Estuarine, Coastal and Shelf Science (2001) **53,** 351–384
doi:10.1006/ecss.2001.0796, available online at http://www.idealibrary.com on IDEAL®

Structure and Function of South-east Australian Estuaries

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Received 19 November 2000 and accepted in revised form 26 March 2001

An attempt is made to synthesize the geological properties, water quality attributes and aspects of the ecology of south-east Australian estuaries so as to provide a framework for addressing coastal management issues. The approach is based on the underlying causal factors of geology and morphology and more immediate environmental factors (e.g. salinity and sediments) which are associated with ecological distributions, species richness and fisheries catch. This ‘ broad brush ’ approach seeks to maximize reality and generality, albeit at the expense of precision and local variability in individual circumstances. It disregards small-scale ecological patterns as noise. Unlike in the Northern Hemisphere, conditions in temperate Australia are characterized by irregular flood and fire regimes that strongly influence estuary hydrology and nutrient inputs. Three main types of estuary (tide-dominated, wave-dominated and intermittently closed) are recognized based on geological criteria and having particular entrance conditions that control tidal exchange. Four zones (marine flood-tidal delta, central mud basin, fluvial delta and riverine channel/alluvial plain) are also recognized common to each type of estuary. These zones correspond to mappable sedimentary environments in all estuaries and have characteristic water quality, nutrient cycling/primary productivity signatures and ecosystems. The ecology of a zone is modified by (a) estuary type which determines the salinity regime; (b) stage of sediment filling (evolutionary maturity) which controls the spatial distribution/size of the zones; and (c) impacts of various forms of development. By using the zones/habitats as a common currency among all estuaries, it is possible to link ecological aspects such as species richness and commercial fisheries production so as to compare different estuaries or within-estuary zones.

Keywords: South-east Australian estuaries; estuary geology; nutrient cycling; estuary ecology; productivity; coastal management

Introduction

Globally, the coastal zone is under unprecedented pressure from various human activities stemming from a population growth of *c*. 50% in the last 20 y. In few other countries is there a higher concentration of urban affluence than in the southeast Australian coastal zone and continued population growth demands enhanced coastal management (Bird, 1974; Yapp, 1986). Recent changes towards greater regulation include the establishment of catchment, estuary and coastal management committees and the introduction of statewide policy and review agencies (e.g. New South Wales State Coastal Policy, Coastal Council of NSW). Examples of coastal development are abundant and range from canal estates in non-tidal waterways to high-rises and international resorts on the beachfront. Less obvious is the growing pressure on local government authorities to control natural estuarine processes such as the build-up of seagrass and/or algal wrack on foreshores and the opening regime of lagoons. While the former minimizes odour and the latter protects property from flooding, there has been little regard for ecological impacts. Hitherto, many estuary entrances were kept permanently open

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with breakwaters and training walls to provide boating access; now, similar engineering works are being contemplated to 'improve' water quality and flushing characteristics (e.g. Lake Illawarra). It is also suggested that well-designed canal estates may enhance an estuary by increasing habitat diversity (Catlan & Williams, 1985).

For commercial fishing, future changes are likely to be dramatic. Recreational fishing in estuaries will become increasingly important and commercial wild-fish fishing will progressively be augmented by aquaculture. Moreover, intermittently closed estuaries in southern New South Wales have high potential for purposes other than commercial fishing (Pease, 1999). Their role as pristine environments or as nurseries for restocking the coastal ocean and for controlled fish breeding requires understanding of linkages between estuary biology and entrance opening regimes. Further, the role of estuaries in pro-active conservation programmes demands knowledge of the relationship between estuary form and ecological function, not only to devise fruitful management strategies but also to mount convincing arguments for allocating public resources (Hodgkin & Hesp, 1998).

Unfortunately, such understanding is hindered by the fact that estuarine ecosystems are complex, dynamic and variable. It is our purpose to present a geologically-based framework for comparing estuaries and to elucidate links to aspects of estuarine ecology such as floral distributions, faunal species richness and commercial fisheries production. These are influenced directly by the estuary's physical and chemical characteristics which are in turn controlled by geological setting, entrance conditions and evolutionary history, the last typically changing slowly and predictably over time spans of centuries to millenia. Our conceptual framework is designed to assist the documentation, management and conservation of estuarine resources, especially in Australia but with application elsewhere. It has the potential of providing a transparent rationale by which coastal managers can assign relative ecological value among whole estuaries or parts of an estuary.

Our approach, in which estuarine geology/geomorphology is used as a vehicle to characterize estuary ecology, involves several concepts/working hypotheses:

1. Fundamentally different types of estuaries can be recognized in southeastern Australia (and elsewhere in the world) and comprise individuals that have infilled with sediment to varying degrees. These represent stages in an evolutionary progression that can be expressed in terms of relative estuary maturity.
2. All estuaries (and their associated alluvial deposits) consist of four main depositional environments whose nature and development depends on estuary size, estuary type and relative maturity.
3. These depositional environments are characterized by particular substratum conditions, hydrological regimes and nutrient cycling behaviours that constitute discrete biological habitats whose distribution can be mapped and quantified.
4. Associated with each habitat are characteristic assemblages of species that can be assigned a value in terms of species richness or productivity.
5. Over the longer-term (decades to centuries), assemblages respond primarily to estuary evolution, especially to changes in habitat distribution. In this context, short-term ecological variability can be ignored.
6. Estuarine habitats are vulnerable to anthropogenic interventions that may affect water and sediment quality and cause subsequent ecological impacts thereby reducing their functionality.

Regional setting

The bedrock valleys in which Cainozoic deposits occur along the south-east Australian seaboard (Figure 1) evolved over tens of millions of years (Bishop & Goldrick, 1997; Roy, 1998) and have undergone multiple phases of excavation and infilling (Roy & Thom, 1981). During Quaternary glacial periods, the coastal zone was displaced seaward onto the continental shelf with rivers cutting to new base levels. During interglacial periods of high sea level, as today, coastal valleys were drowned to form estuaries, which subsequently began filling with sediment from the land and from the sea. Formerly, aqueous environments were, over time, progressively replaced by terrestrial ones as the estuaries infilled. Parallelling these geological changes, the precursors of modern estuarine ecosystems also experienced slow evolutionary change. This cut and fill cycle has been repeated many times with the result that most coastal valleys contain remnants of previous interglacial deposits in addition to those deposited over the Holocene period (the last 10 ka). The most recent phase of estuarine sedimentation was initiated virtually simultaneously throughout the region near the end of the Post-glacial Marine Transgression about 7–8 ka ago (Roy & Thom, 1981; Roy, 1984). Since then, rates of infilling of individual valleys have varied widely depending on the sediment load carried by rivers and the hydrodynamic conditions that transport sediment into the estuary

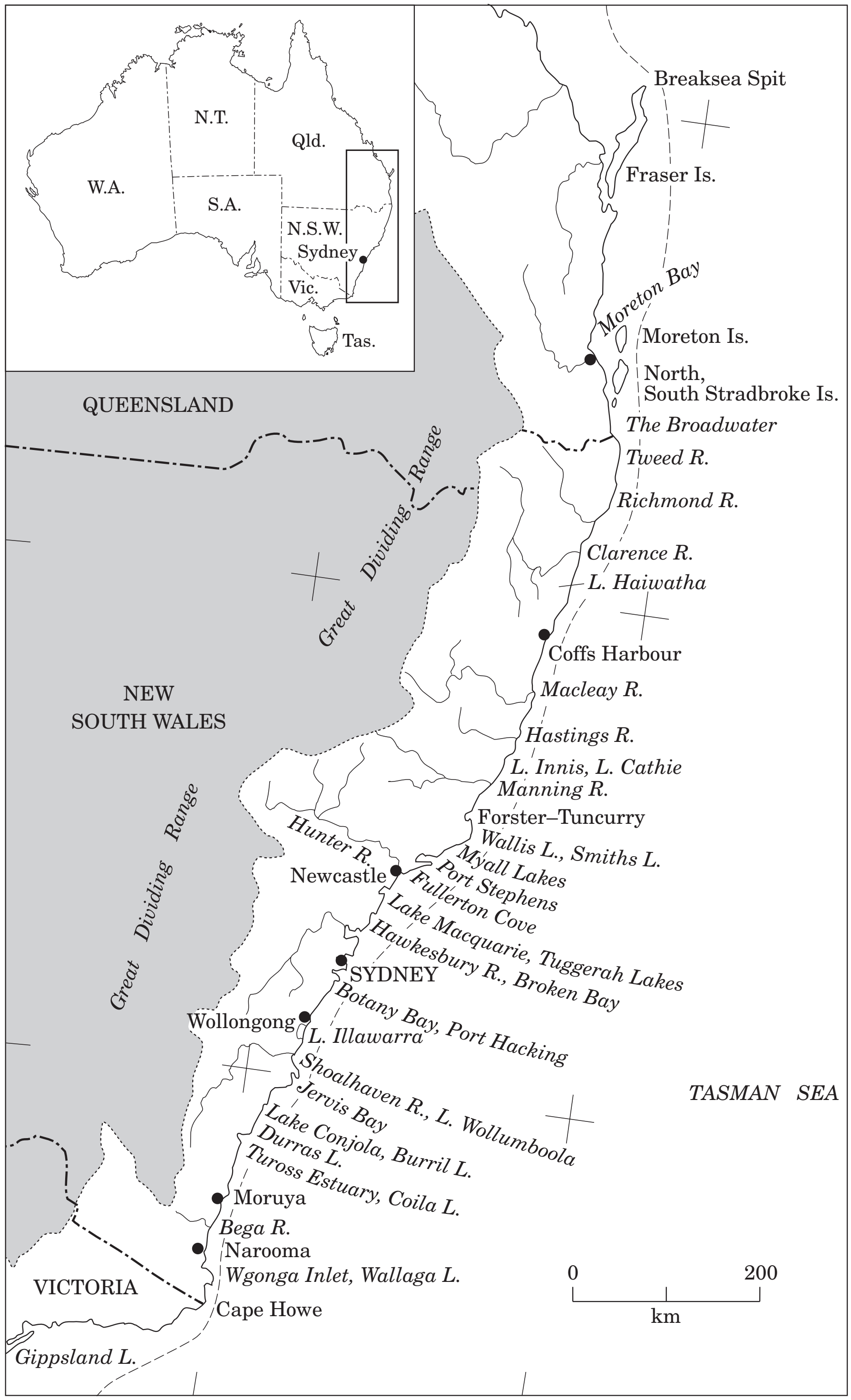


FIGURE 1. The southeast Australian seaboard showing the main coastal rivers, the continental shelf and the location of estuaries mentioned in the text.

mouth. The original size and shape of the pre-Holocene valleys, which determine the accommodation space available for Holocene sedimentation, are the result of prior erosion (i.e. catchment conditions) and the emplacement of coastal sand barriers in the valley mouths.

The main elements controlling the hydrodynamic regime of the south-east Australian coast are storm and swell waves and oceanic and meteorological currents. Climate ranges from warm-temperate at the Queensland border to cool-temperate near Victoria. Rainfall is highly irregular and is dominated by ENSO and longer cycles (Powers *et al.*, 1999); there is slight summer dominance in the north and winter dominance in the south. The coast has a maximum spring tidal range of 2·0 m, tides are semi-diurnal and, except in tidal inlets, generate weak shelf currents (Hamon, 1965, 1984). The coastal ocean is storm dominated; eastward tracking, mid-latitude cyclones, which cross the southern half of the Australian continent, generate southerly storm waves and long-period swell in the South Tasman Sea (Short & Trenaman, 1992). Under the influence of persistent swell, beaches aggrade with sand that moves onshore from the continental shelf (Roy *et al.*, 1997). In contrast, shorter period storm waves tend to erode beaches. ENSO and other, decades long, climatic fluctuations (Powers *et al.*, 1999) alter the balance between swell and storm wave activity. The resulting long-term changes in beach volume (Thom & Hall, 1990) affect estuary mouth opening regimes and tidal exchanges. Although flood-tidal deltas are well developed in these estuaries, their ebb-tide counterparts are reduced to relatively small, river-mouth bars by the high-energy swell wave regime on the open coast.

Within estuarine water bodies wave action is dominated by southerly and westerly winds associated with the passage of large atmospheric pressure systems over the east coast. In addition, strong onshore sea breezes occur in summer. Their effect in terms of generating wind waves is controlled by the size and alignment of the estuary water body and the relief of the surrounding terrain. In estuaries with fetches of more than one kilometer, short period wind waves mix surface waters to a maximum depth of about 2 m and produce set-up effects that are balanced by slow bottom return flows.

The East Australian Current is a western boundary current flowing southwards on the shelf and upper slope at speeds up to 2 m s^{-1} in the north. It diverges seawards around latitude 32.5°S in central New South Wales, forming large counter-clockwise gyres that slowly migrate southwards beyond the shelf edge (Godfrey *et al.*, 1980). Currents on the central and southern shelf typically fluctuate in intensity and commonly reach velocities of 1·0–1·5 m s^{-1}. They reverse direction at intervals of 5 to 10 days and are thought to be related to coastal-trapped waves moving northwards along the south coast (Church *et al.*, 1986; Griffin & Middleton, 1991). The resulting shelf water movements are complex; they largely control sea surface temperatures and determine the movement of larvae and juvenile fish and invertebrates into estuaries along the coast.

Compared to many parts of the world, the nutrient status of Australian ocean waters, including the east coast, is poor (Rochford, 1979), leading to low productivity and low fisheries production. Nevertheless, benthic and pelagic phytoplankton are considered to dominate the primary productivity of estuarine waters, except in wetlands. In the southeast region the latter include intertidal saltmarshes and mangroves, with seagrasses and some algal communities occurring in shallow subtidal waters (West *et al.*, 1985; King *et al.*, 1991).

A geological classification of estuaries

Although the ocean wave climate and tidal regime change little along the south-east Australian coast, local variability in the size and orientation of embayments and headlands, and the availability of sand, affect barrier development and estuary-mouth hydrodynamics. The latter concerns the relative importance of tides as opposed to waves in estuary mouths. In most parts of the region, sediment movement at the coast is dominated by waves, which explains the common occurrence of sand barriers at the mouths of most bedrock valleys. Exceptions relate to particular morphological settings where estuaries debouch into semi-enclosed embayments, such as Broken Bay, in which ocean wave energy is dampened. Here, submerged, rather than emergent, bodies of sand (flood-tidal deltas) occur in the estuary mouth and tidal currents locally become the dominant sediment-transporting agent.

Our classification of south-eastern Australian estuaries is based on two criteria: first, the inheritance of different coastal settings that create distinct estuary types and second, differing rates of sediment infilling that determine how far along their evolutionary continuum the present-day estuaries have progressed. An early classification (Roy, 1984) recognized three types of estuaries but was restricted to embayed, bedrock-controlled sectors of the coast. Subsequently, this classification was expanded to include a greater diversity of estuary types throughout Australia (Table 1) (Roy, 1994; Roy & Boyd, 1996). Bucher & Saenger (1991, 1994), Digby *et al.* (1998), Ferguson (1996), Kench (1999) and Edgar *et al.* (2000) present comprehensive reviews of other estuary classification schemes and discuss distinctive aspects of Australian estuaries.

This paper focuses on estuaries in New South Wales, these being generally representative of

TABLE 1. Types of coastal water bodies in eastern Australia

Groups	Types (and examples)	Mature forms*
I. Bays	1. Ocean embayments (Botany Bay)	
II. Tide-dominated estuaries	2. Funnel-shaped macrotidal estuary (South Alligator River, Northern Territory)	Tidal estuaries
	3. Drowned valley estuary (Hawkesbury River)	
	4. Tidal basin (Moreton Bay)	
III. Wave-dominated estuaries	5. Barrier estuary (Lake Macquarie)	Riverine estuaries
	6. Barrier lagoon (The Broadwater/South Stradbroke Island)	
	7. Interbarrier estuary (Tilligerry Creek, Port Stephens)	
IV. Intermittent estuaries	8. Saline coastal lagoon (Smiths Lake)	Saline creeks
	9. Small coastal creeks (Harbord Lagoon, Sydney)	
	10. Evaporative lagoons (The Coorong, South Australia)	
V. Freshwater bodies	11. Brackish barrier lake (Myall Lakes)	Terrestrial swamps
	12. Perched dune lake (Lake Hiawatha)	
	13. Backswamp (Everlasting Swamp, Clarence River)	

*Mature forms refer to infilled estuaries.

estuaries in south-eastern Australia and forming a sub-set of the wider range of estuary types found throughout Australia (Table 1). Water bodies are divided into five groups according to decreasing marine influence. Group I comprises semi-enclosed bays that are characterized by marine waters with little fresh water inflow. They are transitional between true estuarine environments (Groups II–IV) and the coastal ocean. The fresh water members (Group V) include coastal water bodies that rarely, if ever are brackish but have occasional linkage to the sea. Subdivision of the various types of estuaries in Table 1 is based on the nature of their present-day entrances which determine the exchange of water between the estuary and the sea.

Tide-dominated estuaries (Group II) have the largest entrances and tidal ranges similar to the open ocean. They are typified by funnel-shaped macrotidal estuaries described by Boyd *et al.* (1992) and Chappell & Woodroffe (1995) from coasts with large tidal ranges. However, this category also includes estuaries in microtidal areas where tides are locally more important than waves in moving water and sediment. The best known examples of the latter type are the tidal basins of the Dutch and Danish Wadden Sea (e.g. Oost & de Boer, 1994). On the high wave-energy coast of south-eastern Australia the occurrence of tide-dominated estuaries is due to particular coastal settings where wave action is locally subdued. Drowned valley estuaries [Figure 2(a)] typically occupy deeply incised bedrock valleys that are aligned normal to the coastal trend and open into semi-protected bays. The Hawkesbury River estuary flowing into Broken Bay is an example of this association. Tidal basins such as Moreton Bay by contrast are more equi-dimensional water bodies usually located in low-relief coastal areas behind sand islands that are partially detached from the present coast. Drowned valley estuaries and tidal basins contain large flood tide deltas composed of shelf sand (Roy, 1998). Except during floods, which temporarily overwhelm the effect of daily tidal flushing, tide-dominated estuaries are less influenced by river discharge than other estuary types.

Wave dominated estuaries (Group III) have tidal inlets that are constricted by wave-deposited beach sand and flood-tidal deltas that are commonly smaller than those in tide-dominated estuaries. Tidal ranges within estuary basins are usually considerably less (*c.* 5–10%) than in the ocean and tidal currents are negligible; local wind waves and wind-induced water movements are the dominant sediment transporting mechanisms. Compared to their tide-dominated counterparts, wave-dominated estuaries are more strongly influenced by river discharge. In New South Wales, barrier estuaries, with open (albeit constricted) inlets, are associated with larger rivers whose discharges tend to counteract the flux of wave-transported beach sand in the estuary mouths [Figure 2(a)]. They occur behind sand barriers on exposed sections of the coast. The Clarence, Richmond, Manning and Hunter Rivers in northern and central New South Wales are examples. Barrier lagoons (rare on this coast) and inter-barrier estuaries are associated with low relief, coastal plain coasts. Inter-barrier estuaries occur in the depression between the Holocene and Last Interglacial-aged barriers (the ' Inner ' and ' Outer ' Barriers of Thom, 1965). Examples include North and South Arms of the Brunswick River, Warrell Creek on the Nambucca River, the Macleay

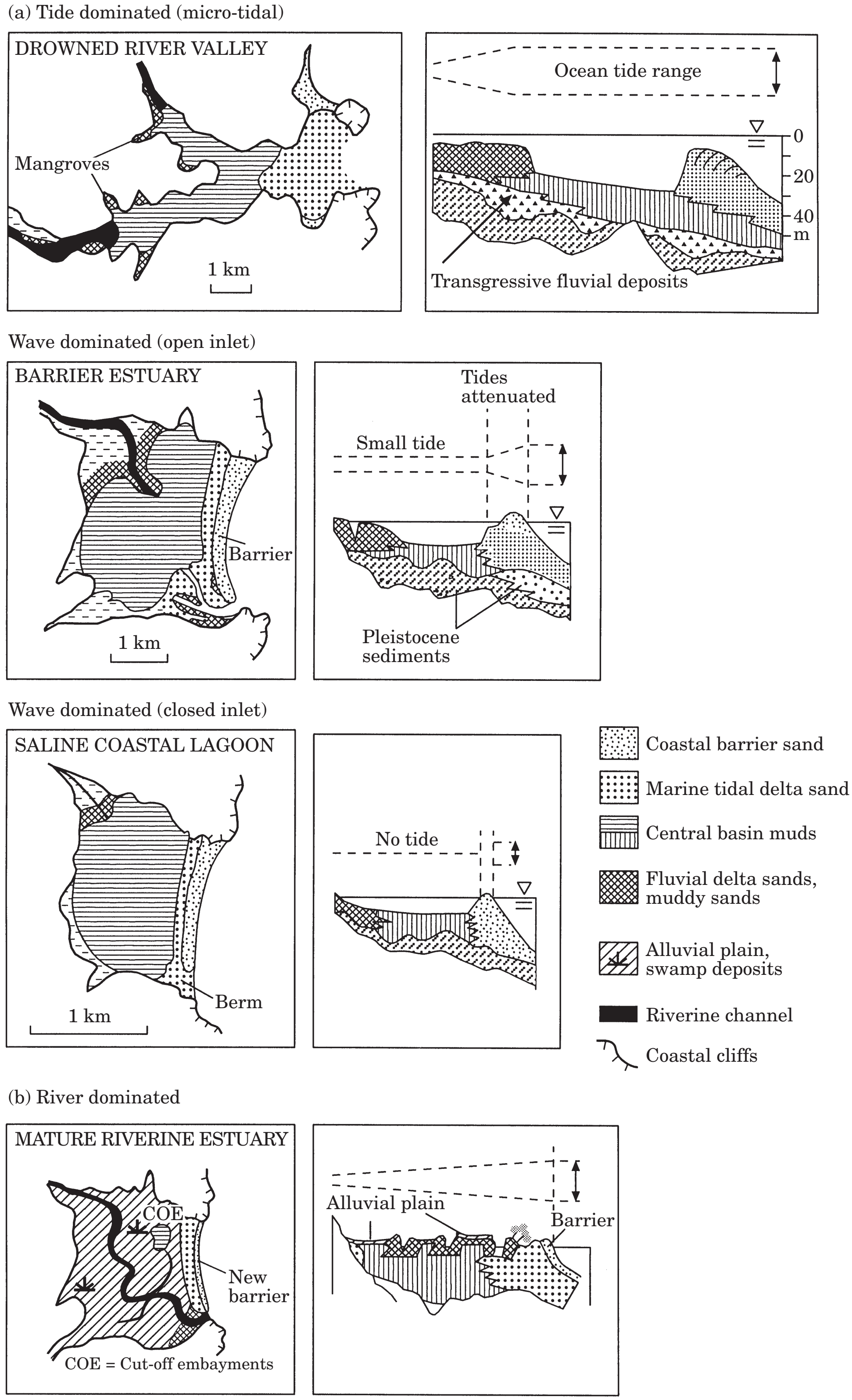


FIGURE 2. (a) Three main estuary types in New South Wales showing idealized sediment distributions in plan and cross section. Tidal ranges in the estuaries are shown in relation to the ocean tide which varies from 1·5 m on neaps to 2·0 m on springs. (Interbarrier estuaries and small coastal creeks are not shown.) (b) Example of a mature, infilled estuary at which stage the riverine channel zone is the dominant estuarine environment and the estuary overall can be considered to be ‘ River Dominated ’.

Arm of the Macleay River and Tilligerry Creek flowing into Port Stephens.

Intermittent estuaries (Group IV) refer to those coastal water bodies that, for a combination of climatic and other reasons, become isolated from the sea for extended periods of time. In south-eastern Australia saline coastal lagoons (Roy, 1984) and small coastal creeks [Figure 2(a)] occur in similar settings to barrier estuaries but, because of small catchments and river discharges, their mouths are blocked by beach sand for much of the time. The estuary water bodies are thus non-tidal for long periods but after heavy rain their beach berms are breached by storm waves and/or raised water levels in the estuary, a process that, increasingly, is manipulated by man to reduce flooding. The unpredictability of rainfall in southeast Australia means that the opening behaviour is intermittent and erratic and the salinity regime of these types of estuaries is highly variable. Examples of relatively large saline coastal lagoons are Smiths Lake (Robinson *et al.*, 1983), Coila Lake (Roy & Peat, 1976) and Dee Why Lagoon. Many of the small coastal creeks are infilled (i.e. mature) coastal lagoons.

According to Williams *et al.* (1998), at least 950 water bodies join to the Tasman Sea along the New South Wales seaboard. The vast majority of these are very small and belong to the intermittent category. Attributes of over 130 water bodies larger than 0·05 km^2 in area have been documented by Bell and Edwards (1980) and West *et al.* (1985) (Appendix). Their water areas range up to about 130 km^2 in the case of drowned valley and barrier estuaries, but are less than 10 km^2 for saline coastal lagoons (Figure 3). Of these, 62 are saline coastal lagoons or small coastal creeks, 49 are barrier estuaries and eight are drowned valley estuaries. Half of the barrier estuaries have training walls at their mouths. Except for drowned valley estuaries, which (for geological reasons) occur mainly on the central New South Wales coast, there is no regional pattern in estuary distribution (Pease, 1999). Histograms grouping catchment areas and water areas for each estuary type (Figure 4) show that, although saline coastal lagoons and their catchments are generally smaller than the other types, there is considerable overlap. Clearly these attributes (or associated ones such as river discharge) do not, on their own, serve to discriminate between estuary types on the southeast Australian seaboard.

In their natural, pre-European, state, southeastern Australian estuaries would have grouped according to their entrance conditions (and salinity regimes) into two main types: (1) a small group of drowned valley estuaries with large, permanently open entrances allowing full tidal exchange, and (2) a much

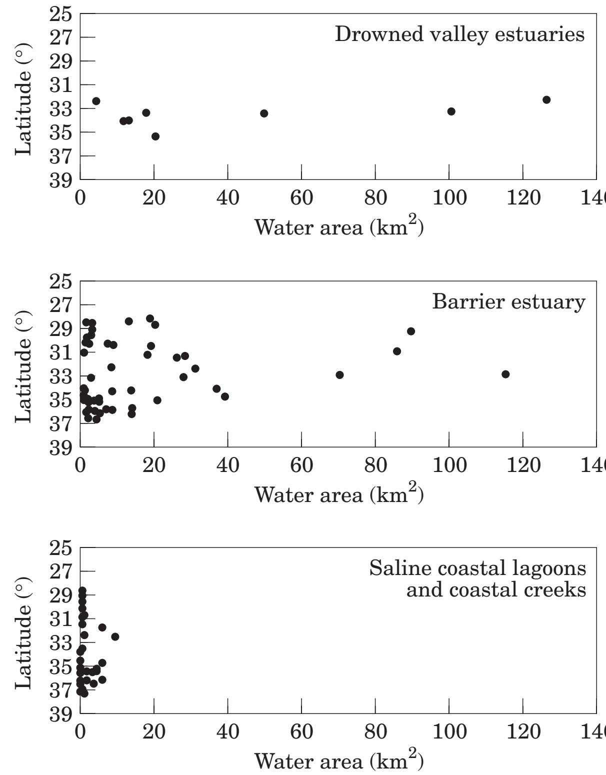


FIGURE 3. Regional distribution of the estuary types in New South Wales. Data from West *et al.* (1985).

larger group of estuaries with much smaller entrance channels in which tidal exchange was impeded by beach sand deposits in the estuary mouth. This latter group exhibited a spectrum of entrance conditions ranging from (almost) always open, through intermittently closed to (almost) always closed. The degree of ‘ openness ’ depended primarily on exposure to ocean waves and on fluvial discharge, with the latter also influenced by climatic fluctuations on decadal time scales. These latter affect long-term rainfall patterns (and thus both river and sediment discharges) as well as beach sand budgets that modify the amount of sand in the estuary mouths. As a result, even large riverine estuaries, such as the Clarence, may have closed for months at a time in pre-European times, while moderately large barrier estuaries, such as Wallis Lake, occasionally would have been closed for years (Select Committee, 1889). Smaller estuaries with entrances that were predominantly open for several decades could switch to predominantly closed during following decades.

Since European colonization, and especially during the last century, many estuaries with constricted entrances have been permanently changed by the construction of training walls at their mouths. Today there are three relatively distinct groups of estuaries in

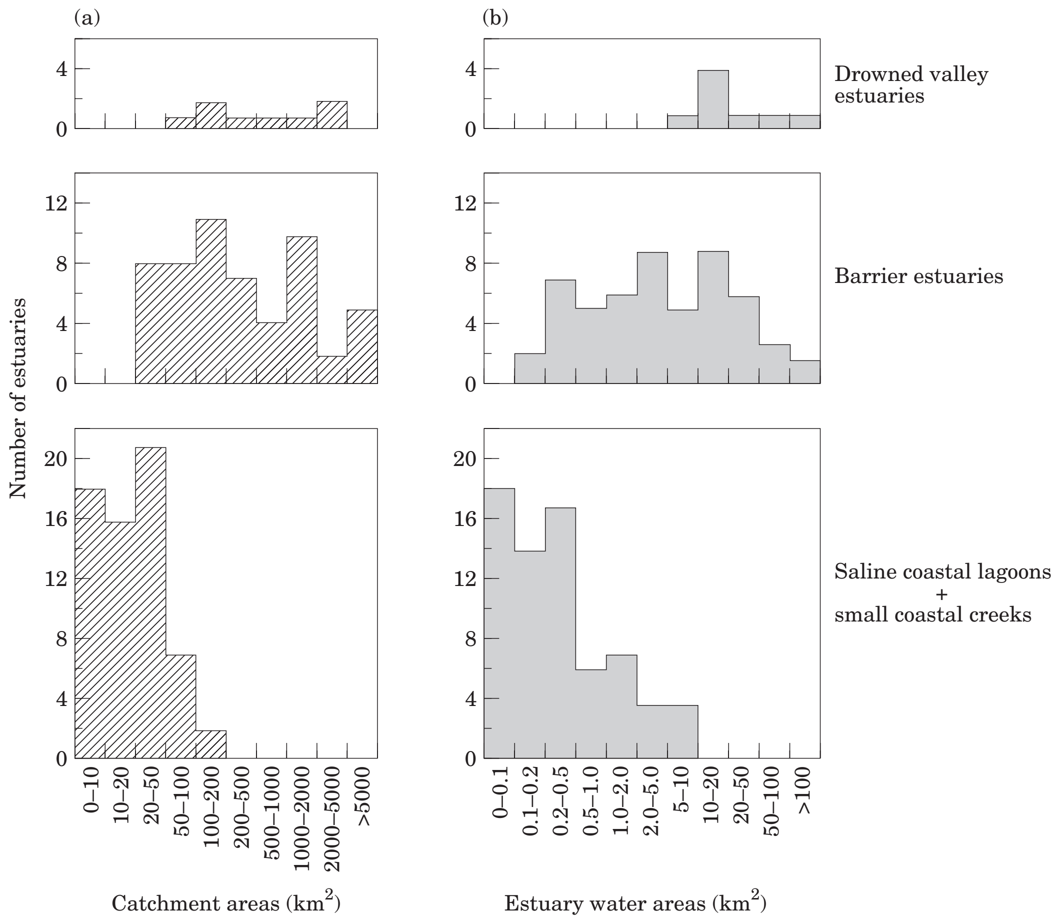


FIGURE 4. Relationships between catchment areas (a) and water areas (b) for the three main estuary types in New South Wales. Data from West *et al.* (1985).

TABLE 2. Estuary zonation based on depositional sedimentary environments (from Roy, 1984, 1994; Roy & Boyd, 1996)

Main depositional environments	Sub-environments/habitats	Hydrological zones (Rochford, 1951) and substrate types
Marine tidal delta	Rocky shoreline and rock reefs, tidal channels, tidal banks, tidal flats, delta front slope, back barrier sand flat	Marine (Vegetated and unvegetated sand and muddy sand and rocks)
Central mud basin	Rocky shoreline and rock reefs, slope and shoreline zone, basin floor, shell biotherms	Tidal (Unvegetated muds, sandy muds and muddy sands, vegetated rocks)
Fluvial delta	Levees, distributary channels, mid-channel shoals, delta mouth bar, crevasse splays, delta top and delta front, interdistributary bays	Gradient (Vegetated and unvegetated, sandy muds, muddy sands and sands)
Riverine channel and alluvial plain	Riverine channel, point bars, mid-channel bars, eroding banks, levees*, floodplain*, backswamp*	Freshwater (Unvegetated sands, gravelly sands and muddy sands)

*Subaerial depositional environments.

TABLE 3. Estuary zonation, summary of sediments and average hydrological properties modified from Rochford (1951)

Depositional environments (Hydrogeological zone from Rochford, 1951)	Main sediment types	Hydrogeological properties			
		Annual salinity range (ppt)	Annual temperature range (°C)	Total phosphorous ($\mu g\, l^{-1}$)	Nitrogen concentration ($\mu g\, l^{-1}$)
Marine tidal delta (Marine)	Clean quartzose sand and muddy sand	30–35	5	10–23	<25
Central mud basin (Tidal)	Organic-rich mud and sandy mud	20–30	7	30–80	<25
Fluvial delta (Gradient)	Sandy mud and muddy sand	10–20	10	15–50	100
Riverine channel (Freshwater)	Fluvial sand and muddy sand	<10	10–15	10–25	500

New South Wales [Figure 2(a)]: (1) tide-dominated, drowned valley estuaries with entrances unchanged; (2) wave-dominated barrier estuaries, 50% with trained entrances, that are permanently open or (like Tuggerah Lake, Lake Illawarra, Tuross Lake and Bega River estuary) are untrained but are kept partially open (leaky); and (3) smaller, saline coastal lagoons and small coastal creeks, with entrances that are mostly closed. Recently the acronym ICOLL has been coined for all ' intermittently closed and open lakes and lagoons ' which includes all of Group (3) above, as well as occasionally closed barrier estuaries (Group 2) with untrained entrances.

All estuaries follow similar evolutionary paths as they infill with sediments: water areas and depths decrease with time and, as a result, hydrological characteristics and biological communities change (Hodgkin & Kendrick, 1984; Roy, 1984). In this geological classification, river dominance is linked to estuary evolution via the concept of estuary (and valley-fill) maturity [Figure 2(b)]. In this respect the classification diverges from that of Boyd *et al.* (1992), Dalrymple *et al.* (1994) and earlier writers who express present-day coastal diversity in terms of waves, tides and rivers as dominant sediment transporting mechanisms. The linking of maturity to river dominance [Figure 2(b)] allows us to avoid being unduly influenced by absolute river size in classifying present-day estuaries. Mature forms of the various estuary systems are listed in Table 1.

Estuary zonation

Our bridge between estuary form and function is based on linkages between:

- depositional environments with various morphologies and types of sediment that determine styles of nutrient cycling and create biological substrates (Roy, 1984, 1994);
- hydrological zones with characteristic water quality properties (Rochford, 1951, 1955) and
- habitats that, to varying degrees, support estuarine biota (MacIntyre, 1959; Jones, *et al.*, 1986).

Within all south-east Australian estuaries we recognize four geomorphic zones having characteristic hydrological and biological attributes (Table 2). From seaward to landward they are: (1) marine flood-tidal delta; (2) central mud basin; (3) fluvial delta; and (4) riverine channel and alluvial plain. Their main sedimentological and hydrological properties are summarized in Tables 2 and 3 and their general distributions are indicated in Figure 2. Our scheme differs from Rochford's (1951) as he categorized estuaries on the basis of seasonal rainfall characteristics using a series of hydrological features to describe four estuarine zones: marine, tidal, gradient and freshwater. Rochford did not recognize intrinsic differences among southeast Australian estuaries, nor the changes which occur as an estuary infills and matures. An important aspect of infilling is that salinity structures change and this will have fundamental impacts on the distribution of flora and fauna as discussed later. Detailed relationships between Rochford's hydrologic attributes and the geomorphic characteristics we describe remain to be investigated. At this stage of our understanding we assume they are roughly coincident.

The four geomorphic zones are present to varying degrees in most estuaries but in some they are very restricted or occasionally absent. For example, fluvial deltas are virtually absent in inter-barrier estuaries such as Tilligerry Creek because of the restricted catchment area. Sediments that infill estuaries and form their biological substrates are mixtures of sand, silt and clay-sized particles from the hinterland,

TABLE 4. Average aerial extent of estuarine flora grouped according to estuary type and stage of development (data from West *et al*., 1985). Figures in brackets are areas normalized for estuary water area

Estuary type and development stage	Number of estuaries	Average estuary water area (km^2)	Mangroves and salt marsh (Av. km^2/estuary)	Seagrass (Av. km^2/estuary)
1. Ocean embayments	5	46·7	1·12 (0.02)	2·51 (0.05)
2. Drowned valley (tide dominated estuaries)	8	42·6	7·01 (0.16)	1·42 (0.03)
3. Barrier (wave dominated) estuaries	54	13·7	1·65 (0·12)	2·76 (0·20)
3A	7	28·1	1·16 (0·04)	8·85 (0·30)
3B	11	19·2	0·43 (0·02)	4·27 (0·22)
3C	10	5·2	1·78 (0·34)	2·10 (0·40)
3D	26	9·6	2·25 (0·23)	0·37 (0·04)
4. Intermittent estuaries	64	0·89	0·16 (0·18)	0·16 (0·18)
4A	4	5·1	0·07 (0·01)	0·91 (0·18)
4B	20	0·9	0·29 (0·32)	0·19 (0·21)
4C	27	0·6	0·10 (0·17)	0·09 (0·15)
4D	13	0·2	0·09 (0·45)	0·02 (0·10)

organic detritus, including phytoplankton, and bioclastic material. These substrates may be vegetated with seagrass, algae, mangrove or saltmarsh communities and support an epifauna and infauna of fish, crustaceans, molluscs, polychaetes and other animals.

Marine tidal delta zone

Located in the estuary mouth, the marine flood-tidal delta zone is composed of moderately well sorted quartzose sand derived from the open coast and subordinate amounts of mud; it is influenced to varying degrees by tidal currents and wave action. High and low-energy subenvironments exist: the former include 5–10+ m deep tidal channels and shoaling bay beds with unvegetated sandy substrates that are mobilized by tidal currents and waves, and are periodically exposed to storm reworking; low-energy subenvironments have lower velocity water movements. The latter correspond to shallow subtidal (*c.* <2 m) and intertidal sand flats and shoals that usually occur along channel margins and the muddy slope-zone on the delta front. Low-energy subenvironments form stable substrates with variable admixtures of sand and organic-rich mud, colonized by seagrass in the photic zone and fringed by mangroves.

The extent of the two subenvironments varies with estuary type. High-energy environments are best developed in the open mouths of tide-dominated, drowned valley estuaries, such as Port Hacking. They are restricted to the seaward-most part of the entrance channels of barrier estuaries (Lake Macquarie), and are virtually non-existent (or of short duration) in intermittent estuaries (Smiths Lake). Low-energy environments that occur landward of the high-energy zone are usually best developed on the delta surfaces of barrier estuaries, and along the inner sides of the barriers. Marine tidal delta zones are juxtaposed to coastal sand barriers that impound barrier estuaries, and to rocky reefs and headlands in the mouths of drowned valley estuaries. They receive surface drainage and nutrients from inter-dune swamps and inter-barrier creeks, periodic influxes of marine wrack after storms, and occasionally, of toxic algae when blooms occur in adjacent ocean waters.

Central mud basin

Central mud basins are primarily uniform, low-energy environments in the deeper parts of estuaries but also include narrow slopes bordering their sides. Typically, light levels are significantly reduced and fine silt and clay-sized river sediment, supplied mainly during floods, settles from suspension. The resulting deposit consists of dark grey to black mud, rich in estuarine shells, foraminifera and organic material (Roy, 1981). Although anoxic with reducing conditions a centimetre or so below the bed, the muds are extensively bioturbated and bio-irrigated by molluscs, polychaetes and crustaceans to depths of 15–20 cm. As a result, faecal pellets often make up a large proportion of the sediment and virtually all small-scale primary sedimentary structures are destroyed (S. Nichol, written comm., 1991). Weak salinity gradients exist within central basins with upstream sectors near fluvial deltas being more brackish and possibly also more nutrient rich, than seaward sectors. Physical conditions are essentially placid with slow, wind-induced circulation in deeper areas and wave stirring of surface layers to a depth of about 2 m. At shallower bed depths (e.g. in Tuggerah Lakes, Lake Illawarra), the mud substrate is frequently stirred by wind waves with the result that nutrient loadings and turbidity levels are increased in the overlying water. Mud basins are mostly unvegetated although plants may occur in protected embayments with particularly clear water. Except for scattered biohermal shell banks (Peat & Roy, 1975; Roy, 1981; Thom *et al*., 1992) and small mounds produced by burrowing organisms, the mud surface is planar.

Sandy shoreline facies along the flanks of the basins lie within the photic zone and support seagrass beds and a generally rich mollusc fauna (Thom & Murray-Wallace, 1988; Murray-Wallace *et al*., 1996). These facies include areas of wave reworking and erosion in their upper parts grading into basin muds with increasing water depth and distance from shore. Organic carbon contents in the central basin muds vary considerably between estuaries and seem to correlate with rates of infilling, the terrigenous mud acting to dilute organic material concentrations. Organic carbon values in mature and semi-mature estuaries (e.g. Wapengo Lagoon) are only 1–12%; in deeper, immature estuaries (e.g. Lake Conjola) they are 17–33%; in saline coastal lagoons values may be even higher (T. Hunter, written comm., 1993).

Fluvial delta

The most complex association of physical settings and ecological habitats are found in fluvial deltas where rivers and streams enter estuarine water bodies and deposit their sediment load. Conditions range from shallow subtidal (saline to brackish), through intertidal to terrestrial; salinities and temperatures fluctuate in response to river flow, intertidal exposure and tidal exchange (Table 3). Subenvironments, listed in Table 2, include river and distributary channels of various sizes, mid-channel shoals and distributary mouth bars that may be vegetated, levee banks that also extend below water level as silt jetties (Bird, 1967), crevasse splays where levees are breached by flood waters, delta-top platform and muddy, delta-front slopes extending below the photic zone, and finally, interdistributary bays grading into fresh-water swamps. Sediment types range from relatively clean fluvial sand and gravel in channel beds and on shoals in the river mouth, to poorly sorted mixtures of sand, mud and organics in levee deposits and on the delta-front platform, becoming very muddy and organic-rich in marginal embayments and brackish swamps. Fluvial delta morphologies vary from classic delta shape with multiple distributary channels (e.g. Karuah River, Tuross Estuary), to elongated ‘ birds-foot ’ deltas with levee jetties (e.g. Camden Haven River). In confined, tide-dominated estuaries such as the Hawkesbury, the fluvial delta zone is attenuated over 20 km and has a single distributary channel.

The size of intertidal areas within fluvial delta environments depends on tidal range and this also controls the distribution of mangroves and saltmarsh. The intricate network of channels and tidal creeks which are constantly eroding and reforming, create a diverse and dynamic association of intertidal vegetated habitats providing food and shelter to a variety of animals. In drowned valley estuaries, the fluvial delta tends to be elongated and is mostly a subaqueous feature with extensive intertidal areas. By contrast, the fluvial delta zone in barrier estuaries is less extensive (because of their smaller tidal ranges) with more restricted areas of mangroves and saltmarshes. In intermittent estuaries with negligible tides, mangrove and saltmarsh areas are virtually absent (Table 4).

Seagrasses occur on stable parts of the delta surface but in shallower depths than elsewhere in the estuary because of relatively high turbidity levels. Water circulation within fluvial delta environments is dominated by tidal currents in drowned valley estuaries (e.g. Hawkesbury River) and by wind stress-induced circulations in barrier estuaries (such as Tuggerah Lakes and Lake Illawarra) and intermittent estuaries (e.g. Smiths Lake). Surface waters carrying organics and nutrients drain from terrestrial backswamps via interdistributary and cut-off bays into the estuaries' central basin. Time-averaged, mean salinities decrease upstream from the fluvial delta into the riverine channel zone.

Riverine channel and alluvial plain

Elongate riverine channels intersect alluvial plains formed through the progradation of fluvial deltas into former estuaries. Channel environments are characterized by fluctuating fresh and brackish water conditions controlled by river discharge (Table 3) and in the case of tide-dominated estuaries, by the rise and fall of tidal water levels. For the purpose of this study, the upstream limit of the riverine channel zone is defined as the maximum landward extent of brackish conditions during droughts and is transitional with permanent freshwater (river) environments. For example, in the Hawkesbury River the upstream limit of the riverine channel zone is just above the confluence with the Colo River, about 110 km from the coast (Jones *et al*., 1986). The riverine channel zone grades downstream into the fluvial delta environment, a transition marked by subtle changes in the nature of

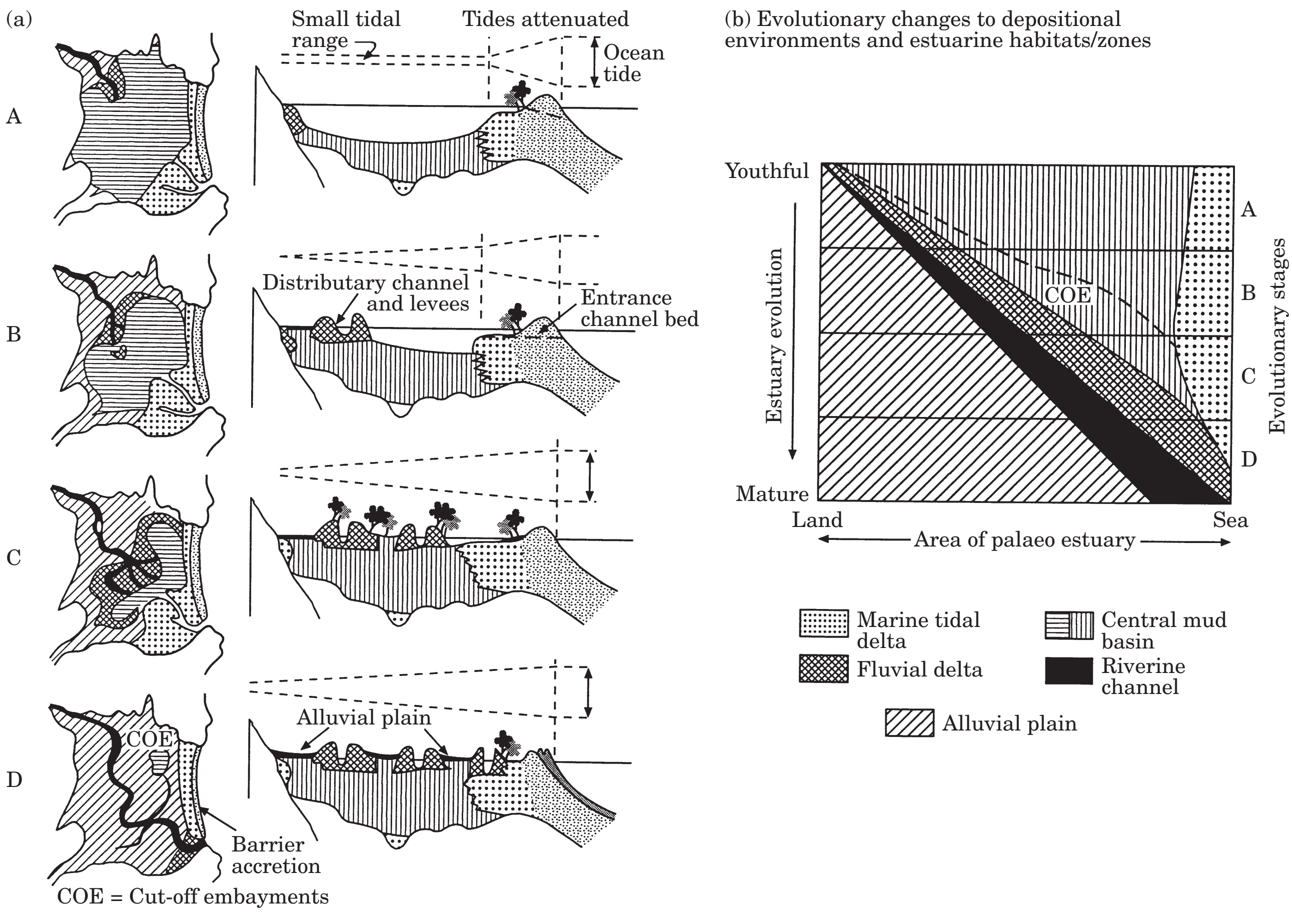


FIGURE 5. (a) Stages of infilling in the evolution of an idealized barrier estuary: A=youthful, B=intermediate, C=semi mature, D=mature. (b) Field diagram showing changes in surface areas of the various depositional environments/zones as the estuary evolves from youth to maturity.

the channel-margin deposits, channel widths and the salinity regime (Table 3). Channel banks are usually vegetated by *Phragmites australis*, mangroves only occurring in downstream locations in tidal estuaries; seagrass and salt marsh are rare. In the Hawkesbury, the riverine channel and fluvial delta zones are elongated and their transition probably corresponds to the upstream limit of the turbidity maximum zone located near the junction with Mangrove Creek, 30–40 km from the coast (Hughes *et al.*, 1998). This area coincides with a marked downstream increase in channel width and the extent of intertidal mud flats.

Riverine channel sediments are typically sandy, sometimes gravelly and periodically remobilized by flood flows. It is common for channels to be incised into relict estuarine muds, deposited before the estuary infilled, but now veneered with sand (Roy *et al.*, 1995). Usually, sandy point bars that occur at meander bends are mirrored on the opposite bank by undercutting and bank collapse, a natural process that becomes more pronounced as the alluvial plains aggrade and meandering increases (Hashimoto & Roy, 1996). Bank erosion has been exacerbated in the last 200 years by land clearing, especially of riparian vegetation, and unwise agricultural and engineering practices (Erskine & Warner, 1988; Warner, 1994). Species diversity in riverine channels is generally lower than in downstream environments due mainly to lower salinities.

The subaerial alluvial plains associated with riverine channels comprise levee, flood plain, backswamp and abandoned channel subenvironments. Although not strictly estuarine, alluvial plains contain freshwater swamps that, after heavy rains, drain into the estuary water body, thus contributing additional nutrients and temporarily establishing corridors linking terrestrial and estuarine ecosystems. The strongly reducing conditions existing in muddy estuarine sediments, together with saline water and sulphur fixing bacteria, are responsible for the *in situ* (diagenetic) formation of iron sulphide minerals such as pyrite (Melville *et al.*, 1991). As the estuaries infill, pyrite bearing sediments aggrade to near mean sea level and are progressively blanketed by alluvium. Because of their rich soils, the coastal alluvial plains have been the preferred sites for tree clearing, agriculture and urban development, and in many cases swampy areas have been drained for agriculture (grazing, sugar cane and tea tree cultivation) or habitation (canal estates). Their contained pyrite is chemically stable as long as the deposits remain below the water table but where acidic subsoils were exposed to oxidation by drainage works that, over decades, have lowered water tables, highly acidic groundwaters have been produced. Acid discharge into the estuary changes water chemistry, kills and/or induces fish diseases, and impairs oyster production and other benthic communities (Sammut *et al*., 1993, 1995; Roach, 1997; Gibbs *et al*., 1999). Areas particularly affected are riverine channel zones in coastal lowlands of large infilled barrier estuaries in northern New South Wales (Hashimoto & Roy, 1996). The potential magnitude of the problem in coastal New South Wales is shown on the 1:25000 Acid Sulphate Soil Hazard maps (DLWC, 1997).

Estuary evolution—geological and ecological trends

Estuaries are the most dynamic of coastal environments not only in terms of short-term responses to climate forcing but, more importantly, at geological time scales due to natural processes that progressively convert estuarine water areas to terrestrial flood plains, levees and backswamps. (Here the term ‘ estuary ’ includes the bounding substrate as well as the water body.) Transformations at geological time scales constitute estuary evolution and all types of estuaries are affected (Figure 5). The time frame for the most recent cycle of infilling commenced with the drowning of coastal valleys as global sea levels rose (Thom & Roy, 1985). Depending on the depth of the palaeovalleys (they range from − 20 m to − 50 m at the present coast), inundation of their thalwegs occurred around 7–8 ka BP with maximum landward flooding coinciding with the sea stabilizing near its present level (possibly a metre or so higher) at about 6·5 ka BP (Thom & Roy, 1985; Roy & Boyd, 1996). Since this time, all estuaries have trapped sediment eroded from the hinterland by rivers and washed into the estuary mouth by waves and tidal currents (Roy, 1984). The extent to which present-day estuaries have been filled is a function of the rate of sediment supply over this period (that depends in turn on catchment area, vegetation cover, disturbance, lithologies, rainfall) and the accommodation space contained in the palaeo-estuary. The degree of infilling varies widely; the resulting depositional styles and stratigraphic architectures have been described for the main estuary types on the New South Wales coast by Roy (1994, 1998), Nichol *et al*. (1997), Devoy *et al*. (1994). Although infilling is a seamless progression, we adopt the same four stage subdivisions as Roy (1984) [Figure 5(a)] to represent the succession from relatively unfilled, youthful (or immature) estuaries: (Stage A, 0–25% filled), through intermediate (Stage B, 25–50% filled) and semi-mature (Stage C, 50–75% filled) to filled, mature estuaries (Stage D, more than 75% filled). Changes in the distributions of the various depositional environments (zones) as an idealized estuary evolves, are shown in a field diagram in Figure 5(b). Initially, all estuaries were essentially unfilled; subsequently, some estuaries have filled so slowly that they are still designated as immature, whereas others have infilled rapidly and now are at a mature stage of development (see Appendix).

The temporal progression in estuary evolution has a spatial counterpart. Figure 6(a) shows an estuary in which seaward growth of the fluvial delta and alluvial plain has created a gradient, or hierarchy, in maturity; landward parts of the palaeo-estuary being more mature than seaward parts. Because rates of infilling are non-uniform, slow filling parts of an estuary tend to be bypassed, forming cut-off embayments, as the delta front builds seaward. The sequence of events depicted in Figure 6(b) shows an embayed part of the central mud basin being cut off by a prograding delta, shoaling and eventually forming a backswamp. As remnants of central mud basins, cut-off embayments become increasingly important as the estuary evolves; they trap organic materials, act as nutrient factories and are biologically highly productive. In the Clarence River, a mature barrier estuary, examples of cut-off embayments at progressive stages of infilling are Lake Wooloweyah, The Broadwater and Everlasting Swamp. Cowan, Berowra and Mooney Mooney Creeks form a succession of cut-off embayments in the Hawkesbury, a tide-dominated, drowned valley estuary where the build-up of fine fluvial sediment in the mouths of the tributary valleys is subaqueous, forming ‘ reverse ’ deltas. In the case of Berowra Creek estuary, the reverse delta is considerably larger than the fluvial delta/alluvial plain in Berowra Creek valley.

These evolutionary trends in zonal development have been documented in a study of 68 barrier estuaries and saline coastal lagoons in southern New South Wales by S. Nichol (written comm., 1991) who mapped the aerial extent of the various palaeo-environments and measured their areas. The results, plotted in Figure 7, confirm a statistical relationship between estuary water area and its maturity (degree of

(a)

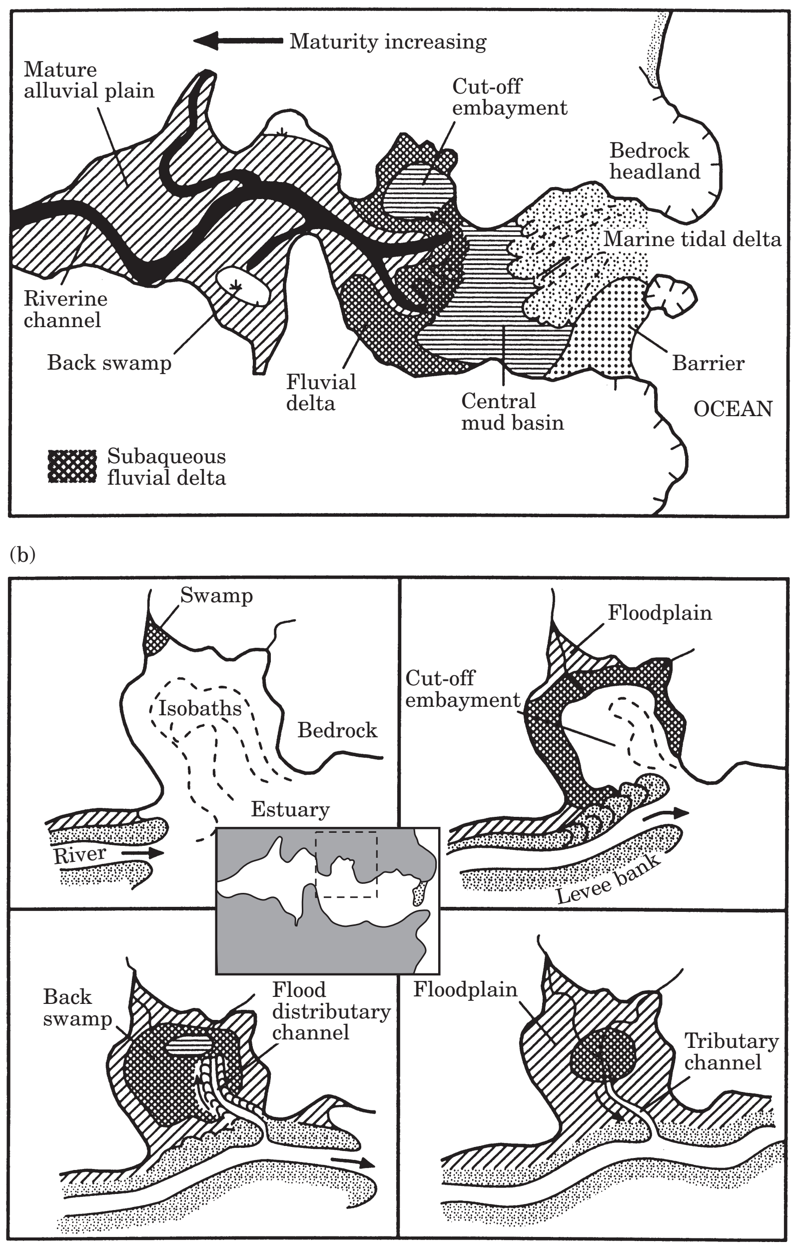


FIGURE 6. (a) Idealized estuary at a late intermediate stage of infilling showing a hierarchy of depositional morphologies ranging from mature forms in its landward part to more youthful forms near its mouth. (b) Stages in the genesis of a cut-off embayment as the fluvial delta builds seawards.

infilling) as measured by the combined size of the fluvial delta and alluvial plain. No relationship exists between estuary maturity and the size of the marine tidal delta. Evolutionary stages of other New South Wales estuaries listed in the Appendix are estimated from local field observations.

In the case of the larger river systems in New South Wales (Tweed, Richmond, Clarence, Macleay, Hastings, Hunter, Shoalhaven), there is a clear connection between their present-day maturity and their catchment sizes. In contrast, the smaller estuaries studied by Nichol showed no consistent relationship between catchment size and estuary maturity; Pease (1999) reported a similar finding. Other variables, such as palaeo-estuary size, weathering characteristics of the rocks in the hinterland etc, are also important. Volume measurements of the sandy Holocene fluvial deltas in 14 estuaries along a 60 km long sector of

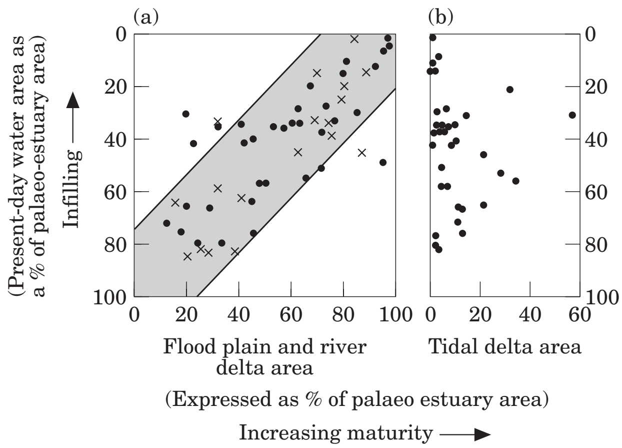


FIGURE 7. Plots for estuaries in southern New South Wales showing changes in the proportional sizes of the fluvial delta and alluvial plain (a) and marine tidal delta zone (b) in relation to estuary infilling. (Infilling is expressed as a percentage of present day water area to area of the palaeo-estuary.) (Data from S. Nichol, written comm., 1991). In (a), barrier estuaries (**x**) are distinguished from saline coastal lagoons (●).

coast in the Narooma-Bermagui region (Roy, 1998), determined a total annual rate of fluvial sand supply of less than 10 000 m^3 or about 150 m^3 km^{-1} length of coast. Clearly, rates of denudation in south coast catchments are very slow and this accounts for the large number of small estuaries that remain immature in this region.

Whereas the geological results of estuary evolution are reasonably well known, parallel changes that must have affected estuary biota and ecology are less so. Resident plant and animal communities in present-day estuaries trace their succession back to parent populations in proto estuaries in the early Holocene (Nichol *et al.*, 1997). In extreme cases, such as the Clarence, Hunter and Shoalhaven estuaries, former water bodies >100 km^2 in area have shoaled and, in the last three to four thousand years, have contracted in size at rates estimated at 20 000–50 000 m^2 yr^{-1} (Roy, 1994). Clearly, physical changes of this magnitude were accompanied by rapid evolution of estuarine ecosystems. An evolutionary ecology record is potentially accessible from the fossil remains in the estuarine sediments; for example, M. Buman (written comm., 1995) documented changes in molluscan assemblages in the Shoalhaven as the estuary became shallower and more turbid over the last 5 ka. Alternatively, it may also be possible to piece together a succession from living assemblages in present day estuaries that exhibit different degrees of infilling (all else being equal). Certainly this line of enquiry would seem warranted where coastal managers are considering dredging or reclamation works to either retard or speed-up the natural evolutionary progression in particular estuaries. Ecological changes presumably have already been induced in many estuaries by anthropogenic manipulations of their salinity regimes due to dam building and irrigation works that have reduced fresh water flows in coastal rivers (e.g. Hawkesbury) and the construction of training walls at estuary mouths that have increased tidal exchange (e.g. Wallis Lake). The nature of these ecological changes remains to be documented.

For the purposes of this study, estuary evolution can be represented by spatial changes to the four geomorphic zones described previously (Figure 5). Thus, youthful (Stage A) estuaries are characterized by large and relatively deep, central mud basins and very small fluvial deltas and alluvial plains. Increasing maturity (stages B to D) involves the seaward progradation of the fluvial delta into the central basin and the expansion, behind it, of the alluvial plain and riverine channel zone. This is exemplified in the upper Hawkesbury estuary where geological studies (Nichol *et al.*, 1997) have shown that in the mid-Holocene, estuarine conditions existed well upstream of the present riverine channel zone but have been displaced downstream as the estuary infilled. At youthful stages the fluvial delta expands slowly into the relatively deep central mud basin zone but, as accommodation space is reduced by aggradation, the rate of delta progradation accelerates and its surface area increases. Marine flood-tidal deltas exhibit contrasting styles of evolution depending on estuary type (Roy, 1994). In tide-dominated, drowned valley estuaries, such as the Hawkesbury, the flood tidal delta grew continuously for thousands of years while accommodation space existed in the central parts of the estuary but eventually it was buried by the prograding fluvial delta [Figure 5(b)]. In slow-filling cases of these estuaries, such as Port Stephens, Port Hacking and Pittwater, present-day tidal deltas continue to grow into deep central basins. In barrier estuaries, on the other hand, tidal deltas seem to have been emplaced rapidly at the end of the Post-glacial Marine Transgression (Roy, 1984, 1994) and are largely relic features today except where they have been reactivated by entrance training works (e.g. Wallis Lake, Lake Macquarie).

One of the major regulators of estuarine productivity is the areal extent of the central mud basin and the vegetated zone around the estuary margins. Other factors include river discharge and tidal exchange which flush nutrients and sediments out to sea (Eyre, 1998) thus slowing evolutionary changes. The latter causes shoaling of the central mud basin and modifies the distribution of vegetated areas. It is reasonable to assume that, as the basins fill in and their side slopes become shallower, and more light and O_2 are available for benthic vegetation, photosynthesis and rates of primary production increase. Maximum productivity presumably occurs at shallow depths but is modulated by wave stirring that not only mobilizes nutrients but also increases turbidity thereby inhibiting photosynthesis.

Evolutionary patterns affecting vegetated zones include their expansion as the surface area of the fluvial delta increases (Figure 5, Stage C) and contraction as the central mud basin infills and the two delta zones merge (Stage D). As suggested by Roy (1984, Figure 6), we infer a general increase in biological productivity as estuaries evolve towards intermediate and semi-mature stages followed by a decline as they approach full maturity. The decline is mainly attributable to the loss of water area, especially the central mud basin, and the expansion of the less productive riverine channel zone and associated alluvial plain.

Water quality

Estuary hydrology is characterized by fluctuations in salinity due to inflows of freshwater and saltwater, ambient heating and cooling as seasonal weather conditions change, and mixing by currents. Time-averaged, these properties vary in broadly predictable ways according to estuary type, stage of infilling and inherited factors (Rochford, 1951; MacIntyre, 1959; Roy, 1984, 1994). Mixing of water masses is influenced by tidal exchange (which relates to estuary type) and also by the size and shape of the estuary basin (a function of inheritance and maturity) which determine the effectiveness of wave stirring and wind-induced currents. Inherited factors such as river size and climate determine freshwater flows and evaporation that, in temperate parts of eastern Australia, are highly erratic (Digby *et al.*, 1998). In broad terms, a salinity gradient exists between the estuary mouth and its inflowing rivers; an upstream increase in temporal variability is also apparent (Rochford, 1951; Rochford & Newell, 1974). However, spatial trends are less clear in youthful estuaries where salinities are fairly uniform throughout their extensive central basins. Salinity gradients become more pronounced as the estuaries approach maturity, mud basins infill, fluvial and estuarine deltas merge and riverine channel zones elongate (Figure 6). The effect of flooding on estuarine salinity regimes increases as the estuary matures and its water body decreases in size. The large water area of youthful estuaries acts to buffer flood inflows which form a thin surface layer of freshwater discharging slowly to the sea. In contrast, floods in mature (riverine) estuaries are more intense and may result in complete expulsion of the saline waters while the flood discharges to the sea.

Salinity gradients are particularly enhanced in lower reaches of some semi-mature barrier estuaries where their side arms (inter-barrier creeks and cut-off embayments) experience more marine conditions than the main channel (examples are found on the Brunswick, Richmond, Clarence, Bellinger and Nambucca Rivers). Heightened salinities in the side arms are responsible for a higher diversity of mangrove species and large saltmarsh areas (West *et al.*, 1985), as well as more diverse fish and invertebrate communities. Of the three main estuary groupings, drowned valley estuaries have the most consistent salinity and temperature regime and are well flushed by tides; wave-dominated (barrier) estuaries, have more variability (Yassini & Jones, 1995), and intermittent estuaries (saline coastal lagoons and coastal creeks) with their long periods of enclosure, have the most variable hydrology (Robinson *et al.*, 1983; Pollard, 1994*a*). The large abiotic variability constrains species richness in intermittent estuaries.

Unlike Northern Hemisphere estuaries, salinity stratification is not a common or persistent condition in temperate Australian estuaries (Digby *et al.*, 1998). After heavy rains it mainly affects relatively deep parts of central mud basins with slow tidal flushing (e.g. Lake Macquarie, MacIntyre, 1968) but has also been noted in shallower barrier estuaries such as Tuggerah Lake (Bourgues *et al.*, 1999). In the former case, saline bottom waters trapped beneath a buoyant fresh water lens become deoxygenated as organic material decays on the bed of the estuary and, in rare circumstances, this may lead to mass mortality of animals. Examples of areas affected include Berowra Creek in the Hawkesbury Estuary and Southwest Arm in Port Hacking (Rainer & Fitzharding, 1981), both immature drowned valley estuaries; and Lake Macquarie, an immature barrier estuary (MacIntyre, 1959, 1968). Sediment cores in Berowra Creek (Coastal and Marine Geoscience, written comm., 1998) encountered sections of finely laminated muds (representing periods of deposition without bioturbation that normally mixes individual sediment layers) which we infer reflect the mass mortality/failed recruitment of benthic organisms due to prolonged deoxygenation of bottom waters.

Shallow barrier estuaries are generally well mixed, but dissolved oxygen stratification in conjunction with slight temperature stratification is sometimes observed (Bourgues *et al.*, 1999). It can be enhanced during periods of non-mixing when nutrients released from bottom sediments stimulate phytoplankton and algal growth in surface waters. Heat trapped during photosynthesis produces a marked thermocline with bottom water (2–4 °C cooler) becoming deoxygenated by oxygen-consuming bacteria. Anoxic chemical reactions in the sediment release adsorbed phosphorus which, together with nutrients from decomposing plant material, stimulates further algal growth in the surface waters. The positive feed-back loop breaks down with wind-wave stirring. Other aspects of nutrient release are discussed in the next section.

Other anthropogenic impacts that degrade estuary water quality are acidic ground waters (acid sulphate soils) which change water chemistry, increase water toxicity and deplete dissolved oxygen (Melville *et al*., 1991; Sammut *et al*., 1993, 1995; Roach, 1997; Gibbs *et al*., 1999) and the introduction of contaminants such as trace metals and organochlorines which accumulate in biota (Mackay *et al*., 1975; Williams *et al*., 1976; Scanes, 1993, 1997; Scanes & Roach, 1999), bottom sediments (Roy & Crawford, 1984; Birch, 1995) and saltmarsh areas (Chenhall *et al*., 1992). Muddy environments including central mud basins and interdistributary bays within fluvial deltas are the main zones affected by eutrophication and contamination problems. Acid sulphate soils are mostly associated with the draining of alluvial plains with the result that discharges of acid ground waters mainly affect the riverine channel zones.

Nutrient cycling and primary productivity

Estuaries receive and store sediments and nutrients from the land; they cycle nutrients internally and regulate their discharge to the coastal ocean; some nutrients are sequestered with the estuarine sediments as they accumulate (McComb, 1984). In temperate Australia, because of the eucalypt-dominated vegetation, and the resultant fire regime and poor soils (Roy, 1998; Thomas *et al*., 1999; Harris, 1999*a*), estuaries in pre-European times were low nutrient systems (Rochford, 1979), in particular, nitrogen limited (Specht & Specht, 1999). Two hundred years of land clearing, agriculture and urban development have greatly increased nutrient loadings and undoubtedly have enhanced primary productivity in most estuaries, in some cases beyond sustainable levels (SoEAC, 1996).

Our interest in nutrient cycling in estuaries is based on the assumption that rates of primary production and estuary productivity overall are regulated by the rate at which nutrients are introduced and cycled (i.e. nutrient turnover). Cycling is facilitated by the bacterial decomposition of organic matter and attendant re-mineralization of nutrients necessary for photosynthesis. Geochemical and biochemical processes are most intense in muddy sediments where bacterial densities are possibly an order of magnitude larger than in sandy sediments (Volk & Wheeler, 1973). The largest repositories of nutrients in estuaries occur in their central mud basins and in interdistributary embayments in the fluvial deltas where disturbance by waves and currents is minimal. Here, breakdown of complex organic compounds and dead biomass into smaller and simpler molecules by oxidative and reductive reactions, mediated by microbial action, ensures a continuous flux of nutrients into the water column. Nitrogen release is primarily a function of biochemical processes while the release of phosphorus is geochemically controlled.

In contrast to the muddy areas, smaller stores of nutrients are contained in sandy sediments. These occur in marine tidal deltas, shallow-water zones around the sides of the estuaries and on the beds of channels in the fluvial delta and riverine channel. Here, rates of nutrient cycling and photosynthesis may be high depending on the stability of the substrate (a function of bed reworking) and water depth/clarity that influences the availability of sunlight. The transfer of nutrients to micro-organisms (mainly phytoplankton) that form the base of the estuarine food chain is accomplished in two ways depending upon the availability of light and the nature and stability of the substrate.

Nutrient cycling in the photic zone

Shallow-water areas have adequate light for photosynthesis and high concentrations of dissolved O_2 and CO_2 due to mixing by wind waves. Here, nitrogen is made bioavailable by nitrification-denitrification processes involving reduction of organic material to form ammonia (NH_3), its oxidation to nitrite and nitrate by nitrifying bacteria in the sediment and finally, its denitrification (re-mineralization) to gaseous nitrogen, which escapes to the atmosphere. In contrast, soluble phosphorus is stripped from the water column and locked up in various hydroxides in the sediment and is less biologically available. In areas with stable substrates, a variety of seagrasses and macroalgae produce large amounts of detritus and support dense populations of biofilms and epiphytes. Epiphytic flora and fauna provide an immense surface area for microbial metabolism (Harris, 1999*a*). Decay of the dead biomass by reducing and oxidizing bacteria generates a flux of nutrients, which diffuse into the surrounding water and accumulates in the bottom sediments. As well, part of the oxygen intake in seagrass respiration is transferred to the rhizomes creating a thin film of oxygen around the roots and rootlets (Hammer & Bastian, 1990). The oxygenated layer expands the zone of nutrient release by aerobic bacteria into a substratum normally dominated by reductive reactions and anaerobic bacteria (Faulkner & Richardson, 1990).

Nutrient cycling below the photic zone

In deeper parts of an estuary where light levels at the bed are typically inadequate for photosynthesis of higher plants, nutrients in the organic-rich muddy sediments are cycled by geochemical and biochemical processes under oxic and anoxic conditions. The presence of oxygen in water at the sediment interface allows organic materials to be digested by aerobic bacteria in a number of oxic reactions. The products of these reactions (CO_2, NO_3, O_2, PO_4) diffuse into the water column where they are directly consumed by benthic micro-organisms living on the sediment surface and by phytoplankton and other micro-organisms in the surface water layers.

Nitrogen release in sub-photic environments follows similar pathways to the photic zone. In contrast, phosphorus is made bio-available through absorption-desorption processes in the basin muds. The supply of oxygen to the water sediment interface essentially controls the rate of these reactions (Biggs & Cronin, 1981). Oxygenation of interstitial waters in the upper sediment layers is greatly enhanced by physical mixing of the sediment, including bioturbation, and by bio-irrigation which circulates water through cavities in the sediment. Conversely, phenomena such as eutrophication and stratification that reduce oxygen availability at the bed greatly retard adsorption-desorption reactions and stimulate anoxic processes. In anoxic bottom sediments, the products of these reductive reactions (e.g. NH_3, H_2S, CH_4) are assimilated into the sediments by chemoautotrophic bacteria (Webb, 1981). Except for ammonia which is readily assimilated by macroalgae and phytoplankton, these products are either toxic to biota or unusable in primary production without first being oxidized. Further denitrification generates N_2 gas, which is lost to the atmosphere.

The simplified primary production model shown in Figure 8(a) divides the estuary first into two horizontal layers, a sun-lit surface layer (the ‘ photic ’ zone) and a deeper layer with insufficient light for photosynthesis of higher plants; and second into stable and mobile substrate/sediment types that reflect ambient wave and current energy levels. This subdivision defines four primary production domains:

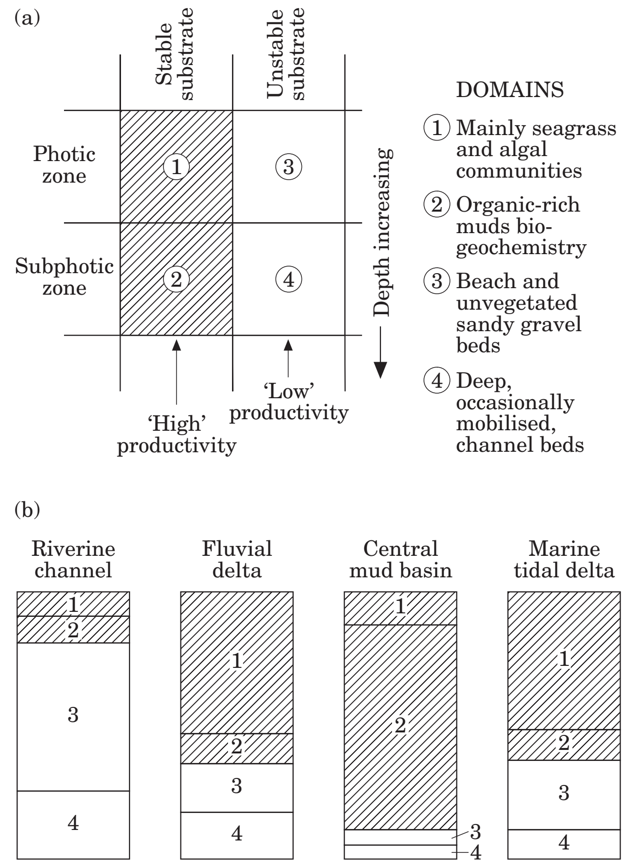


FIGURE 8. Estuarine nutrient recycling domains. (a) Domains defined in terms of water depth/light penetration and stability of the substrate. (Cross hatching indicates domains with relatively high rates of nutrient cycling.) (b) The four main estuarine zones showing notional contribution in each of the various nutrient cycling domains.

1. Stable substrates in the photic zone around the margins of the estuary (and extending into the intertidal zone) where photosynthesis in sea-grass and algal communities promotes primary productivity.
2. Stable substrates in deeper water below the photic zone, where the bed of the estuary is composed of organic-rich mud, and oxic geochemical reactions promote high rates of nutrient release to benthic microalgal films on the bed and to phytoplankton in the overlying water column.
3. Relatively high-energy (unstable) parts of the photic zone such as beaches and channel beds, where the bottom sediments are too mobile to support sea grass or algal communities. Although these unstable sediments can support photo-synthetic micro-organisms such as diatoms, rates of primary productivity are assumed to be comparatively low.

4. Sub-photic areas in deep channels where high energy currents and/or periodic flood flows mobilize the mainly sandy bed and restrict biogeochemical cycling of nutrients.

While it is clear that domains 1 and 2 have greater rates of nutrient cycling than domains 3 and 4, primary productivities per unit area in the various domains are yet to be fully evaluated. Figure 8(b) suggests linkages between the various nutrient cycling domains and the four main estuary zones discussed previously: marine tidal delta, central mud basin, fluvial delta and riverine channel.

The majority of the central mud basin is involved in biogeochemical nutrient cycling (domain 2); a much smaller area, corresponding to vegetated parts of its photic zone, also has high rates of nutrient cycling due to photosynthesis and regeneration (domain 1); and a very small sector, its beaches, has comparatively low rates of nutrient cycling (domain 3). The various domains in the fluvial and marine tidal deltas have similar proportional representation with nutrient cycling in both zones dominated by photosynthesis (domain 1) in sea grass and algal films on the delta surfaces. Bio-geochemical processes (domain 2) operate in deeper water on the muddy delta fronts below the photic zone, while domains 3 (and to a lesser degree 4) operate in tidal and distributary channels that intersect the delta surfaces. Although riverine channel sediments support benthic micro and macroalgae communities during periods when current velocities are relatively low, overall nutrient cycling rates are inferred to be low due to periodic bed instability, high turbidity levels, reduced light penetration and low salinities that favour domains 3 and 4. The patterns of nutrient cycling depicted in Figure 8(b) suggest that estuary primary productivity is controlled by three factors: (1) the aerial extent of those domains where nutrient cycling is most active—the bed of the central mud basin and shallow water/intertidal areas on the fluvial and marine tidal deltas; (2) tidal exchange with the coastal ocean which flushes nutrients out to sea; and (3) factors that modify the rate at which biochemical processes operate. Point (1) is the combined result of inherited estuary size and the present-day stage of infilling; point (2) is a function of entrance conditions and thus, of estuary type; and point (3) has various anthropogenic causes.

Estuarine ecology

Empirical evidence suggests that associations exist between estuary form and ecological function (Roy, 1984) and consequently there is a basis for making predictions concerning species diversity and abundance and aspects of primary production. Investigating these associations is difficult as there are few data sets that can be applied over the scale of the southeast Australian coast. We use commercial fisheries catch data, the only available surrogate for fish production/abundance, and acknowledge the assumptions in doing this.

Estuarine flora

Unlike phytoplankton, whose role has already been discussed, estuarine macrophytes are not a major food source. Their principal contribution to the estuarine system is production of detritus, provision of substrates for epiphytes and shelter for small fish, crustaceans and molluscs and the stabilization of sediments. These important functions dominate the ecology of those parts of estuaries where saltmarsh, mangrove, seagrass and macro algae occur.

Saltmarsh and mangrove occupy the intertidal and supratidal zones of fluvial and tidal delta environments (West *et al.*, 1985). As a consequence of the regional climate trend, species diversity of mangrove communities decreases (from six to one species) from north to south along this section of coastline, while the diversity of saltmarsh communities increases (Saenger *et al.*, 1977). Their coverage in any one estuary is influenced by various habitat characteristics, in particular the extent of stable substratum. Consequently, their areal extent increases with tidal range and with decreasing gradient of the intertidal zone as estuaries infill with sediment (D. Stolper, pers. comm., 1997). When compared against the three main estuary types and their stages of evolution/infilling (Table 4), saltmarsh and mangrove are shown to be most widespread in drowned river valley estuaries, less abundant in barrier estuaries, and generally poorly developed in saline coastal lagoons. This trend reflects the large water areas and tidal ranges found in drowned river valleys—compared to barrier estuaries; saline coastal lagoons are even smaller and functionally non-tidal. There is also a trend, independent of estuary size, of expanding saltmarsh/mangrove area with increasing estuary maturity (Table 4). This pattern is best displayed in barrier estuaries due to the expansion of fluvial deltas as the estuary infills with sediment, and an associated increase in tidal range (Roy, 1984).

Due to high wave energies along the open coastline, seagrasses and associated species in the region are almost exclusively confined to estuarine waters, where they are typically found on the upper surfaces of fluvial and marine tidal deltas and fringing the central mud basins (West, 1983; West *et al.*, 1985, 1989). The number of seagrass species increases southwards from five to eight species (Robertson, 1984). Their distribution is strongly influenced by light penetration, depth, salinity, nutrient status, bed stability and wave energy (West *et al.*, 1989; King *et al.*, 1991; Dennison, 1987; Abal & Dennison 1996; Udy & Dennison, 1997). We also suspect that the salinity of interstitial pore water is a controlling factor: the discharge of fresh ground water favours euryhaline species such as *Ruppia* sp. Seagrasses are most prolific in barrier estuaries; these tend to have wide photic zones on gently sloping sides and delta surfaces (Table 4). Seagrass meadows are less well developed in drowned valley estuaries due to steeper side slopes, stronger currents and higher turbidity levels. The most widespread species is *Zostera capricorni*, which dominates most zones in all estuary types. *Posidonia australis*, the other major species, is confined to fewer estuaries (16 out of 135 in West *et al.*, 1985) and appears to prefer areas along the central and southern coast where salinity is high and nutrient levels are low. As a consequence, *Posidonia australis* is found in areas composed of marine sands in open embayments (Jervis Bay and Botany Bay), the entrances to drowned valley estuaries (Sydney Harbour and Port Hacking) and youthful barrier estuaries with well developed marine tidal deltas (e.g. Wallis Lake and Brisbane Waters). In contrast, *Ruppia megacarpa*, occurs in parts of some barrier estuaries (Tuggerah and Illawarra Lakes) and in saline coastal lagoons with particularly low salinities. The area covered by seagrass tends to contract as the estuaries infill. Two factors are responsible: a general decrease in water area as the fluvial delta expands into the mud basin, and an increase in turbidity as the central basin shoals and its muds are resuspended by wave action.

Estuarine fauna

There are obvious and strong links between estuarine fauna and the fauna of inshore marine waters and, to a much lesser extent, coastal freshwater systems. Some species are found in a combination of these three habitats, sometimes using a specific habitat at a particular life history stage (e.g. Lenanton & Potter, 1987; Pollard *et al.*, 1990; Pollard & Hannan, 1994). Some estuarine fauna are categorized on the basis of salinity tolerance (e.g. in regard to benthic invertebrates see Boesch, 1977). In contrast, fish species that spend the majority of their life in the estuary can be defined as residents, and species that move regularly into estuaries and/or pass through estuaries can be called migrants (Day *et al.*, 1981) whereas transients can be defined as short term visitors, usually from inshore marine waters. Of the commercial fish species in New South Wales, the most common and valuable are migrants, fewer are residents, and virtually none are transients.

Species richness

The number of species at any given point in an estuary is influenced by salinity (Jones, 1988; Kinne, 1964), the variety and area of habitats, and conditions such as calmness of water, food, shelter and protection from predators (Blaber & Blaber, 1980; Pollard, 1984; Bell & Worthington, 1992; Jones *et al.*, 1986; Gray *et al.*, 1996). Maximum richness of resident species should be achieved during semi-mature stages of estuary evolution when fluvial deltaic environments have expanded to their maximum size and provide the greatest range of habitats (Roy, 1984). However, in absolute terms, this trend is countered by the progressive reduction in water area (and in central mud basin environments) as the estuary infills which presumably affects the abundance of migrant species in particular. In terms of salinity tolerance, species found in estuaries may also be classified as being predominantly freshwater, estuarine or marine in their salinity preference. The pattern, described by the Remane curve (Remane & Schlieper, 1971), shows a fall in species richness from a maximum near the estuary mouth where salinities are more than 30 to a minimum at salinities of about 5–8 near the landward limit of the riverine zone. Similarly, the Venice System (Carriker, 1967) divides the estuary longitudinally into salinity divisions that reflect ecological groupings (see Wolff, 1983 and Hodgkin & Kendrick, 1984 for reviews, and Jones *et al.*, 1986; Gray *et al.*, 1990; West & King, 1996; and West & Walford, 2000). In tide dominated, drowned valley estuaries (e.g. Sydney Harbour) and mature barrier estuaries (e.g. Clarence River) where there is a pronounced salinity gradient from the entrance to their upper reach, species richness declines in the same direction. In youthful and intermediate barrier estuaries (e.g. Lake Macquarie) and coastal lagoons (Coila Lake) where salinity is more uniform, there are also fewer differences in faunal richness. Mean salinity and its variability appear to be important and flood/drought events can have large effects (Day & Grindley, 1981; Jones, 1987, 1989). Factors other than salinity may become dominant in youthful estuaries where gradients are weak or at smaller within-estuary scales where morphological or sedimentary factors can be important (Jones, 1988). For example, macrobenthic invertebrate species seem to be strongly influenced by sediment grade, with mixed muddy-sands usually being richer than either fine muds or clean mobile sands (Day, 1981b).

Our particular interest is in the relationship between the number of estuarine species and their abundance, and the underlying geomorphology of the estuaries, that in part controls these factors. In light of this, the principal physical attribute appears to be the nature of the estuary mouth. Entrance conditions control not only water exchange between the ocean and the estuary (thereby influencing salinity) but also the access and movement of fauna across that boundary, especially migrant and transient species (Robinson *et al.*, 1983; Pollard, 1994*b*; Potter & Hyndes, 1994, 1999; Hannan & Williams, 1998; Pease, 1999; Griffiths & West, 1999). Such movements may involve not only regular life-cycle migrations but also ecological recovery following disturbances (e.g. floods and anthropogenic impacts). Entrance conditions are in turn controlled by estuary type and maturity. The open and often deep mouths of drowned valleys (e.g. Sydney Harbour, Hawkesbury River), and mature barrier estuaries (e.g. Clarence and Richmond Rivers) provide large, high-salinity areas where faunal diversity and abundance is enhanced due to the occurrence of migratory and transient species. Diversity is more restricted in youthful barrier estuaries (e.g. Lake Macquarie, St. Georges Basin) being greatest in the high-salinity sections of the narrow inlet where tidal flows are strongest. Species richness is at a minimum in saline coastal lagoons and small creeks with even less tidal exchange because their mouths are mostly closed. Entry of migrant and transient species to saline coastal lagoons only occurs during brief openings and so the presence of many species is unpredictable (Robinson *et al.*, 1983; Pollard, 1994*b*; Allan *et al.*, 1985; Griffiths & West, 1999). Migratory and transient species trapped in these closed coastal lagoons for any length of time rarely survive because of strong fluctuations in water variables (particularly oxygen and salinity).

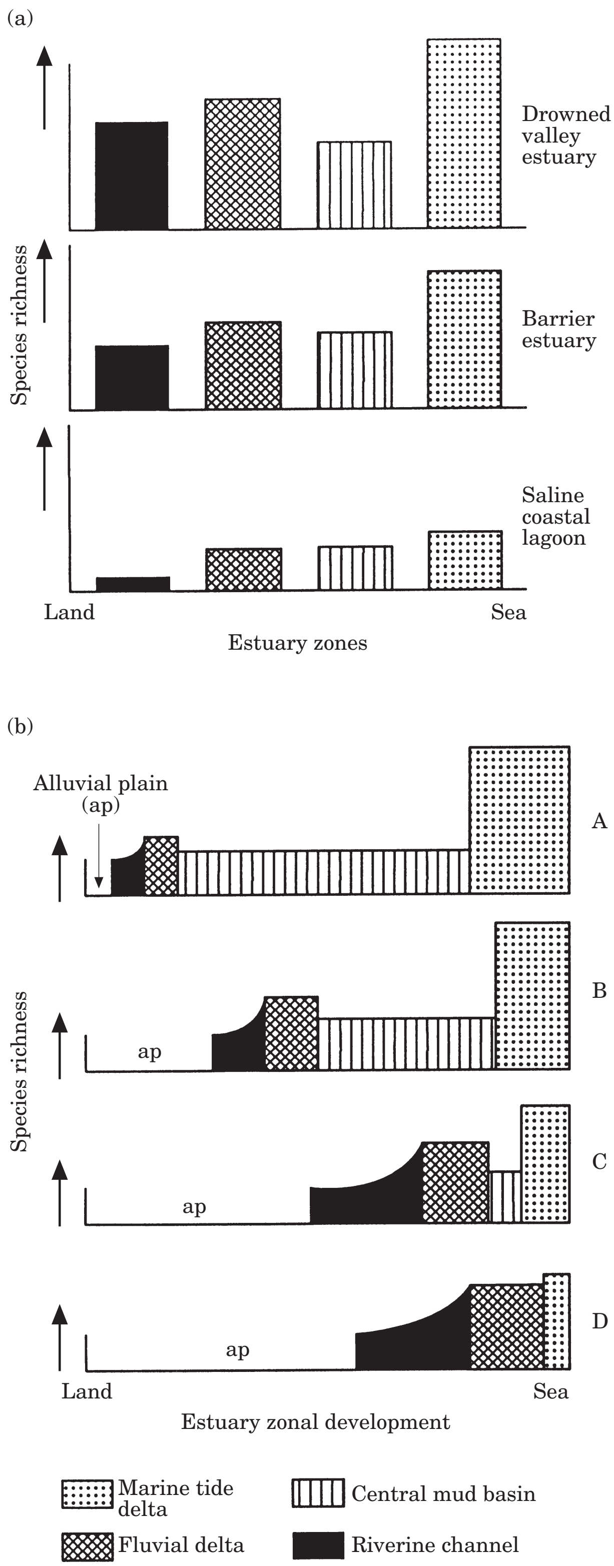
The relationships described above linking salinity regime and sediment distributions to within-estuary depositional zones (Table 2), encourage us to attempt a synthesis of the effects on estuary fauna of mouth conditions, salinity and sediment. We propose a generalized distribution of species richness among zones for each class of estuary at different stages of maturity. Drowned river valleys are richest and intermittent coastal lagoons poorest [Figure 9(a)] because of the nexus between mouth conditions and tidal exchange which mediate salinity and faunal recruitment and migration. The patterns among depositional zones reflect both salinity and sedimentary factors. Species richness in the riverine channel and central mud basin are relatively poor because of low salinity and fine sediment grade, respectively. In contrast, the marine and fluvial deltas are influenced by high salinity and mixed sediments respectively, which, together with their complex microtopography and vegetation, enhance species richness [Figure 9(a)]. The change in relative area of the zones with increasing maturity causes temporal reduction in overall species richness as they reduce in size [Figure 9(b)]. At the same time, the riverine zone enlarges with the seaward movement of the fluvial delta, the central mud basin shallows, becomes more turbid, and is eventually obliterated. The areal extent of the marine tidal delta also shrinks [Figure 9(b)] and its faunal richness in the seaward zones may well decline as the estuary approaches full maturity.

Abundance of fauna

The abundance of animals in estuaries is linked to levels of primary productivity which, we assume, correlates with the spatial coverage of various substrates and habitats: large estuaries have more fish than small estuaries. But it is more important to consider that, because of their linkage with nutrient cycling domains, some habitats are more productive than others and that evolutionary changes in habitat coverage (i.e. expansion of the fluvial delta at the expense of the central mud basin, [Figure 9(b)] will cause the abundance of some species to change over time. However, data on these zonal relationships are not presently available.

Commercial fish catch data analysed by West *et al.* (1985), Pease (1999) and New South Wales Fisheries (Commercial Catch Database, 1990–1997) (Appendix) shows conclusively that the biggest estuaries in New South Wales produce the largest catch of fish [Figure 10(a)]. Ninety-nine percent of the commercial fish catch comes from the 44 largest estuaries with water areas of more than $2{\cdot}0\ km^2$. Seventy percent of these are wave-dominated (barrier) estuaries with the remainder equally divided between drowned valley estuaries and saline coastal lagoons. More than 60% of the fish, prawn and oyster harvest is caught from the six largest estuaries, all with water areas in excess of $70\ km^2$: Port Stephens, Lake Macquarie, Hawkesbury River, Clarence River, Wallis Lake and Tuggerah Lakes. The dominance of estuary size holds true when data are adjusted for effort [Figure 10(c)], but largely disappears when data are normalized against estuary water area [Figure 10(b)].

When grouped according to estuary type (Table 5), drowned valley estuaries, with the largest average water areas, have the largest catches, whereas saline coastal lagoons, with the smallest water areas, have the smallest catches. Barrier estuaries are intermediate in terms of size and fish catch and (together with saline coastal lagoons) show a progressive decrease in fish catch as they infill and their average size reduces. When the fish catch data are normalized against water area (an approximate measure of productivity), differences between estuaries at various stages of infilling are greatly reduced [Figure 10(c), Table 5]. There is also a tendency for fish catch, expressed in terms of effort, to decrease with increasing maturity. In the case of barrier estuaries, the trends in Table 5 are somewhat compromised because of the atypically small water areas (av. 3·9 km^2) for the semi-mature group estuaries [3(c) in Table 5] for which data are available.



Discussion

A range of geologic and geomorphic factors control the type and function of estuaries in southeastern Australia. These estuaries (Table 1) have markedly different tidal exchanges, flushing characteristics, capacities to trap or bypass contaminants, and accessibility for migratory fish and invertebrates. There is no strong correlation of estuary type with latitude (Pease, 1999) (Figure 3).

We posit interplay of structural conditions that influence estuarine function: (a) entrance conditions which control tidal exchange, salinity regimes, and the recruitment and migration behaviours of the biota and (b) catchment conditions which determine the nature of the original estuary basin, its infilling history, the distribution of its present-day zones and ecological habitats, the extent of freshwater mixing, nutrient cycling and survival regimes for the biota.

Estuarine sedimentation leads towards increasing maturity. As a result, habitats change spatially, estuary water bodies progressively decrease in area, and turbidity levels increase as central mud basins become

FIGURE 9. (a) Suggested generalized distribution of species richness of benthos, epibenthos and fish among estuarine zones in different types of estuaries. Causal factors considered are salinity, sediment type and estuarine vegetation. (b) Notional changes in species richness (benthos, epibenthos and fish) of estuary zones at successive stages of maturity in an idealized barrier estuary. In the case of the fluvial delta and the marine tidal delta, changes over time are mainly due to the expansion and contraction (respectively) of their surface areas; in the riverine channel zone, increasing species richness is due to a predicted increase in tidal exchange as the estuary infills (see Figure 6). Key to symbols on Figure 9.

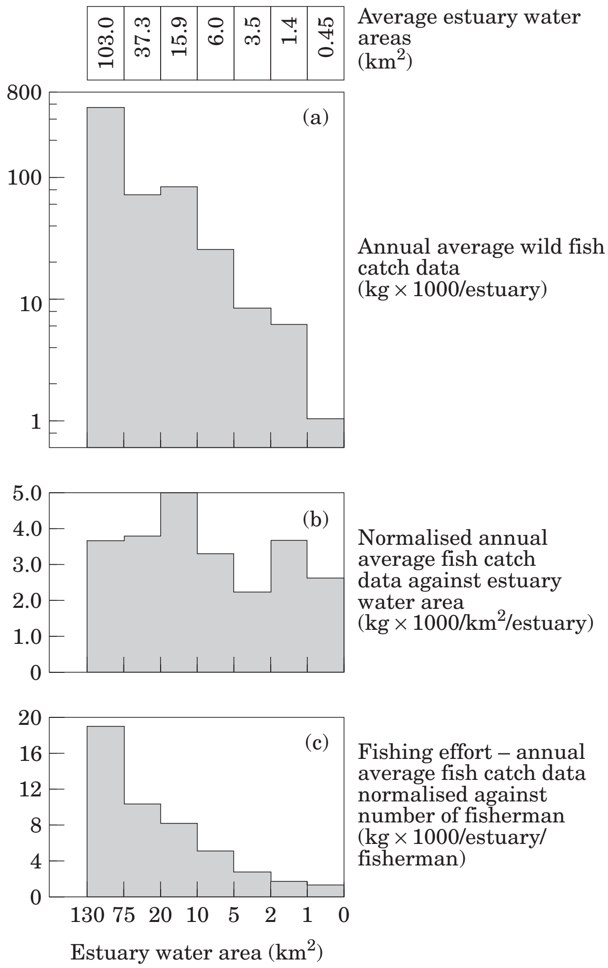


FIGURE 10. Average annual wild fish catch and effort data (from Pease, 1999) plotted against estuary water area.

shallower. In barrier estuaries these changes are accompanied by enlarged tidal ranges and improved flushing characteristics. Estuary substrates and biological habitats reach greatest diversity at semi-mature stages of evolution characterized by the expansion of their fluvial deltas (Roy, 1984, Figure 5). These evolutionary changes influence estuary biota, especially abundances of populations which overall (judging by fish catch statistics) are greatest in large estuaries. However, when fish catch data are normalized to fish abundance per unit water area, populations appear to reach greater densities in small, relatively immature barrier estuaries and occasionally, under favourable conditions, in saline coastal lagoons. The control exerted by estuary structure on estuary ecology is exemplified by the occurrence of the seagrass *Posidonia australis* and the spat of the oyster *Saccostrea commercialis* in very localized habitats in the lower reaches of immature drowned valley and barrier estuaries where salinities are high and environmental conditions are quite stable. Conversely, the limited assemblage of resilient species that characterize intermittent estuaries, reflects the extreme temporal variability of their environments.

From the foregoing it is reasonable to predict that a combination of an open estuary mouth and a semi-mature stage of evolution provide conditions favouring maximum species richness, maximum faunal abundance and minimum opportunity to trap pollutants. In balanced mesotrophic systems, organic loading is adequately assimilated by biota and balanced nitrification-denitrification processes prevent excessive algal growth (Heggie *et al.*, 1999). Portions of the Hawkesbury and Wallis Lake estuaries on the central coast, and some of the large riverine estuaries on the north coast (eg. Clarence River), exemplify these optimal conditions to varying degrees. However, their ecologies are degraded by anthropogenic factors such as excess nutrient, acid groundwater and effluent discharges, recreational boating and bank erosion. At the other extreme, relatively low species richness and population numbers, that peak and then collapse due to erratic water quality fluctuations, are typical of saline coastal lagoons and poorly flushed barrier estuaries. While the resident species are relatively tolerant, these types of estuaries are particularly vulnerable to the trapping of contaminants, fluctuating water levels and occurrence of excessive macroalgal growth.

Since European colonization, estuaries have acted as repositories for by-products of urban, industrial and agricultural activities that increasingly give rise to management issues. Of major concern are elevated levels of nitrogen and phosphorus carried by surface run-off and ground waters from urban areas, sewage treatment works and agricultural land on alluvial plains (Environment Protection Authority, 1997). Resulting blooms of algae and phytoplankton, increased turbidity levels and eutrophication can lead to deoxygenation of bottom waters, fish kills and the build-up of rotting accumulations of wrack on downwind shorelines (Collett *et al.*, 1981). High nutrient loads in shallow, well-lit barrier estuaries and saline lagoons (e.g. Tuggerah Lakes, Lake Illawarra) favour the development of substantial biomass of attached and floating macroalgae (Collett *et al.*, 1981), whereas blooms of phytoplankton typically occur in deeper drowned valley estuaries (e.g. Berowra Creek) and in riverine channel zones of mature estuaries.

Once established, excessive algal blooms are very difficult to rid from the system. Nutrient loads need to be reduced to levels much less than those that resulted in the bloom. This condition, known as ‘ hysteresis ’ is

TABLE 5. Average annual commercial wild fish catch data aggregated according to estuary type and stage of evolution. Data sources: (1) NSW Fisheries Commercial Catch Data Base 1990–97; (2) Fishing effort data compiled by Pease (1999)

Estuary type and stage of infilling	Number of estuaries		Average annual fish catch (1)			Av. annual fishing effort (2) kg × 1000/fisherman
	(1)	(2)	Av. water areas km²	Av. annual fish catch kg × 1000	Normalized fish catch data kg × 1000/km²	
Drowned valley estuaries	4	—	74·0	220·2	2·44	—
Barrier estuaries	35	28	28·7	106·8	3·58	7·46
3A	3	3	68·3	219·7	3·56	10·25
3B	6	5	30·9	126·5	3·82	10·03
3C*	4	5	3·9	11·2	2·87	2·24
3D	22	15	11·9	69·8	4·07	7·33
Saline coastal lagoons	26	18	2·6	7·25	2·42	1·90
4A	3	3	6·6	22·3	3·16	4·24
4C	14	8	0·9	1·8	2·12	1·40
4D	2	1	0·2	0·6	2·05	0·58

*Sample of semi-mature estuaries with atypically small water areas which probably affects fish catch statistics.

TABLE 6. Natural and anthropogenic impacts on estuary zones, categorized according to whether they relate to the type of estuary, the stage of infilling or European development

Estuary zones	Estuary type (Entrance conditions)	Estuary evolution (Sediment infilling)	Human impacts
Marine tidal delta	Increased tidal exchange causes areal expansion and enlarged inter-tidal areas		Dredging and reclamation
Central mud basin		Shoaling that increases wave reworking changes rates of primary production and recycling of contaminants	
Fluvial delta	Increased tidal exchange and tidal range causes area expansion and greater habitat diversity		Reclamation at the heads of tributary arms of drowned valley estuaries
Riverine channel		Channel elongation increases bank erosion	Developments on alluvial plain increases potential acid groundwater, excess nutrient and pollution discharges

a result of non-linear interactions among major functional groups in the estuaries and non-linear responses of micro- and macro- algae and benthic micro-organisms to nutrient loads (Harris, 1999*a*, *b*). Of even greater concern are increasing reports of fish kills and human illness caused by toxic micro-organisms in enclosed waters. According to Burkholder (1997) and Hallegraeff (1988) there is growing evidence that a combination of pollution and climatic conditions can trigger blooms of toxic phytoplankton. Remedial measures should focus on controlling nutrient discharges from land and, possibly, improving tidal flushing of intermittent estuaries (Harris, 1999*a*). Recent modelling of barrier estuaries has shown that the effect of flushing is a non-linear function related to the dimensions of entrance channels which, when below a critical threshold, have little impact on nutrient assimilation processes (Harris, 1999*b*).

The existence of linkages between sedimentary and geomorphic environments on the one hand, and zones with characteristic hydrological regimes and nutrient cycling/biological properties, on the other, suggests that semi-objective measures of ‘ estuary value ’ can be determined for a particular estuary by measuring its zonal areas (see also Rochford, 1951) and giving them weighted values.

The strategy proposed here is based on our conviction that depositional zones/biological habitats, as the common currency of all estuaries, are suitable building blocks for such a data model. In this scheme, estuary type, evolutionary progression and anthropogenic impacts are important, lower-order phenomena that modify natural habitats in predictable (and measurable) ways. Properties such as short-term variations in river flow (floods), in water quality (temperature and salinity) and seasonal changes in fish stocks and benthic communities are higher-order phenomena that do not significantly affect the nature of estuarine habitats. The challenge therefore is to devise a conceptual model for estuarine ecosystems in southeastern Australia that encapsulates their most important (low order) attributes but treats other (higher order) characteristics as noise.

In its simplest form, a south-east Australian estuary can be viewed as a natural system, comprising a number of functional units: (1) shallow water and intertidal zones (the fluvial delta and low energy parts of the marine tidal delta) with richly diverse substrates and habitats and various types of estuarine vegetation that provide food and shelter for animals; (2) a zone of organic-rich muddy sediment in moderately deep water-mainly corresponding to the central mud basin zone that acts as a factory for nutrients promoting primary production in the overlying water and acting as a repository for contaminants; (3) a tidal entrance that, to varying degrees, allows tidal exchange, modulates salinity fluctuations, provides access for migratory fish and facilitates recruitment of larvae and phytoplankton; and (4) a conduit, the riverine channel zone, carrying fresh water, sediments, nutrients and contaminants from the land.

Theoretically, each of the four habitats/zones can be envisaged as 100% functional under ideal conditions but which may be reduced in functionality by various natural and man-made phenomena. It seems reasonable to suppose that comparative ‘ values ’ can be assigned to each habitat, and the degree to which a habitat’s ‘ value ’ is reduced (or enhanced) by particular phenomena can be measured semi-quantitatively.

Comparing the relative functionality of estuarine habitats/zones requires quantification of two attributes: first, the spatial distribution and area of individual zones in an estuary compared to other estuaries; second, the degree to which the zones have been modified by natural and anthropogenic processes operating in individual estuaries. The latter class of attributes relates to estuary type, estuary evolution, and human activities around the estuary (Table 6). For example, because of the role of the estuary mouth in controlling tidal exchange, the various types of estuaries show marked differences in the ecology of their marine tidal delta and fluvial delta zones [Figure 9(a)]. An expression of this relationship might be incorporated in a conceptual model (e.g. an inverse function based on the estuary’s tidal range) so as to maintain the highest possible functionality of the delta zones in the case of tide-dominated estuaries and to a much lesser degree in intermittent estuaries that are mostly non-tidal. In this context anthropogenic impacts on barrier estuaries which are ‘ ventilated ’ by training walls are significant: here tidal exchanges have been increased, salinity regimes made more stable and hydrological extremes significantly reduced (e.g. Wallis Lake, see Nielsen & Gordon, 1986). In most cases, estuaries with trained entrances have been made more accessible to migrating fish, their flushing characteristics and ability to expel contaminants have ‘ improved ’, and intertidal areas (and the mangroves that colonize them) in both the marine tidal delta and the fluvial delta zones are slowly expanding (Saintilan, 1997, 1998; Saintilan & Williams, 1999). However, the degree to which faunal assemblages in these estuaries are adapting to the changed conditions is still a matter of speculation.

In contrast to the delta zones, the functionality of the central mud basin and the riverine channel zones are primarily orchestrated by estuary evolution [Figure 9(b); Table 6]. As the estuary infills, the central basin shoals and the reduction in surface area transforms it from being a placid nutrient sink to a more turbid environment after it aggrades above the threshold depth for wave reworking. We suspect that, when this stage is reached, significant changes in recycling of nutrients and contaminants occur because of resuspension. In terms of functionality of a particular central mud basin zone, this effect could be expressed in the data model by a factor relating to the proportional occurrence of areas above and below the threshold water depth for wave stirring. The ratio of shoreline length to water area could be another important variable.

In the case of the riverine channel zone, the evolutionary changes taking place as the estuary infills with sediment (channel elongation, bank instability etc.) are compounded by human activities such as land clearing, drainage works, farming and urban development on the alluvial plain (Table 6). Such impacts not only affect the riverine channel zone itself (inflows of acid groundwaters, excess nutrients/algae blooms/ eutrophication) but also influence other parts of the estuary system, especially the central mud basin, which acts as a repository for contaminants etc. Ways to incorporate the diverse factors relating to the riverine channel zone into the data model would include a measure of its length as well as other parameters related to its substrate/habitats.

Conclusions

In presenting the above generalized relationships between the structural and functional processes in estuaries, our approach differs from other management strategies which rely only on simple indicators of estuary health such as dissolved oxygen, species richness and species diversity. In contrast, we believe that a holistic understanding of estuaries allows us to predict the biological and ecological effects of human interventions (training walls, reclamations, channel dredging, catchment disturbance, etc.), and to devise practical management responses.

We draw the following conclusions:

1. Geological and geomorphological criteria allow us to classify New South Wales estuaries into discrete physical types with markedly different entrance conditions (openness to tidal exchange) and associated salinity regimes. In individual estuaries, these characteristics have persisted for thousands of years.
2. Additional geological criteria relating to inheritance (palaeo-estuary and river catchment sizes) and degree of sediment filling (estuary evolution/maturity) account for present-day estuary water areas and the distribution of various ecological zones/habitats.
3. The location and extent of these zones change relatively slowly over decades to centuries. They have diagnostic attributes, including parameters such as salinity and sediment type that allow them to be mapped in the field and plotted on aerial photographs.
4. Although supporting data are less comprehensive, we believe that, in terms of nutrient cycling, primary productivity and estuarine flora and benthic fauna, the various zones have characteristic ecological signatures. The signatures are modulated by estuary type and anthropogenic impacts.
5. It is theoretically possible to assign values to the functional processes within zones of particular estuaries and, by mapping their spatial extent, make meaningful comparisons between estuaries and within estuaries.
6. Further, it is possible to use a structural/functional framework to evaluate semi-quantitatively the effects of imposing changes in estuary management.
7. Our approach is deliberately based on the generality of geological/geomorphological phenomena in all estuaries in southeastern Australia, and the reality drawn from empirical relationships between substratum, salinity and morphology on the one hand, and various ecological patterns on the other (see Wolff, 1983; Day, 1981a and Hodgkin, 1994 for reviews, and Jones *et al.*, 1986 for a Hawkesbury example). We ignore small scale ecological patterns and processes which, although important in terms of local variability, introduce levels of precision inappropriate for coastal management.

We hope that these preliminary findings stimulate future research to test regional concepts of estuarine ecology and explore in greater depth relationships between estuary form and function.

Acknowledgements

The authors of this work have all been inspired by the examples of the late David Rochford, Ernest Hodgkin and John MacIntyre and dedicate this manuscript to their memories. Our attempt to synthesize various physical, chemical and biological attributes of southeast Australian estuaries relies on numerous contributions and discussions, spanning many years, from scientists of various disciplines. Roy acknowledges Bruce Thom (New South Wales Coastal Council) and Riko Hashimoto (The University of Sydney) for their ideas on estuary evolution, David Heggie (Australian Geological Survey Organisation) for advice on geochemical matters and John Whitehouse (Geological Survey New South Wales) for his help in compiling and plotting data. We also appreciate the constructive comments of a number of reviewers, especially Burg Flemming. The paper is published with the approval of the Director General, NSW Department of Mineral Resources.

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APPENDIX 1. Characterization of coastal water bodies (water areas >0·05 km^2) in NSW. (Data from West *et al.* (1985), Nichol (1991), NSW Fisheries Commerical Fisheries Data 1990–1997)

		Estuary characteristics										Seafood production data	
Estuary name	Latitude (°S)	Entrance conditions 1	Estuary group/type 2	Evolution stage 3	Water area (km^2)	Catchment area (km^2)	Paleo-estuary area (km^2)	% Infill 4	Mangrove area (km^2)	Seagrass area (km^2)	Saltmarsh area (km^2)	Average annual commercial wild fish catch (kg)	(kg km^2)
Tweed River	28·10	O/T	III/5	D	17·916	1000			3·091	0·331	0·213	112 121	6264
Cobaki-Terranora B water	28·12		III/5	B	12	113							
Cudgen Lake	28·16	O/T	V/11	A	1·427	37			0·094	0	0·561	0	0
Cudgera Creek	28·22	O	IV/9	C	0·238	60			0·138	0·016	0·016	0	0
Mooball Creek	28·24	O/T	III/7	B	0·492	125			0·053	0·013	0	0	0
Brunswick River	28·32	O/T	III/5	D	2·222	160			0·018	0·816	0·056	157	71
Belongil Creek	28·37	I	IV/9	B	0·126	18			0·050	0	0·054	0	0
Tallow Creek	28·40	I	IV/9	B	0·082	2·7			0	0	0·003	0	0
Broken Head Creek	28·42	I	V/11	C	0·050	0·9			0	0	0·036	0	0
Richmond River	28·53	O/T	III/5	D	19·071	6850			4·949	0·189	0·099	133 903	7010
Evans River	29·07	O/T	III/7	A	1·787	62			0·330	0	0·375	23 309	12 949
Jerusalem Creek	29·13	I	III/7	B	0·214	42·5			0	0	0·021	0	0
Clarence River	29·25	O/T	III/5	D	89·243	22 400			5·208	19·072	1·954	619 481	6945
Sandon River	29·41	O	III/5	D	1·414	109			0·533	0·028	0·258	3814	2724
Wooli Wooli River	29·53	O/T	III/5	D	1·900	190			0·493	0·028	0·531	0	0
Station Creek	29·57	I	IV/8	D	0·306	24			0	0	0	0	0
Corindi River	29·59	O	III/5	D	0·873	148			0·189	0·033	0·293	186	207
Arrawarra River	30·04	I	IV/8	D	0·123	19·5			0	0·003	0·008	0	0
Darkum Creek	30·05	I	IV/8	D	0·046	12			0·001	0	0	0	0
Woolgoolga Lake	30·06	I	IV/8	B	0·180	25			0·002	0	0	583	2915
Hearns Lake	30·08	I	IV/8	B	0·106	8·5			0·044	0	0	0	0
Moonee Creek	30·12	O	III/7	C	0·333	39·5			0·036	0·004	0·073	389	1297
Coffs Harbour Creek	30·18	O	III/5	C	0·308	25			0·167	0·018	0	4177	13 923
Boambee Creek	30·21	O	III/5	D	0·573	45			0·066	0·011	0·158	509	848
Bonville Creek	30·23	O	III/5	D	1·244	110			0·053	0·008	0·148	32	27
Bellinger River	30·30	O/T	III/5	D	6·576	1110			0·847	0·059	0·029	16 461	2494
Dalhousie Creek	30·32	I	IV/9	C	0·051	17			0	0	0	0	0
Oyster Creek	30·34	I	IV/9	D	0·084	11			0	0	0	0	0
Deep Creek	30·36	I	IV/8	C	1·021	105			0·008	0·007	0·604	3642	3642
Nambucca River	30·39	O/T	III/5	D	7·738	1460			0·779	0·224	1·034	55 575	7217
Macleay River	30·52	O/T	III/5	D	18·169	11 385			5·201	1·097	3·652	92 048	5057
Saltwater Creek	30·53	I	IV/8	C	0·078				0	0	0	0	0
South West Rocks Creek	30·53	O/T	IV/8	C	0·118				0·528	0·024	0·141	0	0
Korogora Creek	31·03	O	III/7	B	0·221				0·013	0	0·014	0	0
Killick Creek	31·11	I	IV/8	B	0·198	5			0	0·011	0·008	0	0
Wallis Lake	31·13	O/T	III/5	A	85·559	1420			0·786	30·785	4·005	361 006	4219
Hastings River	31·25	O/T	III/5	D	17·287	3595			2·078	1·141	0·804	96 801	5595
Lake Innes/Lake Cathie	31·29	I	IV/8	C	5·821	92			0·001	0·007	5·972	5397	930
Camden Haven River	31·38	O/T	III/5	B	27·833	440			0·873	6·336	0·780	116 952	4207
Manning River	31·53	O/T	III/5	D	25·348	8320			3·582	0·329	0·721	134 715	5324
Khappinghat Creek	32·01	I	IV/8	D	0·960	102			0	0·019	0·002	0	0
Smiths Lake	32·23	I	IV/8	A	9·371	33			0	2·080	0·003	53 346	5693

APPENDIX 1. *Continued*

Estuary name	Latitude (°S)	Estuary characteristics: Entrance conditions 1	Estuary group/type 2	Evolution stage 3	Water area (km^2)	Catchment area (km^2)	Paleo-estuary area (km^2)	% Infill 4	Mangrove area (km^2)	Seagrass area (km^2)	Saltmarsh area (km^2)	Seafood production data: Average annual commercial wild fish catch (kg)	Average annual commercial wild fish catch ($kg\ km^{-2}$)
Myall Lakes	32·32	O	V/11	A	101·933	1510			0	0·079	0	156 597	1535
Karuah River	32·39	O	II/3	C	3·876	2200			3·479	0·380	4·828	0	0
Myall River	32·40	O	III/7	C	7·541	1660			1·021	2·736	1·784	41 781	5541
Port Stephens	32·42	O	II/3	A	125·970	4950			23·260	7·453	7·719	437 364	3471
Hunter River	32·55	O/T	III/5	D	30·421	22 000			15·481	0·153	5·049	141 681	4660
Lake Macquarie	33·05	O/T	III/5	A	115·112	700			0·998	13·391	0·705	327 244	2843
Tuggerah Lakes	33·16	I	III/5	B	70·299	760			0	11·619	0·007	297 156	4227
Wamberal Lagoon	33·25	I	IV/8	B	0·495	5·7			0	0·245	0	0	0
Terrigal Lagoon	33·26	I	IV/8	B	0·258	8·7			0	0·046	0	0	0
Avoca Lake	33·28	I	IV/8	A	0·649	10·4			0	0·161	0	0	0
Cockrone Lake	33·30	I	IV/8	B	0·320	6·7			0	0	0	0	0
Brisbane Waters	33·31	O	III/5	A	27·241	170			1·635	5·490	0·918	6358	233
Hawkesbury River	33·34	O	II/3	C	100·005	21 500			10·654	0·470	1·126	301 416	3014
Pittwater	33·35	O	II/3	A	17·314	77			0·180	1·934	0·026	39 787	2298
Narrabeen Lagoon	33·43	I	IV/8	B	2·181	55			0	0·468	0	0	0
Dee Why Lagoon	33·45	I	IV/8	C	0·238	6·2			0	0·034	0·044	0	0
Harbord Lagoon	33·46	I	IV/8	C	0·058	4·5			0	0	0	0	0
Manly Lagoon	33·47	I	IV/8	C	0·086	13·5			0	0·004	0	0	0
Port Jackson	33·50	O	II/3	A	49·667	116·5			0·914	1·286	0·073	127 644	2569
Botany Bay	34·00	O	I/1		49·100	300			3·996	3·403	1·601	231 996	4725
Georges River	34·01	O	II/3	B	12·466	800			2·038	0·268	0·247	0	0
Port Hacking	34·05	O	II/3	A	11·298	180			0·328	0·869	0·106	114	10
Towradgie Creek	34·25	I	IV/8	C	0·060				0	0·036	0	0	0
Port Kembla Harbour	34·28	O/T	III/5	C	0·098	45			0	0	0	0	0
Lake Illawarra	34·33	O/T	III/5	B	36·270	150			0	6·116	0·203	166 639	4591
Bensons Creek	34·34	I	IV/8	C	0·087				0	0·028	0	0	0
Minnamurra River	34·38	O	III/5	D	0·601	110			0·484	0·232	0·197	237	395
Wrights Creek	34·40	I	IV/8	D	0·033				0	0·003	0	0	0
Werri Lagoon	34·44	I	IV/8	B	0·113	23·5			0	0·017	0	0	0
Crooked River	34·46	O	III/5	D	0·221	32			0	0·004	0	0	0
Shoalhaven River	34·52	I	III/5	D	12·889	7500			0·670	0·340	0·146	87 419	6777
Crookhaven River	34·54	O/T	III/5	C	7·883				2·806	0·678	1·396	16 044	2035
Lake Wollumboola	34·57	I	IV/8	B	6·211	35			0	1·145	0	5014	809
Jervis Bay	35·06	O	I/1		102·129	1150			1·250	9·061	2·330	94 374	924
St Georges Basin	35·11	O	III/5	B	38·859	390			0·252	8·538	0·036	138 439	3559
Swan Lake	35·11	I	IV/8	A	4·082	32	5·10	20	0	0·587	0	7948	1938
Berrara Creek	35·12	I	IV/8	B	0·124	36	0·24	48	0	0·006	0	0	0
Nerrindillah Creek	35·14	I	IV/8	C	0·065	18	0·08	19	0	0·005	0	0	0
Lake Conjola	35·16	O	III/5	B	4·280	145	9·86	49	0	0·527	0·013	11 937	2776
Narrawallee Inlet	35·18	O(I)	III/5	D	0·456	85	10·27	95	0·378	0·014	0·091	318	636
Mollymook Creek	35·20	I	IV/8	D	0·022	2·7	0·30	93	0	0·009	0	0	0
Ulladulla Harbour	35·22	O	I/1		0·119				0	0·010	0	0	0
Burrill Lake	35·24	O(I)	III/5	A	4·206	65	5·17	19	0	0·508	0·157	17 516	4170

Appendix 1. *Continued*

		Estuary characteristics										Seafood production data	
Estuary name	Latitude (°S)	Entrance conditions 1	Estuary group/type 2	Evolution stage 3	Water area (km^2)	Catchment area (km^2)	Paleo-estuary area (km^2)	% Infill 4	Mangrove area (km^2)	Seagrass area (km^2)	Saltmarsh area (km^2)	Average annual commercial wild fish catch (kg)	($kg\ km^2$)
Touburee Lake	35·27	O(I)	IV/8	C	1·380	48	4·08	66	0	1·199	0·010	2209	1578
Termeil Lake	35·28	I	IV/8	C	0·445	15	1·61	72	0	0·070	0	673	1682
Meroo Lake	35·29	I	IV/8	C	0·635	21	2·17	71	0	0·115	0	949	1582
Willinga Lake	35·30	I	IV/8	D	0·282	4	2·23	87	0	0·004	0	0	0
Kioloa Lagoon	35·33	I	IV/8	D	0·637	9	1·64	98	0	0·003	0·006	0	0
Durras Lake	35·38	I	IV/8	B	3·214	63	5·11	37	0	0·509	0·046	4983	1557
Clyde River	35·42	O	II/3	B	19·898	1791	31·23	36	2·318	0·092	1·017	14 328	716
Cullendulla Creek	35·42	I(O)	III/5	D	0·239	17	1·53	84	0·916	0·064	0·006	13 265	55 502
Batemans Bay	35·43	O	I/1		5·301				0	0·071	0	0	0
Tomaga River	35·50	O	III/5	D	1·214	98	9·30	87	0·210	0·046	0·351	1893	1577
Candlagan Creek	35·51	O	III/5	D	0·067	30	4·50	98	0·021	0·016	0·031	0	0
Moruya River	35·55	O/T	III/5	D	4·222	1445	28·79	98	0·380	0·644	0·674	5734	1365
Congo Creek	35·57	I	IV/8	D	0·128	43	7·91	98	0	0	0	16	160
Meringo Creek	35·59	I	IV/8	B	0·097	3	0·17	43	0	0	0	0	0
Coila Lake	36·02	I	IV/8	A	6·341	59	8·35	24	0	1·862	0·317	23 810	3779
Tuross Lake	36·04	O	III/5	C	13·299	1816	34·18	61	0·566	0·452	0·401	40 806	3068
Lake Brunderee	36·05	I	IV/8	C	0·184	6	0·59	70	0	0·064	0·246	62	310
Lake Brou	36·08	I	IV/8	C	1·663	44	4·10	60	0	0·078	0·250	0	0
Lake Dalmeny	36·10	I	IV/8	B	1·393	28	1·96	29	0	0·294	0·055	4285	3061
Kianga Lake	36·12	I	IV/8	C	0·124	8	0·35	65	0	0·011	0·033	185	1850
Wagonga Inlet	36·13	O/T	III/5	A	6·276	97	7·50	16	0·249	1·484	0·056	0	0
Nangudga Lake	36·15	I	IV/8	C	0·461	10	1·30	65	0	0·120	0·115	1309	2618
Corunna Lake	36·17	I	IV/8	B	1·669	33	2·57	35	0	0·179	0·033	6012	3536
Tilba Tilba Lake	36·20	I	IV/8	C	0·640	18	1·86	66	0	0	0	1238	2063
Little Lake	36·21	I	IV/8	C	0·100	3	0·28	64	0	0·003	0·047	0	0
Wallaga Lake	36·22	O/I	III/5	B	7·805	270	13·20	41	0	1·343	0·295	27 790	3563
Bermagui River	36·26	O/T	III/5	C	1·390	94	3·04	54	0·434	0·338	1·066	3349	2392
Barragoot Lake	36·28	I	IV/8	C	0·377	13	0·93	59	0	0·049	0·053	329	822
Cuttagee Lake	36·29	I	IV/8	B	1·410	55	2·13	34	0	0·430	0·076	4207	3005
Murrah Lagoon	36·32	O	III/5	D	0·816	203	5·30	85	0	0·016	0·109	1817	2271
Bunga Lagoon	36·33	I	IV/8	C	0·094	12	0·23	59	0	0	0·018	0	0
Wapengo Lagoon	36·38	O	III/5	C	3·191	73	7·12	55	0·409	0·360	0·319	0	0
Middle Lagoon	36·39	I	IV/8	D	0·331	28	2·95	89	0	0·081	0·011	1185	3956
Nelson Lagoon	36·41	O	III/5	C	0·713	31	2·16	76	0·271	0·114	0·063	457	653
Bega River	36·42	I/O	III/5	D	2·657	1941	17·14	85	0	0·304	0·411	15 042	5571
Wallagoot Lake	36·47	I	IV/8	B	3·672	31	6·39	43	0	0·647	0·014	5321	1438
Bournda Lagoon	36·50	I	IV/8	B	0·058	3	0·09	36	0	0·043	0	0	0
Back Lagoon	36·53	I	IV/8	C	0·315	31	0·88	64	0	0·204	0·018	374	1247
Merimbula Lake	36·54	O	III/5	B	4·556	48	7·34	38	0·377	2·297	0·629	0	0
Pambula Lake	36·57	O	III/5	C	12·949	299	11·66	75	0·449	0·868	0·188	9091	705
Curalo Lagoon	37·03	I	IV/8	C	0·708	31	2·10	66	0	0·058	0·116	1702	5673
Twofold Bay	37·05	O	I/1		77·049				0	0·026	0·008	5357	69
Nullica River	37·05	I	IV/8	C	0·244	52	0·81	70	0	0·020	0	389	1945

APPENDIX 1. *Continued*

Estuary name	Latitude (°S)	Estuary characteristics										Seafood production data	
		Entrance conditions 1	Estuary group/type 2	Evolution stage 3	Water area (km^2)	Catchment area (km^2)	Paleo-estuary area (km^2)	% Infill 4	Mangrove area (km^2)	Seagrass area (km^2)	Saltmarsh area (km^2)	Average annual commercial wild fish catch (kg)	Average annual commercial wild fish catch ($kg\ km^2$)
Towamba River	37·06	O	III/5	D	1·427	1037	7·12	80	0·900	0·027	0·009	2914	2081
Fisheries Creek	37·07	I	IV/8	D	0·024	7	0·12	80	0	0·046	0·042	0	0
Womboyn River	37·17	O	III/5	A	3·616	320	4·38	17	0	0·237	0·483	26	7
Merrica Lake	37·18	I	IV/8	B	0·106	68	0·22	45	0	0	0	0	0
Nadgee River	37·20	I	IV/8	D	0·162	60	2·14	93	0	0	0	0	0
Nadgee Lake	37·28	I	IV/8	C	0·968	15	2·88	66	0	0·075	0	0	0

Terminology used:
1 Entrance conditions; O=open, T=trained, I=intermittent
2 Estuary group (type—see Table 1); I=oceanic embayment, II=tide dominated estuary (DVE), III=wave dominated estuary (BE), IV=intermittently closed estuary (SCL), V=freshwater
3 Evolution stage; A=youthful, B=intermediate, C=semi-mature, D=mature
4 % Infill; Percentage infill for south coast estuaries based on ‘ measurements by S. Nichol, written communication 1991.’