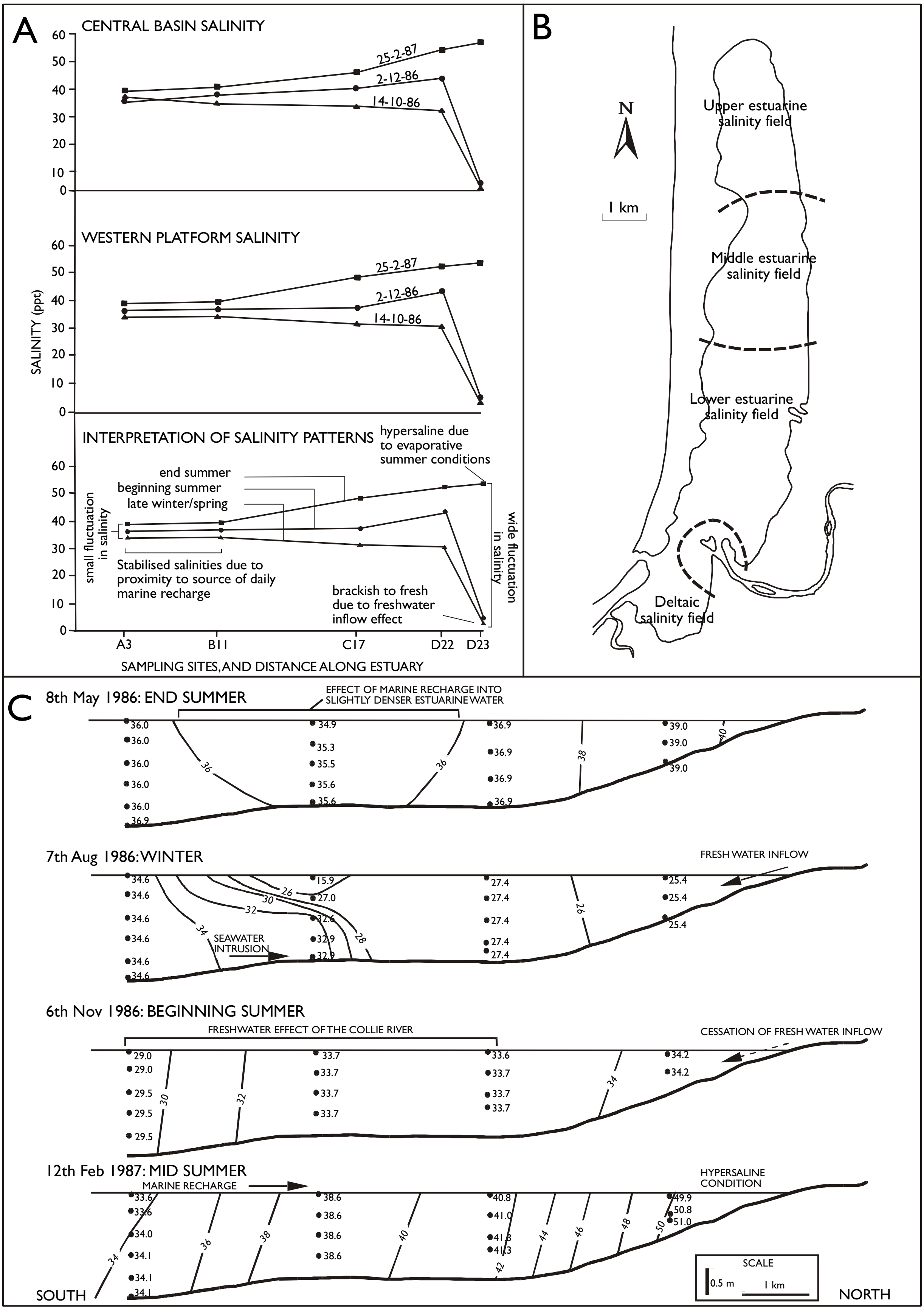

Figure 7. Aspects of the salinity of the Leschenault Inlet estuary. **A:** Salinity of the estuary in the central basin and platform, and interpretation of the trends (modified from Wurm & Semeniuk 2000). **B:** The salinity fields from south to north along the estuary (modified from Wurm & Semeniuk 2000). **C:** South to north salinity profiles and interpretation of dynamics for various seasons 1986-1987 (unpublished data from Wurm & Semeniuk 1986/1987).

tary structures are related to several factors: the nature of the shores that provide reworked material (*e.g.* quartz sand of the eastern shore *vs* quartz and carbonate sand of the western shore), local hydrodynamics (*e.g.* below wave base and thus mud-accumulating, as in the central basin; or predominately wave agitated and hence mud-free sand, as in the eastern platform), and the type of biota as related to environmental conditions.

Hydrological seepages

The Leschenault Peninsula barrier is underlain by dune sand, in turn underlain by muddy to sandy estuarine sediment. Along the estuarine shore, stratigraphic relationships between these sediments are complex. Dune sand fingers extend into muddy environments of the estuary, and muddy sediments accumulate between dune promontories to develop a laterally alternating system of dune sand bodies and muddy sand or mud, each with different hydrologic properties. The barrier separates oceanic water from estuarine water, but beneath the barrier there is a prism of fresh groundwater, with a saline / freshwater interface on both the ocean and estuarine side (Semeniuk & Meagher 1981b). During winter and spring, there is a marked hydraulic head between the fresh groundwater table and marine / estuarine waters, and freshwater discharges into lowlands and adjoining tidal zones as surface seepages (Cresswell 2000). All discharges are pronounced during low tides, especially during equinoctial tides. The consequences of these freshwater discharges are: linear seepage lines along the upper estuarine shore, inhabited by *Juncus kraussii*; more localised, intense discharges inhabited by *Avicennia marina* or by *Melaleuca rhaphiophylla*; and local freshwater to brackish pools in high tidal marshes, which are used by avifauna and mammals.

Peripheral vegetation

Leschenault Inlet estuary is a classic "classroom" for student studies and ecological research of estuarine peripheral vegetation, and it ranks as one of the most significant along the coast of the Swan Coastal Plain (Pen *et al.* 2000). There is a complex of shore types and wetland types peripheral to the estuary (Fig 9). Factors influencing development of these include ancestral landform (*e.g.* the eastern shores), dune dynamics (along the western barrier dune shore), hydrodynamic processes, estuarine coastal processes and sedimentation, and a variable Holocene sea level history. The resulting peripheral estuarine habitats, and salinity gradients therein have resulted in a range of vegetation distributed in mosaics and zones along the shore. The habitats include supratidal flats (samphire-vegetated), high tidal platforms (samphire- or rush-vegetated), tidal embayments (residing between dune corridors), zones of freshwater seepage at interfaces between high tidal platforms and dunes (rush-vegetated), cliffed sandy shores (coastal erosion of dunes), steep dune shores (where dunes are encroaching into the estuary), beachridges, spits, bar-and-lagoon complexes, stranded (relict) sand platforms, and the Collie River and Preston River deltas.

Based on vegetation structure, composition, salinity tolerance, and proximity to shore, five types of vegetation

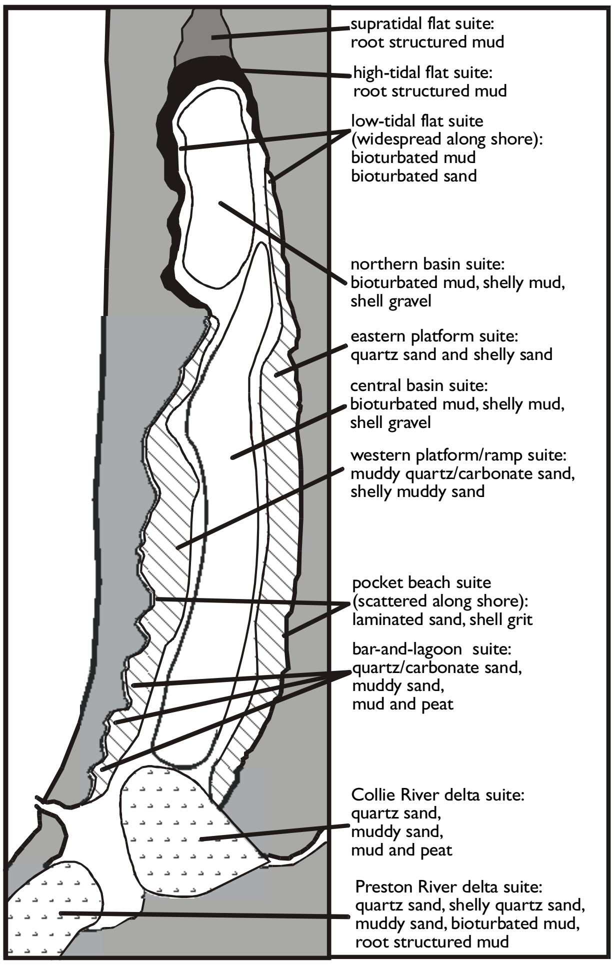

Figure 8. Sedimentary patterns in the Leschenault Inlet estuary showing the main sediment types in the various facies.

are recognised fringing the estuary (Pen *et al.* 2000). There is saltmarsh, comprising samphires and rushes (dominated by *Halosarcia* spp, *Sarcocornia quinqueflora*, *Frankenia pauciflora*, *Juncus kraussii*, amongst others) developed in saline tidal areas. Estuarine fringing forests, typically of small saltwater sheoak (*Casuarina obesa*), saltwater paperbark (*Melaleuca cuticularis*), paperbark (*Melaleuca viminea*), and swamp paperbark (*Melaleuca rhaphiophylla*) inhabit areas where the elevation increases and soilwater salinity is not extreme. There is fringing vegetation consisting of emergent species living more or less permanently in shallow water (*e.g. Schoenoplectus validus*). Sandy rise vegetation occurs on the crest of sand bars, on margins of high coastal sand dunes, or on low estuarine beach dunes. Freshwater vegetation (forest and disturbance-related types) inhabit areas close to the estuary in areas receiving substantial freshwater input.

White mangrove *Avicennia marina*

Avicennia marina forms scrub, heath, or shrubland in three settings, illustrating different relationships to geomorphic setting and salinity (Fig 9). It is best developed in the marine Preston River Delta where there is daily tidal exchange. It forms scattered shrubs in the upper estuary, inhabiting high tidal platforms, and forms a local copse adjoining a steep dune front where there is fresh water seepage. Population structures of *Avicennia* show polymodality with adult-dominated varying to seedling / sapling-dominated populations at different locations. Changes in mangrove distribution and density have occurred over time *viz* an increase of mangroves both in the Preston River Delta and in front of the steep dune shore, and establishment of small shrubs / saplings on high tidal platforms.

Avicennia in this region is scientifically important as the most southerly occurrence of the species in Western Australia. Semeniuk *et al.* (2000a) present hypotheses to explain this occurrence, ranging from a once widespread coastal distribution and then contraction to this region during the latter Holocene, to being only a recent arrival to the estuary, linked to the Leeuwin Current. Palynology supports the idea that *Avicennia* is only a recent arrival to the region.

Pollen

The Leschenault Inlet estuary is a unique natural laboratory in Western Australia for palynological research with regard to vegetation source, wind directions, dispersal via estuarine currents, taphonomy, and establishment of pollen assemblage baselines for the various estuarine environments. From a geoheritage perspective, the estuary would rank as significant at a National level. The estuarine system is comprised of north-south trending sedimentary environments and shore-parallel vegetation complexes, with both easterly and westerly winds and two rivers contributing to the pollen influx (Semeniuk *et al.* 2000b). Using family groupings (*e.g.* Chenopodiaceae, Myrtaceae, Casuarinaceae, Gramineae and Restionaceae) and several diagnostic species (*Frankenia pauciflora*, *Olearia axillaris*, and *Lepidosperma gladiatum*), preliminary results show that the major sedimentary environments (*e.g.* saltmarsh, western and eastern subaquatic platforms, and central basin) have characteristic pollen, with gradients in abundance of specific pollen related to proximity of vegetation source and type of transport.

Estuarine tidal to aquatic benthic habitats

Bathymetry and large scale geomorphology (*i.e.* central basin, eastern and western platforms, northern flat, tidal zones, and the Collie River delta), and their associated substrates, in combination with hydrodynamics, estuarine salinity patterns, and aquatic vegetation are used to categorise habitats for benthos (Wurm & Semeniuk 2000). Excluding high-tidal peripheral saltmarsh systems, 19 low-tidal to subtidal estuarine habitats have been recognised (Fig 10). Within the upper estuarine salinity field, there is intertidal mud, intertidal sand, vegetated flat mud, and vegetated flat sandy-mud. The central basin spanning the mid and lower estuarine salinity fields, contains sparsely vegetated basinal mud and sandy-mud. The western platform, spanning the mid and lower estuarine salinity fields, contains intertidal sand, intertidal mud, intertidal muddy-sand, intertidal sandy-mud, vegetated platform muddy-sand, vegetated platform mud, and vegetated platform sand. The eastern platform, spanning the mid and lower estuarine salinity fields, contains intertidal sand, vegetated platform sand, and vegetated platform muddy-sand. The Collie River delta, within the deltaic salinity field, has intertidal sand and shallow water sand. Along the northeastern part of the estuary, there is a tidal limestone platform (cut into Pleistocene Kooallup Limestone), veneered by mud; the mud is periodically stripped off by waves, locally exposing the platform.

Seagrasses and aquatic algae

At least 3 species of seagrass and 7 species of algae occur in the estuary (Hillman *et al.* 2000; Wurm & Semeniuk 2000). Seagrasses include *Halophila ovalis*, *Ruppia megacarpa* and *Heterozostera tasmanica*. Algae include *Chaetomorpha linum*, *Gracilaria* spp, *Ulva* sp, 2 species of Phaeophyta (including *Hormophysa triquetta*), and *Acetabularia* sp Macrophyte distribution and abundance appears determined by depth, substrate and salinity field. Hillman *et al.* (2000) found a total plant biomass generally of 3 000-5 000 tonnes dry weight, with a maximum in spring, with large differences in biomass of seagrass and macroalgae between their individual surveys. Seagrass and total macroalgal biomass, however, appear relatively stable in the medium term. The greatest biomass was noted for *Halophila ovalis*-dominated platforms (Fig 9). *Halophila ovalis* is the most widespread species in the estuary, inhabiting western and eastern platforms, and the subtidal muddy northern flat. *Ruppia megacarpa* inhabits shallow intertidal depressions. *Gracilaria* also is relatively abundant, particularly in the southern estuary, and drifts occur on otherwise bare mud in most peripheral and intertidal portions of the northern flat. *Chaetomorpha* variously covers shallow water mud areas, and *Chaetomorpha* and brown algae are common towards the northern eastern platform. *Acetabularia* inhabits sandy substrates of the eastern shores of the northern flat. Hillman *et al.* (2000) conclude the aquatic flora of this estuary to be similar to other south-western Australian estuaries, but with a relatively high diversity of red algae, and *Hormophysa triquetra* as the dominant brown alga.

The leaves of *Halophila* have encrusting epibionts that include bryozoa, sepulid worms, other tubular worms, egg cases, and diatoms. Faunal epibiota are not common, but diatoms are locally very dense.

Phytoplankton and zooplankton

Hosja & Deeley (2000) show that marine and estuarine diatoms dominate the phytoplankton community in the estuary for most of the year. Bacillariophyta and Dinophyta were most abundant throughout the year, with Cryptophyta and Cyanophyta additionally present mainly in the winter months. The most abundant taxa include *Skeletonema costatum*, *Rhizosolenia setigera*, *Chaetoceros perpusillum*, *Chaetoceros didymum*, *Chaetoceros straightout*, *Chaetoceros* sp and *Nitzschia closterium*. Spatial and temporal variability in phytoplankton densities and species numbers occurred throughout the estuary, and short-term blooms were observed during autumn and spring. Species with affinity for freshwater were observed during winter and included diatoms, dinoflagellates, cyanophytes and cryptophytes, and were probably transported into the estuary by winter runoff. There was a high proportion of normally benthic or epiphytic species in surface waters reflecting very shallow depths and significant wind mixing in the estuary. Some species were attached to seagrass

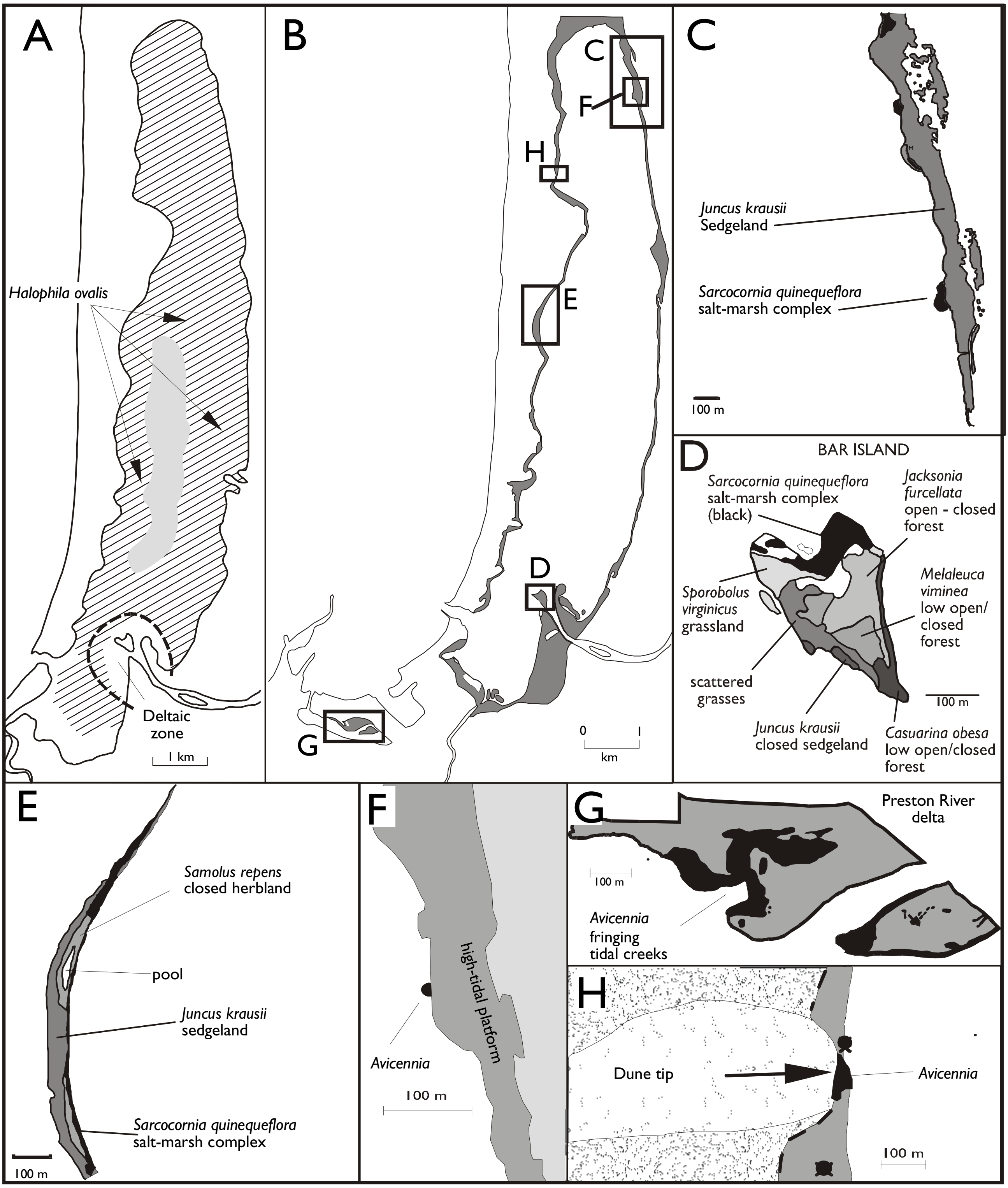

Figure 9. A: Distribution of *Halophila ovalis*, the main seagrass species in the Leschenault Inlet estuary, after Lukatelich (1989), located mainly on the shallow water platforms and their slopes that descend to the central basin. **B:** Distribution of estuarine peripheral vegetation in 1989 (from Pen *et al* 2000); insets show more detailed maps. C, D, & **E:** Details of vegetation types along selected portions of the estuarine shore (simplified from Pen *et al* 2000). F, G & **H:** The three setting for *Avicennia marina* in the area (from Semeniuk *et al* 2000b). **F:** shows mangrove shrubs at edge of high-tidal platform. **G:** mangrove distribution in the Preston River delta. **H:** mangrove located at the tip of a dune encroaching into the estuary.

leaves, the most abundant included *Acnanthes*, *Cocconeis*, *Gramatophora*, *Mastogloia* spp, *Paralia sulcata*, and *Synedra* spp. Changes in composition occurred from south to north.

Zooplankton was sampled during summer by Hosja & Deeley (2000) to identify dominant organisms, which included *Sulcanus conflictus*, *Acartiura*, 3 species of Cyclopoid, 2 species of Copepod, 2 species of Calanoiods, 3 species of Hapacticoids, polychaete larvae, *Naupius* larvae, and Malacostraca.

Foraminifera

The foraminiferal fauna of the Leschenault Inlet estuary is exceptional (Revets 2000), with extremely high diversity, exceeding that in most normal marine environments: 118 species were recorded from a total of 1435 specimens examined. Reworking and relict faunas does not explain this diversity. Diversity decreases from south to north, as environments change from stable marine to more extreme conditions, and from east to west, reflecting an increase in contributions of porcellaneous taxa to the overall species spectrum, with a reduction in numbers and diversity of hyaline taxa. The foraminiferal fauna is benthic, and indicative of shallow water. Revets (2000) found the dominant species to be *Ammonia tepida*, followed by *Paratrochammina challengeri* and *Parrellina hispidula*. Planktonic taxa are absent, signaling no significant transport from the ocean into the estuary. With the exception of a single *Planorbulina acervalis*, encrusting forms also are absent, with *Halophila ovalis* seagrass leaves showing no foraminiferal epibionts. Foraminifera typically associated with marginal environments, such as *Ammotium salsum*, *Jadammina macrescens* and *Miliammina fusca* also were absent.

Molluscs

Thirty one species of shelly mollusc, and one unidentified nudibranch, have been recorded in the estuary (Semeniuk & Wurm 2000). These were classified as true estuarine (*e.g. Acteocina* sp, *Xenostrobus securis, Hydrococcus brazieri, Fluviolanatus subtorta, Assiminea* sp, *Salinator* sp), euryhaline marine (*e.g. Tellina deltoidalis, Tellina* sp, *Theora lubrica, Sanguinolaria biradiata, Philine angusi, Nassarius burchardi, Bedeva paivae, Spisula trigonella, Epicodakia* sp, *Laternula creccina*), and stenohaline marine (*e.g. Bittium granarium*, *Mytilus edulis, Polinices conicus, Pholas australasiae, Nassarius nigellus, Solemya australis, Irus crenata, Venerupis anomala*). Only seven mollusc species were common in the estuary *viz Arthritica semen, Tellina deltoidalis, Nassarius burchardi, Spisula trigonella, Hydrococcus brazieri*, and *Acteocina* sp, and *Bedeva paivae* (Fig 11), inhabiting tidal sand or tidal mud, shallow water platform sand or muddy sand, or deep water basin mud, within lower, middle or upper estuarine salinity fields (Fig 12A). Five years of sampling show the longevity and variability of the molluscan assemblages (Fig 13; Semeniuk & Wurm 2000). The overall character of mollusc assemblages remained similar, but with changes in composition inter-annually and intra-annually: some species were consistently present, though abundance varied seasonally, while others fluctuated markedly, varying from absent to present. Abundance for a given species often fluctuated independently of others and did not appear to reflect patterns in oxygen concentration, temperature or salinity. Many species decreased in abundance over the study period (Cresswell *et al.* 2000). Population structures investigated for *Spisula trigonella*, *Tellina deltoidalis*, and *Nassarius burchardi* over 5 years show *Spisula* populations to be numerically dominated by one age cohort, and not maintained by further recruitment, *Tellina* populations to be maintained by a relatively continuous seasonal low level juvenile recruitment, and *Nassarius* populations to be dominated by a mature age cohort, with a low level intermittent juvenile recruitment.

Small benthic and epibenthic crustaceans

Twenty one species of small benthic and epibenthic crustacea were recorded for the Leschenault Inlet estuary from 1982-1997 (T A Semeniuk 2000). The most abundant species were the isopod *Tanais* sp nov and the amphipod *Corophium* sp (Fig 11). Spatial distributions of crustacean species, encompassing isopods, amphipods, and small crabs, appear to be linked to salinity patterns or to the presence of aquatic vegetation (Fig 12 C). A few species showed preference for particular substrates or depths. Crustacean populations typically showed seasonal unimodal peaks in numbers during summer, with densities typically an order of magnitude greater than winter densities (Fig 13). The magnitude of summer recruitment varied annually for most species, linked to favourable environmental conditions. Changes in population density and distribution were likely linked to adult migration and juvenile recruitment. Over the five years of study, there was an overall decline in abundance of the main species and changes in species composition, signaling a long-term environmental change within the estuary. Hass & Knott (2000), in reporting on sphaeromatid isopods in the area, note that two of the species may have been introduced, most likely by recreational boats.

Blue swimmer crab

The Blue swimmer crab, *Portunus pelagicus* (Fig 11), is a large benthic carnivore in the estuary and the adjoining marine embayment (Koombana Bay). Spawning period, the timing of immigration and emigration and growth patterns of this crab in the estuary are similar each year (Potter & de Lestrang 2000). The crab releases zoeae in Koombana Bay, rather than in the estuary, during mid-spring to late summer, and while a few recruits enter the estuary, their numbers do not start to rise until the following spring, along with rising salinities and water temperatures. After one year, many females and males have reached moderate size (carapace width *ca* 80-90 cm). During the subsequent winter, with lower salinities and water temperatures, numbers of older crabs (*ca* 18-20 months in age) decrease markedly, with a concomitant rise in numbers in the shallows of Koombana Bay.

Polychaetes

A total of 15 polychaete species have been recorded within Leschenault Inlet (Dürr & Semeniuk 2000). Distributions of the dominant species are linked to environmental factors, particularly salinity, water depth and substrate. Three broad polychaete assemblages characteristic of the different environments can be identified (Fig 12 D). Long-term density changes of the three most common species, *Ceratonereis aequisetis, Nephtys gravieri* and *Capitella cf capitata* (Fig 11), followed complex patterns (Fig 13). Population density at many sites typically reached a peak in late summer to autumn, but annual periodicity at the scale of the estuary was not obvious for the overall population density of a given species, because large year-to-year variability at single sites and phase differences between sites probably masked the pattern. Long-term trends for *C. aequisetis* at neighbouring sites showed synchronicity, but no relationship to seasonal variation in abiotic factors, suggesting that spatial and temporal changes in polychaete distribution mostly reflect local environmental conditions.

Ophiuroids

A small cosmopolitan, normally oceanic ophiuroid (a brittle star), *Amphipholis squamata* was recorded at varying times over 17 years (1982-1999) in the estuary (Unno 2000). Between 1982-1987, *A. squamata* formed sporadic low density populations in restricted habitats (Fig 12 B), mostly near the boundary of the middle to upper estuarine salinity fields, in well-oxygenated water, with mud to muddy sand substrates, and with usually some seagrass or algae. At specific times (August 1984, September 1986 to March 1987, and October 1990), ophiuroid populations were extremely dense, with the main population located at the boundary of the middle to upper estuary, but with outliers to the north and south.

Fish fauna

Potter *et al*. (2000) describe the fisheries in the Leschenault Inlet estuary, the marine Koombana Bay, and estuarine reaches of the Collie River. Forty two species of fish were recorded from these nearshore and shallow waters in 1994. The most abundant species were the long-finned goby *Favonigobius lateralis*, the sandy sprat *Hyperlophus vittatus* and the atherinids *Leptatherina presbyteroides* and *Atherinosoma elongata* (Fig 11). Twenty of the 42 species were marine, using the estuary as a nursery area (marine estuarine opportunists), and thirteen complete their life cycles within the estuary. The composition of the fish fauna of the shallows of the estuary differs markedly from that of shallow waters in Koombana Bay. The most abundant species in Koombana Bay, the flathead sandfish *Lesueurina platycephala*, was never recorded in the estuary. Fish catches in the deeper estuarine waters include larger species dominated by marine estuarine opportunists and the Perth herring *Nematalosa vlaminghi*. Fish in the Collie River comprised far more species and relatively greater numbers of teleosts, such as yellow-eye mullet (*Aldrichetta forsteri*), tailor (*Pomatomus saltatrix*) and Australian herring (*Arripis georgianus*), and greater numbers of Perth herring and sea mullet (*Mugil cephalus*). The main commercial species in the estuary are *Aldrichetta forsteri*, *M. cephalus*, *S. schomburgkii* and *N. vlaminghi*. The recreational fishery was dominated by three species of whiting (*S. punctata*, *S. schomburgkii* and *Sillago burrus*) and *P. saltatrix*.

The most abundant species were classed by Potter *et al*. (2000) into 5 categories of feeding modes. These are herbivores feeding mainly on algae associated with seagrass (*e.g. Hyporhamphus melanochir*, *Pelates sexlineatus*), and

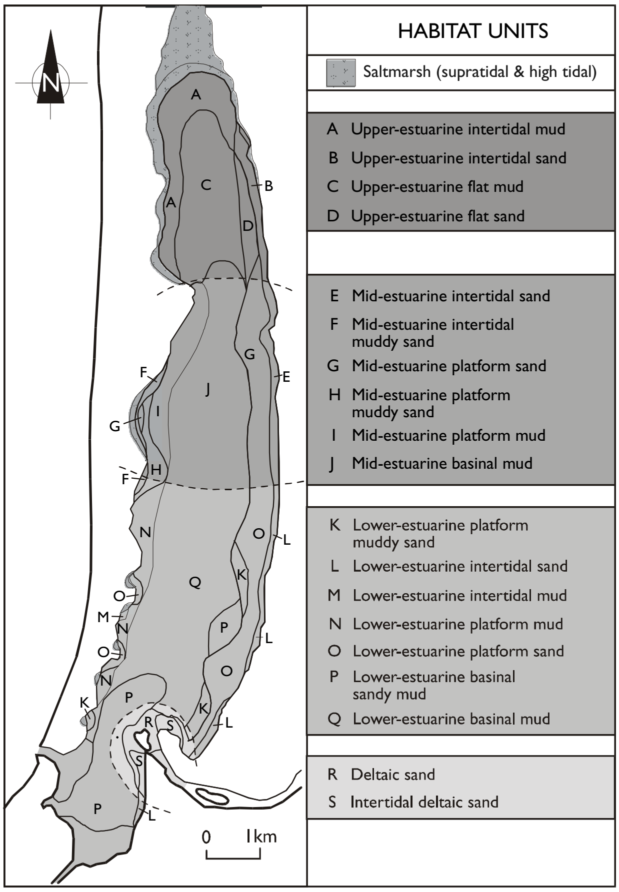

Figure 10. Habitat units in the Leschenault Inlet estuary (modified from Wurm & Semeniuk 2000). The upper, middle, lower and deltaic fields are coded in decreasing shades of grey for ease of referring to the habitat units therein.

detritivores (*e.g. M. cephalus*, *N. vlaminghi*). Omnivores feed on algae and a range of invertebrates (*e.g. A. forsteri*, *Amniataba caudavittata*). Lower order carnivores feed on small benthic invertebrates (*e.g. A. elongata*, *F. lateralis*, *L. presbyteroides*, *S. punctata*, *S. schomburgkii*, *Torquigener pleurogramma*). Higher order carnivores feed on larger and more active invertebrates and fish (*e.g. Argyrosomus japonicus*, *P. saltatrix*).

Avifauna

As a large, permanent water body with a mixed array of habitats, the Leschenault Inlet estuary supports significant waterbird populations. From nine waterbird surveys conducted over 1987 and 1988, some 23 565 waterbirds, comprising 57 species, were recorded from the estuary, its fringing wetland areas, and in some closely associated outlying wetlands (Raines *et al.* 2000). The five most abundant species were (Fig 11): the Red-necked Stint (*Calidris ruficollis*), the Little Pied Cormorant (*Phalacrocorax sulcirostris*), the Silver Gull (*Larus novaehollandiae*), the Black Swan (*Cygnus atratus*), and the Grey Teal (*Anas gracilis*). The noticeable waterbirds along the saltmarsh shore (Fig 11) are the Great Egret (*Ardea alba*) and the White-faced Heron (*Egretta novaehollandiae*). Waterbirds extensively use most habitats within the estuary and outlying wetlands,

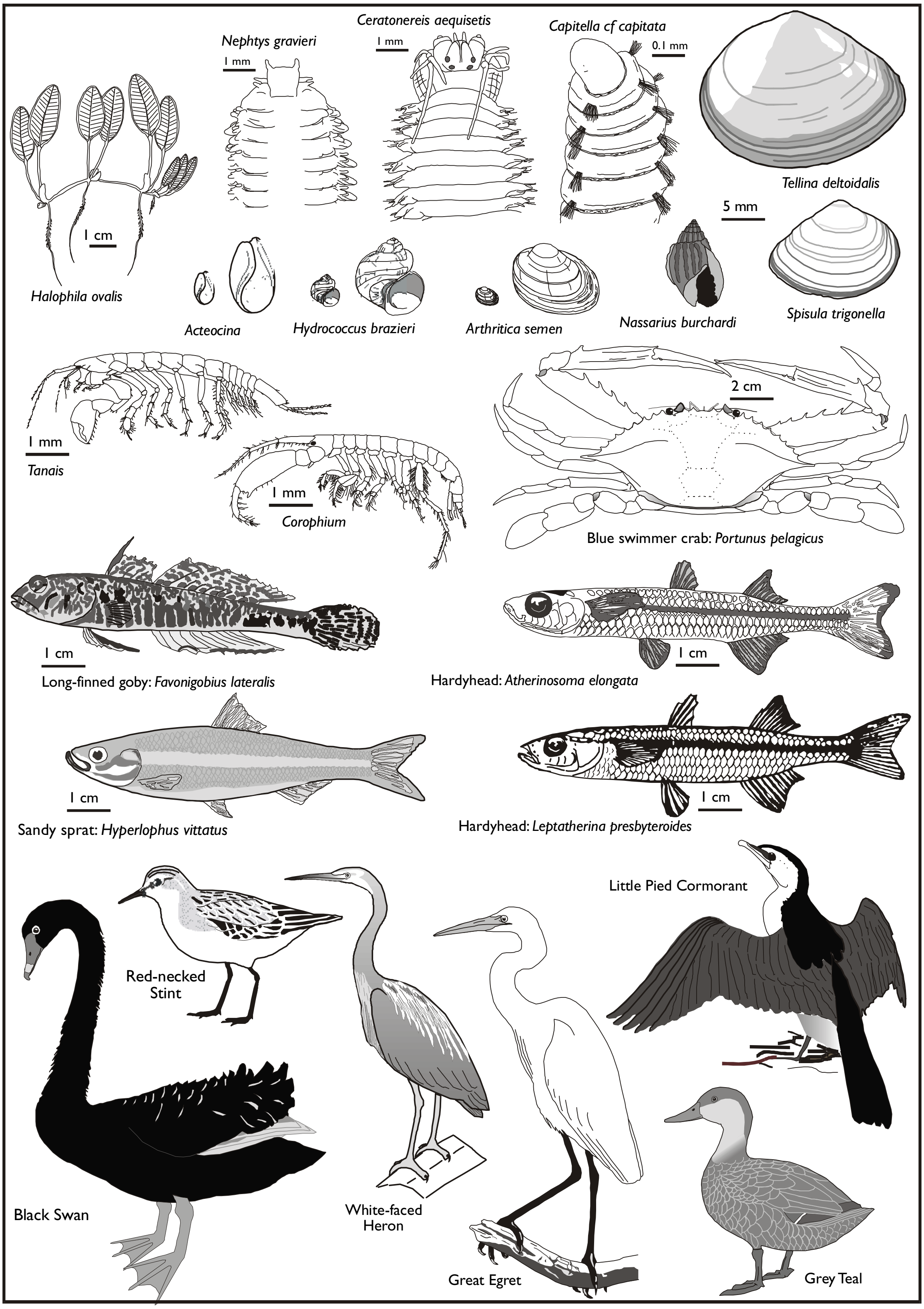

Figure 11. The most common flora and fauna in the Leschenault Inlet estuary. Crustaceans, polychaetes, fish, avifauna, and some molluscs redrawn with modifications from the following sources: Allen (1982), Barnard & Karaman (1991), Boeggemann (1997), Holdich & Jones (1983), Hutchings & Glasby (1985), Hutchins & Thompson (1983), Rainer & Hutchings (1977), Simpson & Day (1996), and Wells (1984). Bar scales are marked for the various species except the avifauna, which mostly are large species (however, the Red-necked Stint is 15 cm in size). While the molluscs relate to a single 5 mm bar scale, the small molluscs are drawn at two sizes; the smaller drawing relates to the bar scale, and the larger drawing illustrates detail.

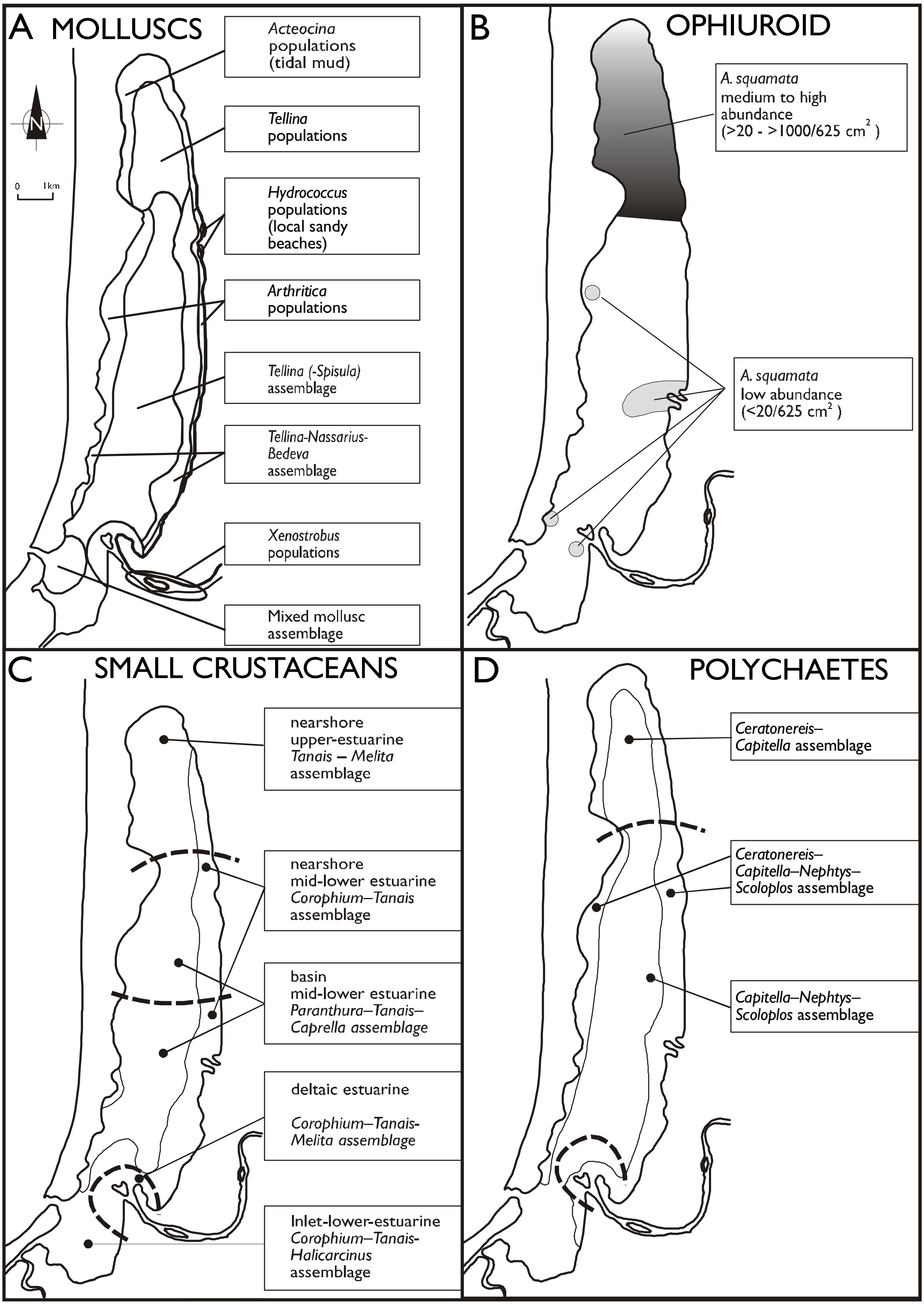

Figure 12. Occurrence of key benthic faunal assemblages and populations in the estuary (data from Semeniuk & Wurm 2000; TA Semeniuk 2000; and Dürr & Semeniuk 2000).

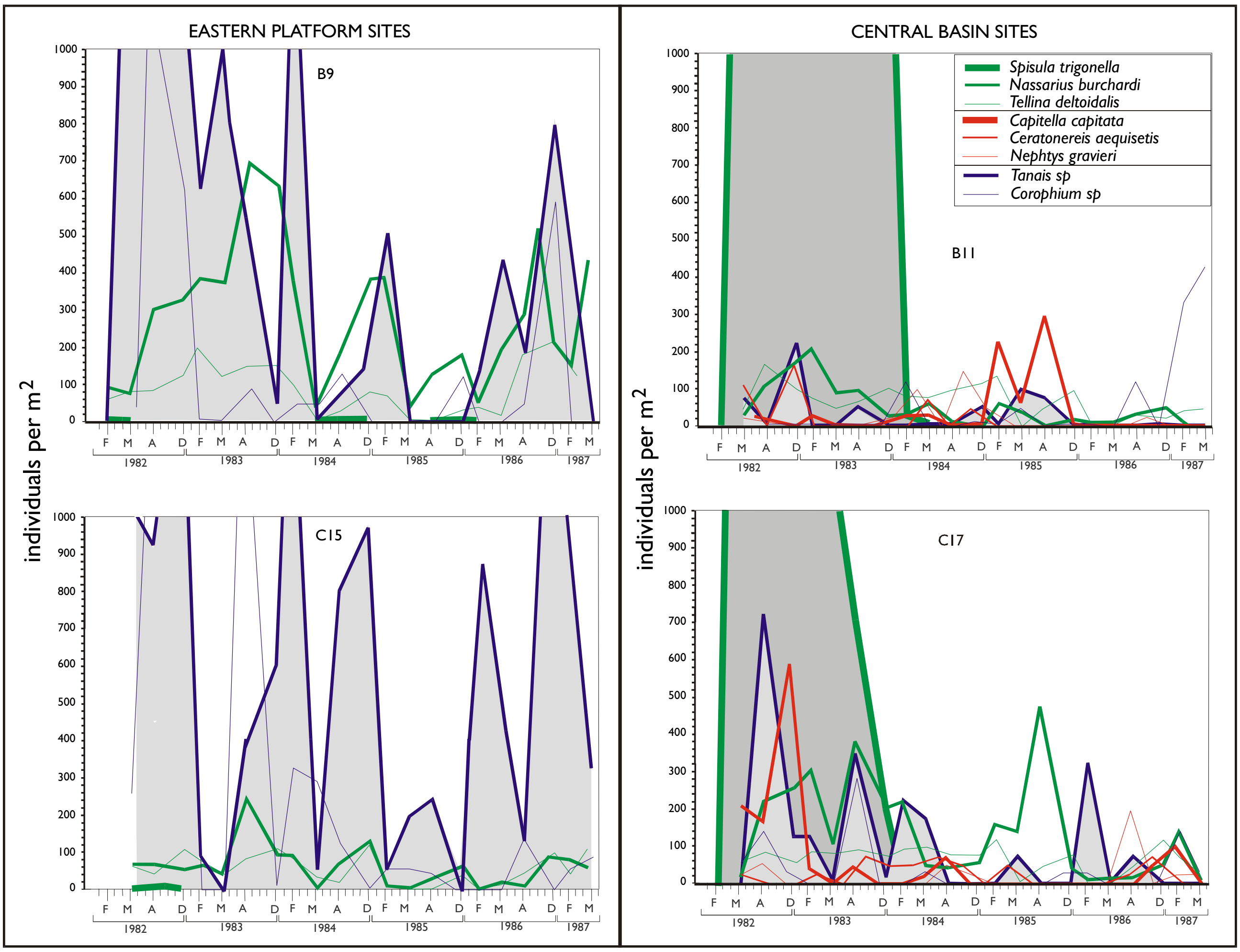

Figure 13. Temporal variation in key species of invertebrate fauna during the period 1982-1987 for selected sampling sites in the estuary (data from Semeniuk & Wurm 2000; TA Semeniuk 2000; and Dürr & Semeniuk 2000). The sites selected are two eastern platform sites (B9 & C15) and two central basin sites (B11 & C17). The graphs showing the two most abundant species are filled in with grey (*Spisula*) and light grey (*Tanais*) to highlight their patterns and to create a backdrop against which to view the other species.

often for different purposes. Open-water habitats (the deep-water basin, sandbars and shallow water reaches) support a large part of the waterbird population (including Little Black Cormorant, White-faced Heron, Hoary-headed Grebe, Black Swan and Musk Duck), and are mostly used for feeding. Fringing wetland habitats (wet and dry salt marshes and pools), support a greater density and a larger variety of waterbirds (including Grey Plover, Red-necked Stint, Sharp-tailed sandpiper, Black-winged Stilt and Grey Teal), and are used for feeding, roosting, and breeding.

Raines *et al.* (2000) determined significance of habitats within the estuary and out-lying wetlands by analysing numbers, species richness and behavioural activity of waterbirds in each habitat type. The estuary is an important waterbird location and is likely to be critical in the wetland network used by waterbirds in this region. As a dry season refuge for waterbirds in mid spring and summer, it ranks amongst the top wetlands in south-western Australia in terms of species richness, numbers of waterbirds and numbers and richness of species protected under international migratory bird agreements.

Population dynamics and episodic explosions

Several studies have shown the variable nature and overall trend of biota in the estuary over the medium term (5-20 years). Some species population numbers fluctuated markedly from year to year, as well as intra-annually. Other species showed seasonal fluctuations. A number of mollusc, small crustacean and polychaete species also showed a general decline in abundance over the period 1982-1987. Using data from Semeniuk & Wurm (2000), T A Semeniuk (2000) and Dürr & Semeniuk (2000), relative abundances of the three most common species of mollusc, two most common species of small benthic crustacea, and three most common species of polychaete over the period 1982-1987 are shown for some selected sites (Fig 13). These results show several patterns (Fig 14). There is marked variation in species abundance from site to site. Species that at times show seasonal fluctuations include *Corophium*, *Tanais*, *Tellina*, and *Nassarius*, with some of these species abundant in the winter to post-winter period, and others in the summer. *Tanais*, and some sites for *Tellina* and *Nassarius* show a general decline in population abundance. There were also

Table 2. Comparisons between 1982-1987 and 1998 in environmental conditions and biota for selected sites (sample sites of Wurm & Semeniuk 2000)

Site	Description 1982-1987	Description May 1998	Habitat changes
A5	shallow water platform: dense seagrass cover, moderate to abundant invertebrate fauna	no seagrass, molluscs and benthic small crustacea absent, low abundance of polychaetes	muddy sand habitat remained similar
B9	shallow water platform: dense seagrass cover, moderate to abundant invertebrate fauna	no seagrass, molluscs and benthic small crustacea absent, low abundance of polychaetes	muddy sand habitat remained similar
B11	deep water basin: low to no seagrass cover, generally moderate to low abundance of invertebrate fauna, except for the *Spisula* invasion	no seagrass cover, absence of invertebrate fauna	mud habitat remained similar
B13	shallow water platform: dense seagrass cover, generally moderate to abundant invertebrate fauna	no seagrass, molluscs and benthic small crustacea absent, low abundance of polychaetes	muddy sand habitat remained similar
C16	shallow water platform: dense seagrass cover, moderate to abundant invertebrate fauna	no seagrass, molluscs and benthic small crustacea absent, low abundance of polychaetes	muddy sand habitat remained similar
C17	deep water basin: low to no seagrass cover, generally moderate abundance of invertebrate fauna	no seagrass cover, absence of invertebrate fauna	mud habitat remained similar
C18	shallow water platform: dense seagrass cover, generally moderate to low abundance of invertebrate fauna	no seagrass, molluscs and benthic small crustacea absent, low abundance of polychaetes	original sandy mud habitat now covered in 2-3 cm of mud
D22	shallow water mud flat: patchy algal cover, temporally variable high, moderate to low abundance of invertebrate fauna	no vegetation cover, molluscs absent, low abundance of polychaetes and benthic small crustacea	mud habitat remained similar

episodic increases in population abundance for some species superimposed on any seasonal fluctuations (*viz Capitella*, *Corophium*, *Spisula*). For the mollusc data, Cresswell *et al.* (2000) corroborate these patterns mathematically, and conclude that inter-annual variation in molluscan composition is so marked that it would be difficult to categorise biota in terms of consistent assemblages.

To determine the status of the estuary 10 years after the previous detailed invertebrate sampling (between 1982 and 1987), we resampled many of the 22 sites described in Wurm & Semeniuk (2000) in April 1997 and in May 1998. The May 1998 survey concentrated on sampling at least one western platform site, one deep water basin site, and one eastern platform site along the Transects A, B, C, and D. Both the April 1997 and the May 1998 surveys showed seagrass generally to be in low abundance or absent throughout the estuary, molluscs similarly to be in low abundance or absent, benthic small crustaceans (whose abundance is related to seagrass cover) to be generally in low abundance to absent, and polychaetes to be generally present but in low abundance (with an added complication that polychaete species composition had changed; Dürr & Semeniuk 2000). The May 1998 results are summarised in Table 2. Some of the fauna changes may be linked to habitat substrate changes: for example, sandy mud at site C18 of Wurm & Semeniuk (2000), that between 1982 and 1987 was consistently covered in dense *Halophila* with moderate to abundant invertebrate fauna, in May 1998, was veneered by 2-3 cm of

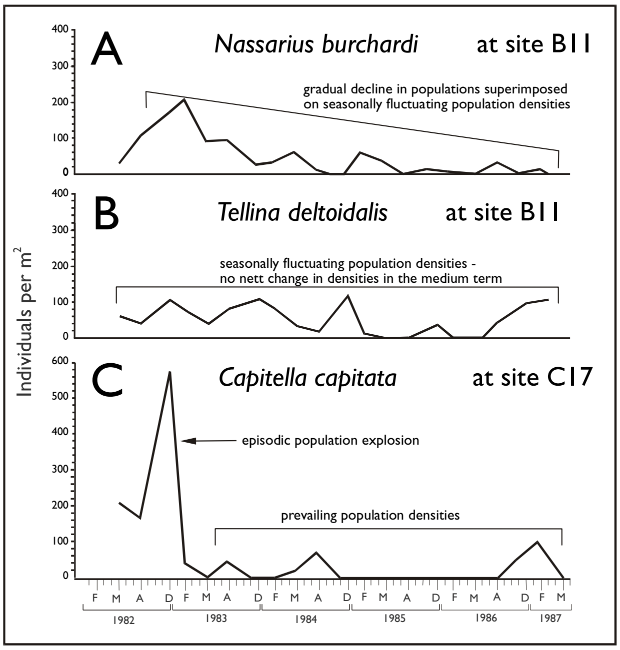

Figure 14. Specific examples derived from Figure 13 of patterns of population abundance for three species. A. Overall decrease in abundance superimposed on seasonal fluctuations in density. B. Seasonal fluctuations in population density. C. Periods of episodic populations explosions amid a prevailing situation of generally low population numbers.

mud, had no seagrass cover, and was depauperate in fauna. However, at other sites there was no change in sediment substrate, but significant change in biota *e.g.* Site A5, that was consistently covered in a dense *Halophila*, with moderate to abundant invertebrate fauna between 1982-1987, in May 1998, though still underlain by muddy sand, had no seagrass cover, and was depauperate in fauna.

In summary, the results from the various invertebrate studies show a general decrease in abundance during the period 1982-1987, commensurate with decreasing biomass of seagrass throughout the estuary over the same period (Hillman *et al.* 2000). Although there was no sampling of invertebrate fauna between 1987 and 1998, Hillman *et al.* (2000) indicate that seagrass was abundant in the estuary over the period 1988-1993, and invertebrate fauna similarly may have been abundant. In April 1997 and May 1998 the estuary was biologically depauperate, with negligible seagrass cover at the sampling sites, and low numbers of invertebrate fauna.

Two of the studies in this Volume describe "population explosions", *viz Spisula trigonella* and the ophiuroid *Amphipholis squamata*. Marked increases in population density are also evident in the *Corophium* and *Tanais*. Between 1982 and 1987, *Spisula trigonella* populations experienced massive juvenile recruitment in early 1983 (the "1983 *Spisula* invasion"), resulting locally in tens of thousands of individuals in a square metre for a short term. The populations then rapidly decreased to low numbers. Prior to this, the species appeared to be in very low abundance when sampled by Chalmer & Scott (1984), although this may have been an artifact of the few sampling sites involved. Similarly, the species mostly was absent with the estuary-wide sampling undertaken by the authors in 1998. The ophiuroid *Amphipholis squamata* also showed marked but episodic increases in population density (Unno 2000). Generally, over 17 years, sporadic low density populations of the ophiuroid were recorded in the estuary, in restricted habitats, but at specific times (August 1984, September 1986 to March 1987, and October 1990), populations were dense.

Anthropogenic impacts

Geographically, the major anthropogenic impacts on the estuary have been (Fig 15): 1. destruction of much of the Preston River Delta through land reclamation, dredging and harbour construction; 2. dredging "The Cut", altering estuarine landforms, hydrodynamics and hydrochemistry; 3. destruction of the southern Collie River Delta through urbanisation; and 4. clearing and drainage of estuarine shores, resulting in changes to the peripheral estuarine vegetation. Four types of impacts can be categorised (Table 3).

Description of the reclamation, modification, dredging and urbanisation of the Preston River and Collie River del-

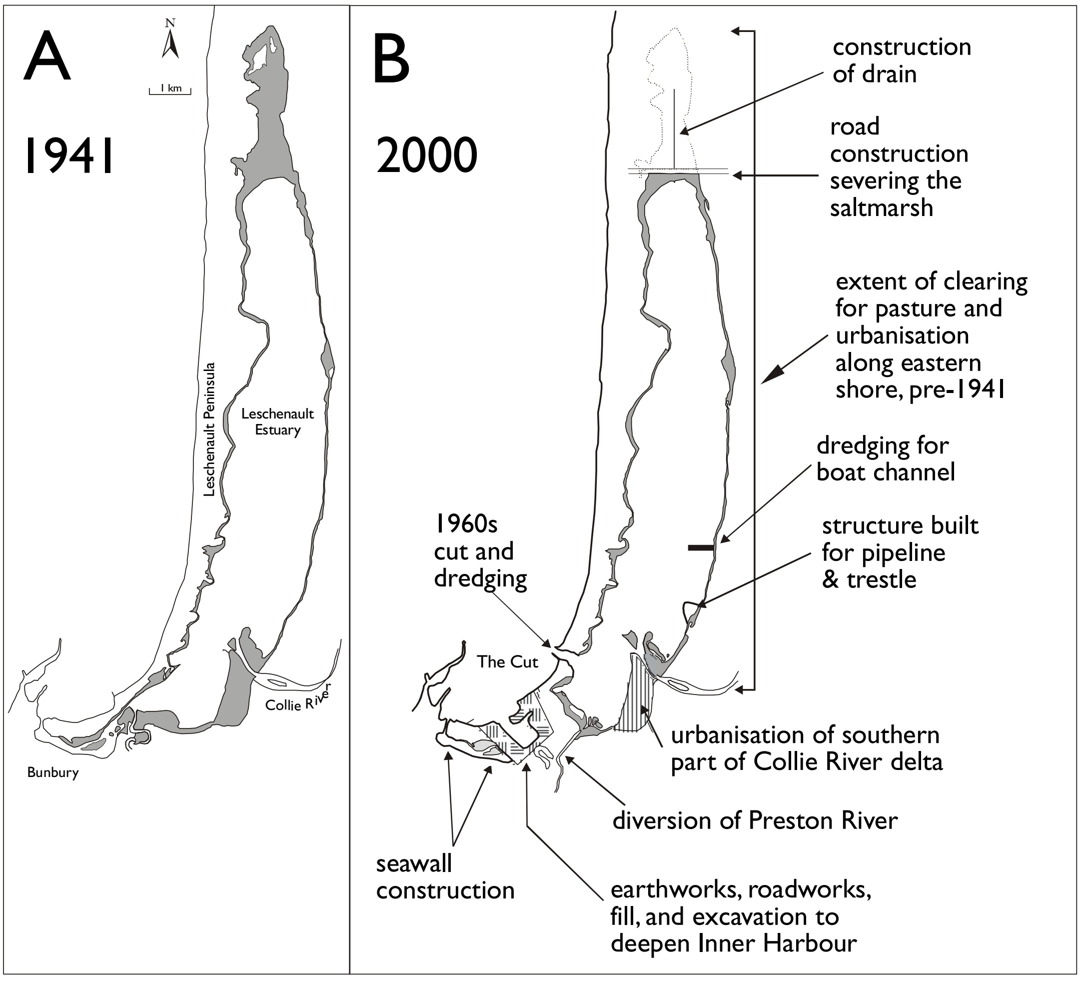

Figure 15. Types and locations of anthropogenic impacts in the Leschenault Inlet area.

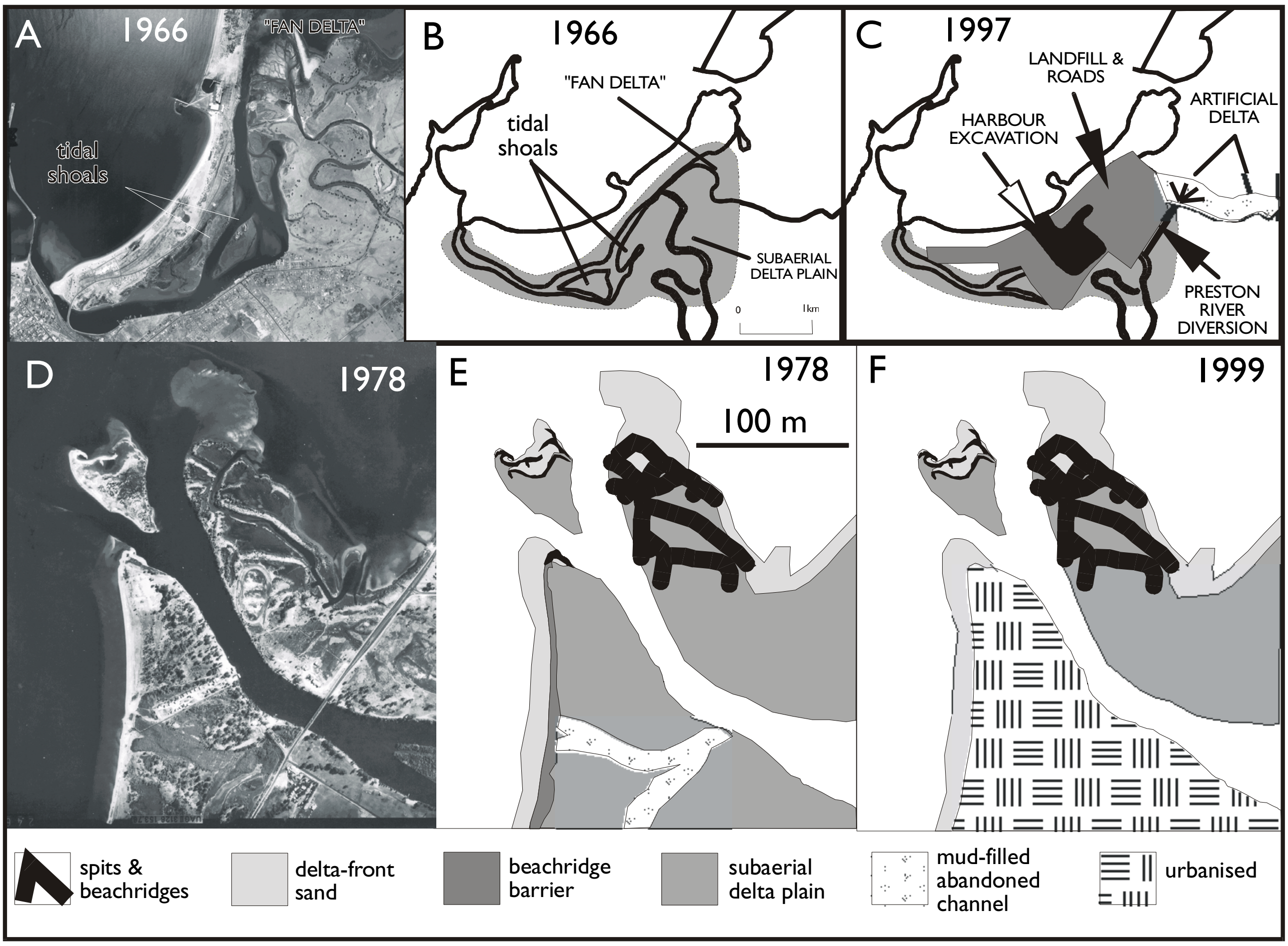

Figure 16. Impacts on the estuarine deltas (A-C: Preston River delta; D-F: Collie River delta). **A:** Aerial photograph of the Preston River delta in 1966, showing tidal shoals, fan delta, and meandering channels on the sub-aerial plain. **B:** Map of the delta in 1966 showing the sub-aerial delta plain, meandering river channels, tidal shoals, and the fan delta. **C:** Four types of anthropogenic impacts on the delta (viz., landfill and roads, harbour excavation, channel diversion, and redirected deltaic sedimentation) largely destroying its integrity by 1997. **D:** Aerial photograph of the Collie River delta in 1978 showing main channel, mid-channel island, cheniers on its northeastern part, sub-aerial plain and abandoned distributary channels on its southern part. **E:** Map of the delta in 1978, showing the geomorphic components. **F:** Map of the delta in 1999, showing extent of destruction of the southern part of the delta through urbanisation.

tas is amplified here and in fig 16, since these geomorphic / sedimentologic features and their vegetation are significant in terms of geoheritage and biogeography (Semeniuk & Semeniuk in press). The deltas in the Leschenault Inlet system comprise the southern part of a dune-barrier-protected elongate shore-parallel lagoon, and both were proximal to the former tidal outlet of the estuarine lagoon. In this context, the Preston River Delta had delta landforms strongly influenced by its tidal setting, resulting in tidal-current oriented deltaic shoals and islands, a type of estuarine delta not present elsewhere in Western Australia. The Collie River Delta, because of its geographic / hydrodynamic setting, has an unusual asymmetry in its internal deltaic landform structure: though overall a fluvially constructed delta and hence forming a projection into the estuary, the delta is beachridge- and chenier-dominated on its northern front facing winter storm waves generated along with the large fetch of the elongate estuarine lagoon, but is fluvial-dominated on its southern front, exhibiting abandoned channels, floodplains and levees.

The deltas of the Leschenault Inlet estuary are / were unlike the estuaries and deltas of the Swan River and other rivers northwards (all of which are shore-normal systems), unlike the Peel-Harvey Estuary, which is a compound type with tidal delta, wave dominated delta and elongate birdsfoot delta (Semeniuk & Semeniuk 1990), and unlike the Vasse-Wonnerup estuarine system which is part of a prograding beach-ridge barrier-and-lagoon complex. Thus, from a State-wide perspective, the assemblage of estuarine and deltaic landforms in the Leschenault Inlet area was unique in central to southern coastal Western Australia. Further, the delta of the Preston River was the main habitat for the most southerly occurrence of the white mangrove *Avicennia marina* (Semeniuk *et al.* 2000b), a feature of State-wide significance.

The Leschenault Inlet estuary currently is mildly nutrient enriched, with nutrient loadings appearing during winter freshwater influx, and related to amount of rainfall and river flow (Anon 1995). The sources of the nutrient are riverine (about 51 tonnes of phosphorous and 610 tonnes of nitrogen enter the estuary annually from such sources; Anon 1995), with contributions from the Collie, Brunswick and Preston

Table 3. Description of impact or effect of the various anthropogenic activities

Activity	Description of impact or effect
Engineering activities	land reclamation and boat harbour construction in the northern Preston Delta; diversion of the Preston River into the (now) southern Leschenault Inlet estuary, and the consequent effects of artificial deltaic sedimentation; dredging and construction of boat harbours, and small to large boat channels; drainage; channeling / dredging of "The Cut" through the Leschenault barrier dune, fundamentally changing the estuarine hydrochemistry and hydrodynamics, and creating a flood tidal delta; landscaping and arresting of dune encroachment, depleting sand supply to the estuary
Alteration of estuarine water quality	nutrient enrichment (fertiliser use) of catchment drainage resulting in influx of nutrients into the estuary; nutrient import from foreshore via fertiliser use and local pastoral activities on the east shore; local contamination through use, storage and leakage of various chemicals and hydrocarbons in the area peripheral to the estuary along its eastern shore
Peripheral land use	clearing for pasture, resulting in nutrient enrichment of water that enters the estuary, and changes in groundwater hydrodynamics and seepage into the estuary; urbanisation resulting in clearing, fertiliser application, and human habitation and consequent destruction of coastal landforms and deltas, nutrient enrichment of water entering the estuary, and changes in groundwater hydrodynamics and seepage into the estuary; drainage alteration
Boating / fishing	boat wake erosion; fishing for fin-fish; netting for crabs; damage to seagrass beds through anchoring

rivers (Fig 1) that drain farmlands in their catchments, as well as local groundwater seepages contaminated by lawn and garden fertilisers, pasture use, and septic tanks. However, studies on phytoplankton and macrophytes of the estuary suggest that the impact of nutrients on the estuary to date has been small (Hosja & Deeley 2000; McComb *et al*. 2000).

Discussion

The Leschenault Inlet estuary is unique in south-western Australia from many perspectives. It is the only estuary formed behind a shore-parallel dune barrier, and wholly Holocene in age (since all other major estuaries in Western Australia have a Pleistocene ancestry). Its estuarine hydrologic structure also is different to other local, more classic type estuaries such as the Swan River Estuary and the Peel-Harvey Estuary, as there is not a simple river-to-sea gradient, but rather rivers enter at one end of a long coastal lagoon that was not formed as part of a fluvial tract. In this context, the Swan River forms a classic estuary, with an upstream riverine system, and a downstream marine setting, while the Peel-Harvey estuary is a compound estuary of three rivers, with the Serpentine and Murray rivers debouching into Peel Inlet (that was formed as a lowland in the zone of fluvial confluence, Semeniuk & Semeniuk 1990), and the Harvey River forming a delta within a fluvially scoured tract leeward of a Pleistocene limestone barrier. Further, of all the estuaries in south-western to southern Western Australia, Leschenault Inlet estuary has had the most complicated Holocene sea level history, resulting in complexity of its shores. The western shore is further complicated because of the dynamic nature of the parabolic dunes that encroach and spill over into the estuary, producing a varied assemblage of shore types. The varied nature of the shores results in variable types of peripheral vegetation, and as such the peripheral vegetation fringing the estuary ranks as one of the most significant in the State. Additionally, through its proximity to the Leeuwin Current, the estuary supports the most southern occurrence in Western Australia of the mangrove *Avicennia marina*.

From a geoheritage perspective, and archive for Holocene climatic and vegetation history, the array of landforms and vegetation in and around the estuary also combine to create an important classroom for pollen studies. From a perspective of biodiversity, the foraminiferal assemblages in the estuary are unusually species rich for an estuary, and potentially globally significant.

In the period from 1982-1998, when detailed monitoring and periodic resampling were carried out, the estuary appeared to be stable in the medium term; that is, while there have been influxes of sediments that changed the depth and nature of the substrate at two sites (one at the mouth of an active delta, the other along the dynamic western shore), overall the depth and substrate character of the estuary, in terms of sediment types, has remained similar. Any changes in the estuarine biotic assemblages over this period would then implicate medium term (decadal) changes in volume of run-off entering the estuary and hence changes in hydrochemistry and nutrient levels, as well as extra-estuarine recruitment, or interactions between biota as driving forces behind these changes.

Monitoring of biota over the medium term in the Leschenault Inlet estuary shows some important patterns. Benthic fauna and seagrass cover were relatively abundant at the beginning of the biota surveys over the period 1982-1987, and appear to have declined towards 1987. In 1997 / 1998 seagrass and invertebrate fauna again were in low abundance. The decline in fauna may be linked to the abundance of seagrass cover in the estuary, which in turn may be linked to medium term climatic patterns of relative drought (with the concomitant effect of reduced fluvial input from the drainage basin, and reduced nutrient content noted above). Recruitment and abundance of fauna may also be linked to extra-estuarine conditions linked to oceanographic factors.

The mangrove *Avicennia marina* presents an interesting situation of the slow responses of environments to human impacts. While the "The Cut" was dredged in the early 1960s, and the Preston River delta with its mangroves was transformed in the 1970s to a marine embayment without freshwater influx, the mangrove populations in both Leschenault Inlet (the former Preston River delta) and the now Leschenault Inlet estuary remained relatively stable until the late 1980s (Semeniuk *et al.* 2000b). Thereafter, the mangrove began to expand its populations in the Preston River delta area and in the northern Leschenault Inlet estuary decades after the hydrodynamic and hydrochemical modifications.

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