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AUSTRALIAN ESTUARIES & COASTAL WATERWAYS

A geoscience perspective for improved and integrated resource management

A report to the National Land & Water Resources Audit Theme 7: Ecosystem Health

A. Heap, S. Bryce, D. Ryan, L. Radke, C. Smith, R. Smith, P. Harris & D. Heggie

*AGSO team

Understanding Australian ESTUARIES

AGSO AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

National Land & Water Resources Audit
A program of the Natural Heritage Trust


Lake Illawarra viewed from the east

Australian Estuaries & Coastal Waterways: A Geoscience Perspective for Improved and Integrated Resource Management

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Theme 7: Ecosystem Health

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Front cover: Lake Illawarra viewed from the east (April 2000).

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Executive Summary

AGSO is a partner in Theme 7 - Ecosystem Health of the National Land and Water Resources Audit (NLWRA). AGSO's role in this theme was to provide geoscience data for a quantitative assessment of the health of Australia's estuaries and coastal waterways. This document presents AGSO's contribution to Theme 7 and summarises the key outcomes of AGSO's contributions to Tasks 1, 2, 3 and 5.

AGSO has developed a nation-wide coverage of physical forces (Wave, Tide and River energies) driving the form and function of Australian estuaries and coastal waterways, and has mapped geomorphic and sedimentary facies for some 405 of Australia's modified coastal waterways. Because facies provide substrates for habitats, they can be used to assess potential habitat abundance and habitat integrity.

AGSO has created a national geoscience database for the NLWRA called OZESTUARIES (www.agso.gov.au/ozestuaries). The OZESTUARIES database integrates data from the Australian Estuarine Database (AED) of Digby *et al*. (1998), and new data acquired for the NLWRA. These new data include geometrical measurements, facies (habitat) areas, denitrification rates and efficiencies, sedimentation rates and sediment TOC, TN and TP contents for estuaries and other coastal waterways. AGSO encourages other geoscientists to add data to this database to develop a resource for the National interest.

Key Findings

Australian estuaries and coastal waterways were classified into six subclasses according to the wave-, tide- and river-energies that shape them (Figure A), and also according to their overall geomorphology. The geomorphic classification confirmed the energy classification.

Within this framework:

- 17% were classified as wave-dominated estuaries;
- 11% were classified as tide-dominated estuaries;
- 10% were classified as wave-dominated deltas; and
- 9% were classified as tide-dominated deltas

Therefore, only ~28% of Australian coastal waterways are actually estuaries. The remainder are delta's (19%), strandplains (~5%), or tidal creeks (~35%). A seventh subclass "others" (13%) includes: Drowned River Valleys, Embayments and Coastal Lakes/Lagoons/Creeks. Strandplains and Tidal Creeks are indicative of very low river-energy (see Figure A), and their joint dominance in the data set (~40%) reflects the fact that Australia is a dry continent, with relatively little river runoff by world standards.

Classifications for 974 of Australia's estuaries and coastal waterways are provided in the OZESTUARIES database (www.agso.gov.au/ozestuaries).

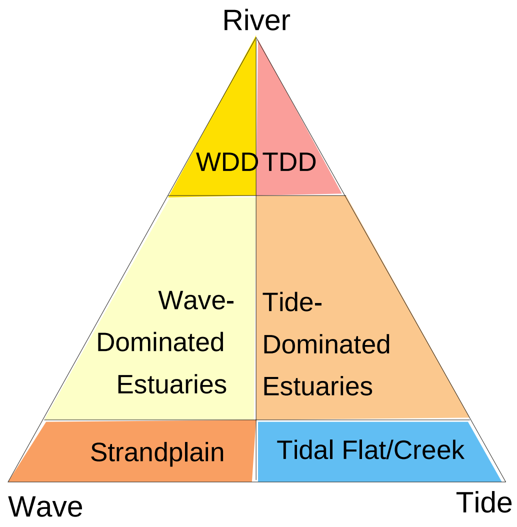

Figure A. Ternary classification of coastal systems divided into six subclasses (after Dalrymple *et al.* 1992; and Boyd *et al.* 1992). WDD = wave dominated delta, TDD = tide dominated delta.

Facies (habitat) data for 405 of the 497 estuaries and coastal waterways were identified by the NLWRA as modified in some way. Saltflat/saltmarsh, mangroves, tidal sand banks, intertidal flats and flood/ebb tide deltas are diagnostic of tide-dominated subclasses. By comparison, fluvial bay-head deltas, central basins and barrier/back-barriers are diagnostic of wave-dominated subclasses. Dominant facies (by area) at the level of subclass are as follows:

- the central basin is the dominant facies in wave-dominanted estuaries;
- mangroves and channels are the dominant facies in wave-dominated deltas;
- intertidal flats, barrier/back barriers and channels are the dominant facies in strandplains;
- mangroves, saltmarsh and channels are the dominant facies in tide-dominated estuaries;
- mangroves are the dominant facies in tide-dominated deltas; and
- mangroves and saltmarsh are the dominant facies in tidal creeks.

Full **geometric measurements** have been made for 909 estuaries and coastal waterways. They show that tide-dominated subclasses have relatively large entrances and generally no major constricting channel. They are relatively long, and comparatively narrow with respect to entrance width, and do not feature large central basins. These features imply more longitudinal transport modes. By contrast, wave-dominated classes tend to have narrow constricted entrances and large widths with respect to the entrance opening.

Tide-dominated subclasses have much longer perimeters than wave-dominated systems, and generally have more complex shorelines with larger potential habitat space for mangroves and saltmarshes.

Denitrification – the conversion of dissolved inorganic nitrogen to biologically unavailable N_2 gas - has been identified as an important self-cleansing mechanism to remove excess N from an estuary or waterway. High denitrification efficiencies ensure efficient processing and removal of N from sediment, and are desirable because N appears to be the most important nutrient in controlling productivity and eutrophication in Australian coastal waters. The median denitrification efficiency was found to be 72%, based on data from 13 Australian estuaries and coastal waterways. In general, this indicates efficient cycling of N from sediment to the atmosphere. However, there were six water bodies in which 25% of the measured denitrification efficiencies were <40%; a value which we believe is indicative of deterioration of sediment and water quality.

The median **sedimentation rate** in Australian estuaries and coastal waterways was 0.2 cm yr^{1}. We have no measurements of the rate of marine sediment infill into wave dominated systems, notably those with modified entrances.

TOC, TN and TP concentrations in sediment varied widely over a few orders of magnitude, and are used to identify organic rich vs. organic poor environment. They may prove to be useful proxies for carbon and nutrient loadings to coastal waterways.

Applications

The data collected by AGSO represents the first quantitative geoscience inventory for estuaries and coastal waterways ever produced in Australia. The work includes a national assessment of facies areas, including those for mangroves, saltmarshes/saltflats and intertidal flats. These are key habitats for State of Environment Reporting (Ward *et al.* 1998), and the inventory should form a comprehensive baseline for their monitoring and management. Managers can use the **OZESTUARIES** database to access the facies areas as well as the geometry and the overall classification of most estuaries or coastal waterways in Australia.

A **Deviation Index**, which relies on the presence/absence of facies in an estuary or coastal waterway, was developed as a tool to assist managers with the quantification of habitat integrity. Deviation scores for 405 systems can be found in Appendix H and will also be available in the OZESTUARIES database. The Deviation Index identifies the following:

- systems that are perturbed from a pristine state; and
- systems that warrant further investigation because they may be significantly modified or degraded.

A **framework** to assess estuarine water and sediment qualities has been developed which uses denitrification efficiencies in conjunction with sediment indicators of organic-rich and organic-poor environments (e.g. TOC, TN and TS). Basic statistics were used to identify sediment concentrations that were typical, anomalous and extreme. An example of this type of assessment is shown in Section 5.

Denitrification efficiencies in particular are emerging as new process indicators of sediment and water quality in wave-dominated subclasses and embayments. Similar comments may also apply to tide-dominated systems, although little is known about the ecological relevance of denitrification efficiencies within the dominant facies (e.g. mangroves and saltmarshes) at the present time. Simple protocols for assessing denitrification efficiencies, and for identifying potential threats to it, are summarised in Section 5.

3D-Conceptual Models illustrating sediment transport and nitrogen cycling through the facies suites of wave- and tide-dominated estuaries and deltas were developed to illustrate links between form (geomorphology) and function (processes) in Australian estuaries and coastal waterways. By integrating both physical and biological processes, the models present a simple, yet holistic picture of these coastal systems. In addition, factors that may compromise the integrity of key facies (habitats) are highlighted, indicators of compromised integrity are suggested, and management options are proposed. The models are tools that should assist managers and stakeholders with the development of coastal waterway management plans, including monitoring protocols.

Recommendations

The six subclasses of estuaries and coastal waterways have developed distinct facies (habitat) suites as a result of different balances of physical forces (e.g. wave-, tide- and river-energies). Therefore, each subclass differs in terms of basic form and overall function, and each may be susceptible to different kinds of stresses. A Geoscience perspective of facies (habitat) integrity at the level of wave-dominated vs. tide-dominated coastal systems is summarised in

Table A. It includes indicators of "good" and "compromised" integrity that AGSO recommend be considered in deliberations concerning estuarine and coastal waterway health. AGSO also recommend that:

- facies (habitats) of pristine estuaries be mapped to establish a baseline;
- the Deviation Index be used to rank all systems for comparative analysis;
- sites with large deviation scores (i.e. >3) be targeted for further investigation;
- facies (habitat) data be utilised to monitor the preservation of key coastal habitats (e.g. mangroves, saltflat/saltmarsh, and intertidal flats);
- substrate abundance, based on facies occurrence and areas, be used with sediment geochemistry and nutrient data as a proxy for habitat integrity;
- denitrification efficiencies continue to be investigated as potential indicators of sediment and water quality;
- TOC, TN & TP concentrations in sediment are indicators of organic-rich and organic-poor environments and should continue to be collected;
- the multi-indicator framework developed for waterway assessments of sediment and water qualities be further developed;
- biomarkers of rural and urban runoff be developed and used as aids to identify sources of anthropogenic pollutants;
- the conceptual models be widely circulated and used as both education and management tools; and
- conceptual models for strandplains and tidal flats/creeks be developed.

Table A. Geoscience perspective of facies (habitat) integrity (good and compromised) in wave- and tide-dominated coastal systems, with possible management responses

Coastal System	Subclasses	Dominant Facies (habitats) by area others	Indicators of 'good' Habitat Integrity	Significant Threats to Habitat Integrity	Indicators of 'compromised' Habitat Integrity	Possible Management Response(s)
Wave-dominated Subclasses	WDD WDE SP	(a) Central Basin Fluvial Bayhead Delta Barrier/Back-barrier (b) Flood-Ebb Tide Delta Intertidal Flats Saltmarsh Mangroves	Deviation Index = 0–2 Denitrification Efficiency > 70% Turbidity is low Bottom water O_2 is high Nutrient loads are probably low Sediment TOC, TN, TP and TS are probably low	Removal of facies (e.g. dredging) Sedimentation/infilling from catchment and marine sources Reclamation of facies (habitats) Construction activities Anthropogenic nutrient and other toxicant loadings from sewage-treatment plants, industrial discharges and catchment activities Persistent stratification and poor ventilation of bottom waters	Deviation Index > 3 Toxic bloom (e.g. blue-green algae) Denitrification Efficiency < 40% There is excess plant growth (eutrophication) Turbidity is consistently high Sediment and bottom waters are O_2 depleted Acidification of water (low pH) Sediment TOC, TN, TP probably elevated; presence of TS	Investigate causes of significant deviation Reduce nutrient loads Reduce particulate/fine material Cost Benefit Analysis on development vs. preservation of habitat Maintain high O_2 in bottom waters
Tide-dominated Subclasses	TDD TDE TC	(a) Mangrove Saltmarsh Intertidal Flats Tidal Sand Banks (b) Flood- Ebb Tide Delta (TDD mainly)	Deviation Index = 0–2 Mangrove and saltmarsh facies (habitats) utilise and recycle nutrients to coastal waters Mangrove and saltmarsh facies stabilise coastal sediment Saltmarsh can form a buffer between coastal waters and agriculture/urbanisation	Removal of facies (e.g. dredging) Reclamation of facies (habitats), notably mangroves and saltmarsh Sedimentation and infilling from catchment and marine sources Toxicant and pathogen discharges	Deviation Index > 3 Mangrove or saltmarsh habitat is reduced or impacted Shorelines are eroded and the style and rate of sedimentation is altered Acid-sulphate drainage Possible eutrophication and appearances of toxic blooms in waters beyond the turbid zone	Investigate causes of significant deviation Preserve and sustain mangrove and saltmarsh facies (habitats) Cost Benefit Analysis on development vs. preservation of habitat

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1. Introduction

The National Land & Water Resources Audit (NLWRA) project is a Federally funded initiative that was instigated to address the need for a comprehensive and integrated inventory and assessment of Australia's natural resources. The NLWRA project comprises 7 themes. Coastal systems are incorporated into Theme 7 – Ecosystem Health. The objective of this theme is to assess the health and status of Australia's natural systems. AGSO's role in Theme 7 was to:

- classify Australia's estuaries and coastal waterways based on the energy distribution and geomorphology of each system;
- develop a suite of conceptual models for major coastal sedimentary system types around Australia;
- develop quantitative indicator's of habitat integrity; and
- design, develop and populate a geoscience database that updates the existing Australian Estuarine Database (AED) (Digby *et al.* 1998).

Coastal systems contain geomorphic and sedimentary facies which provide the substrate for biological habitats. Previous geological studies of wave-dominated coastal systems (e.g. Roy *et al.* submitted) have demonstrated a link between the geomorphic and sedimentary facies and different assemblages of flora and fauna in these systems. The significance of this work is that it directly links the form and function of estuaries to the fate and status of habitats and ecosystems. Over time, these geomorphic and sedimentary facies arrangements change in response to the natural processes of sediment deposition, transport and erosion. Modification by humans can also change arrangements of geomorphic and sedimentary facies, with implications for the distribution and functioning of modern habitats. Informed management of Australia's coastal systems thus requires an understanding of the reasons why present-day facies arrangements exist and why they change.

Previous national studies of Australia's estuaries and coastal waterways (Bucher & Saenger 1991, 1994; Digby *et al.* 1998) have been undertaken to develop a national classification scheme for Australia's coastal systems for the purposes of resource management and conservation. The culmination of these studies was the Australian Estuarine Database (AED), which focussed mainly on biological attributes. AGSO has advanced this work by identifying and quantifying the occurrence and distribution of geomorphic and sedimentary facies for different types of coastal systems, and has applied it to resource management for Australia's estuaries and coastal waterways on a national level.

1.1. Tasks

ASGO has contributed to four of the five tasks listed under Theme 7b in the National Estuary Assessment project specification document (Annexure A). AGSO's primary role was to provide appropriate geoscience information to advance models of Australian estuarine form and function, and to develop a more quantitative national assessment of ecosystem health for Australia's estuaries and coastal waterways. The following objectives were formulated to address each of the tasks identified by the NLWRA for estuaries and coastal waterways.

1. Update the Australian Estuarine Database (AED) to create the OZESTUARIES database and produce a national map of estuarine condition (Task 1).
2. Develop conceptual models of estuarine form and function (Tasks 2 & 5).
3. Identify geoscience indicators suitable for assessing ecosystem health (Task 2).
4. Develop a quantitative indicator of habitat integrity based on facies arrangements (Task 2).

5. Classify estuaries and coastal waterways on the basis of dominant energies (Task 2).
6. Design, develop and populate the OZESTUARIES database with geometric, geochemical/nutrient, and geomorphic and sedimentary facies data (Task 3).
7. Provide geometric data to CSIRO for the numerical modelling in Task 4 (Task 3).
8. Recommend management actions for the different types of coastal systems identified in Task 2 (Task 5).

1.2. Report Structure

This report is divided into seven sections that address the tasks above. Within each section, a more detailed description of the work undertaken is divided into the following sub-sections:

- introduction;
- methodology;
- key findings;
- applications; and
- recommendations.

The balance of discussion in each section focuses on the latter two sub-sections. Background material and detailed methodology have been placed into a series of appendices at the end of the report. The majority of Task 1 (Estuarine Inventory, Classification and Framework) was completed by NLWRA, with AGSO incorporating the results of this initial assessment in the OZESTUARIES database and producing a nation-wide map of estuarine condition (Appendix A).

2. Estuarine Classification and Conceptual Models of Waterway Form

AGSO have classified the estuaries and coastal waterways contained in the AED (780 systems) into different types of coastal systems (subclasses) based on the combination of river, wave and tide energy, and geomorphology. Estuaries and coastal waterways not contained in the AED (194 systems) were similarly classified, but based upon their geomorphic characteristics alone. Conceptual models were then developed for four of the subclasses based on "idealised" wave- and tide-dominated facies models presented in Dalrymple *et al.* (1992). The models facilitate a better understanding of the significance of fundamental processes in different types of coastal systems and should contribute to the development of sustainable management practices.

2.1. Introduction

From a geoscience perspective, estuaries and coastal waterways form a range of coastal sedimentary environments that include: deltas, estuaries, strandplains and tidal flats (Figure 1). In each of these subclasses, sediment is reworked and redistributed by currents derived from river, tide and wave energy sources. The form and function of a coastal system is specific to whether that system is dominated by any one energy source or a combination of energy sources (i.e. mixed). It is the form of the coastal system that provides the framework for hydrological, geochemical and biological processes.

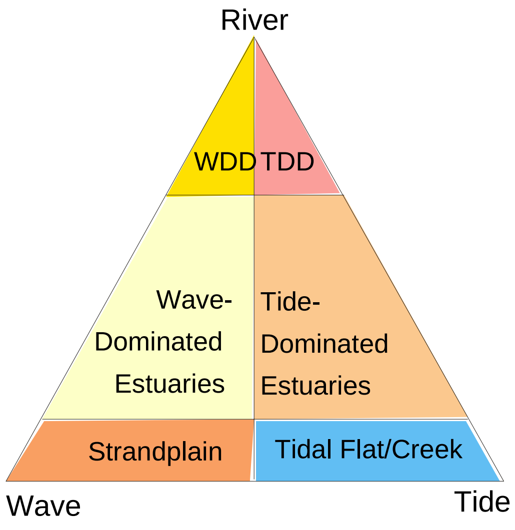


Figure 1. Ternary classification of coastal systems divided into six subclasses (after Dalrymple *et al.* 1992; and Boyd *et al.* 1992).
The position of each subclass with respect to one another depends of the relative influence of wave, tide and river energies. All coastal systems are thus distinguished based on the relative wave/tide power (i.e. the x-axis), and then river energy (y-axis). Deltas (WDD = wave-dominated delta; TDD = tide-dominated delta) have relatively high river energy and therefore occupy the uppermost regions of the triangle. Strandplains and tidal flats occupy the base of the triangle and are characterised by relatively low river energy. Estuaries are located in the intermediate trapezoidal region.

The distribution of energy within a coastal system is translated into a predictable arrangement of geomorphic and sedimentary units. These units are termed facies. They contain a distinctive suite of attributes that are representative of a particular sedimentary environment or process(es). Each of the six subclasses shown in Figure 1 consists of a distinctive group of geomorphic and sedimentary facies, from which they can be classified.

2.2. Definitions

Definitions for the different subclasses are provided below and apply throughout this document.

2.2.1. Delta

Deltas are defined as a coastal accumulation of river-derived sediment that forms a distinct coastline protuberance adjacent to, or in close proximity to, the source stream, including the sedimentary and geomorphic facies (habitats) that have been formed by waves, tides and other currents. All deltas are net exporters of sediment. Generally, wave-dominated deltas have arcuate shorelines, whereas tide-dominated deltas are lobate. Sediment delivered to the coast in regions of high wave energy (e.g. NSW) may be transported along the shoreline and the associated wave-dominated delta may not form a protuberance (e.g. Brunswick River, NSW). An example of a typical wave-dominated delta is Nassau River (QLD) and an example of a typical tide-dominated delta is McArthur River (NT).

2.2.2. Estuaries

For the purposes of this report, AGSO has adopted a geologic definition of an estuary (Boyd *et al*., 1992):

An estuary is defined as the seaward limit of a drowned valley which receives sediment from both river and marine sources and contains geomorphic and sedimentary facies influenced by tide, wave and river processes.

Estuaries are net importers of sediment. Generally, wave-dominated estuaries are characterised by a shore-parallel sandy barrier at the mouths and relatively deep water central basins. Tide-dominated estuaries are typically funnel-shaped, and contain elongate sand bodies known as tidal sand banks in the main tidal channel(s). An example of a typical wave-dominated estuary is Lake Illawarra (NSW), and an example of a typical tide-dominated estuary is Adelaide River (NT). Wave-dominated estuaries are also colloquially known as “Coastal Lakes” or “Lagoons”. However, in this report, coastal lakes and coastal lagoons are considered to be forms of wave-dominated estuaries which are characterised by low to negligible river input (Figure 1).

2.2.3. Strandplain

Strandplains are shore-parallel sand bodies containing beaches and dunes found along prograded linear coasts not associated with embayments. Strandplains are commonly comprised of multiple beach ridges and barriers. Small creeks draining the immediate hinterland may exist within a strandplain, however, they are usually associated with negligible river input. Coastal Creeks are a form of strandplain that do not generally contain multiple beaches and dunes. An example of a strandplain is Mooball Creek (NSW).

2.2.4. Tidal Flats/Creeks

Tidal flats are generally low gradient accumulations of fine sediment (e.g. mud) which have surfaces that dip gently from the hinterland towards the sea. Tidal flats generally consist of a low gradient muddy plain dissected by numerous tidal channels. Tidal flats occur in regions that have a high tidal influence and are most extensive in macrotidal regions (e.g. NT, northwest WA) and along muddy low-gradient coastlines (e.g. Gulf of Carpentaria). Tidal creeks are small tidal channels cut into coastal flats. The surfaces of tidal creeks are generally above the high tide limit. In tidal creek systems, seawater is restricted to the tidal channel. An example of a typical tidal flat system is Moonlight Creek (QLD) located on the south coast of the Gulf of Carpentaria.

2.3. Methodology

An energy classification was undertaken for 780 estuaries and coastal waterways contained in the AED by determining the ratio of wave energy to tide energy at the mouth, and then the amount river energy. As an independent check on the energy classification, a visual inspection was also undertaken of all 974 estuaries and coastal waterways in the OZESTUARIES database to determine the sedimentary facies in each system. Four conceptual models then were developed to represent Australian conditions. Full details of the methodologies used for the classification are presented in Appendix B.

2.4. Key Findings

2.4.1. Estuarine Classification

Initially, the 780 estuaries and coastal waterways contained in the AED were classified on the basis of wave and tide energy. The key findings are:

- the differences between the mean values of the wave/tide power ratio are statistically significant (with 95% confidence limits) for deltas and estuaries but the difference in the means for strand plains tidal flats is not statistically significant (Table 1);
- wave- and tide-dominated systems are strongly partitioned into two separate groups based on their geomorphology (Figure 2); and
- approximately 60% of the estuaries and coastal waterways are tide-dominated systems.

River energy was then included to distinguish between systems that are characterised by river processes and those characterised by wave and tide energies to derive all six subclasses (Figure 3, Table 2). The key findings are

- the difference in mean fluvial discharge for all deltas and estuaries combined (24.47±118.7 $m^3 s^{-1}$, n = 337) is significantly different from the mean fluvial discharge of strandplains and tidal flats (8.08±32.9 $m^3 s^{-1}$, n = 343);
- there is no significant difference between the river energy in deltas and estuaries;
- only 19% of Australia's coastal systems are dominated by river energy, based on their geomorphology; and
- approximately 40% of coastal systems have very low riverine discharge (Figure 3).

Along with the six subclasses (e.g Table 2) there is another subclass labelled "Others". This subclass contains coastal systems such as: Coastal Creeks, Coastal Lagoons, Embayments, Drowned River Valleys and Freshwater Lakes that were also identified by the NLWRA. Because these systems contain few estuarine facies, they have only been given limited treatment and have not been classified on the basis of wave, tide and river energies.

Table 1. Means, standard deviations (SD) and ranges of wave and tide energy for 780 estuaries and coastal waterways contained in the AED

		Wave Energy ($J m^{-2} s^{-1}$)		Tide Energy ($J m^{-2} s^{-1}$)	
Class	**Frequency**	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**
Wave	170	350 ± 250	5.8 – 1200	190 ± 640	7.9 – 6000
Tide	515	49 ± 78	0.002 – 830	1700 ± 2100	32 – 11000
Mixed	99	180 ± 140	5.8 – 1100	480 ± 840	71 – 6000

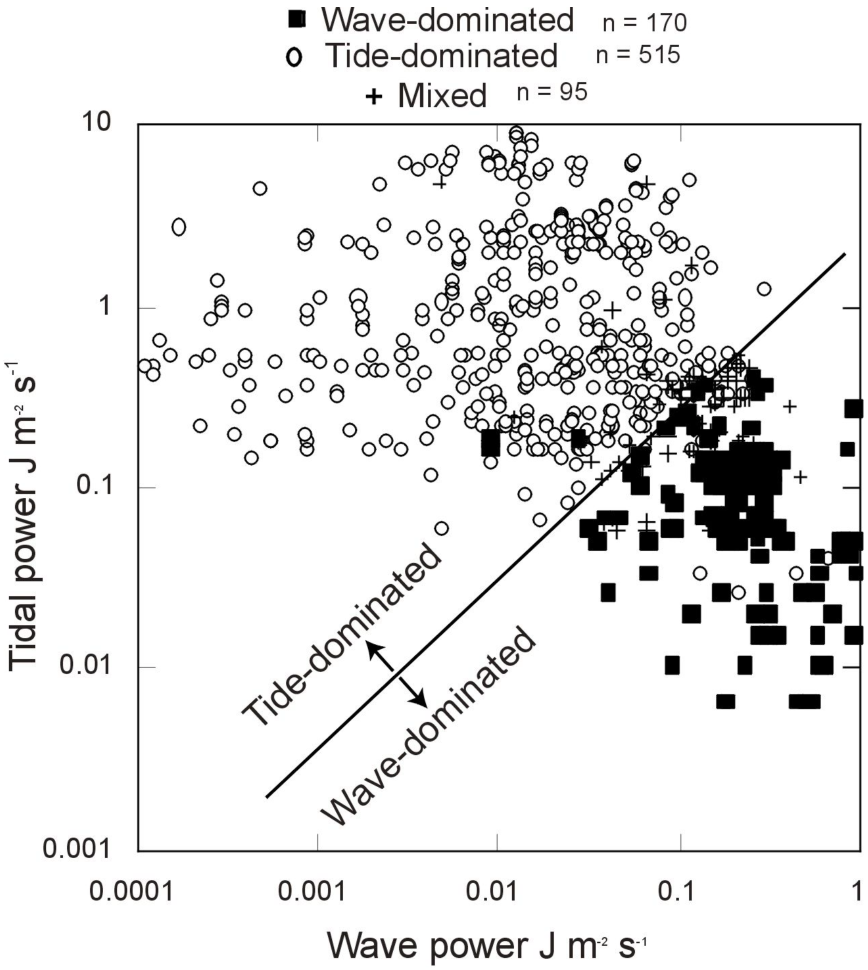


Figure 2. Stability diagram for tide- and wave-dominated systems.
Stability diagram for tide-dominated systems that plot in the upper left hand side of the diagram versus wave-dominated systems that plot in the lower right hand side. The X and Y axes plot wave and tidal power on a log scale calculated for 780 estuaries and coastal waterways contained in the AED. The line separating wave- and tide-dominated systems (based on their geomorphology) was drawn by hand and has a slope of ~3.2.

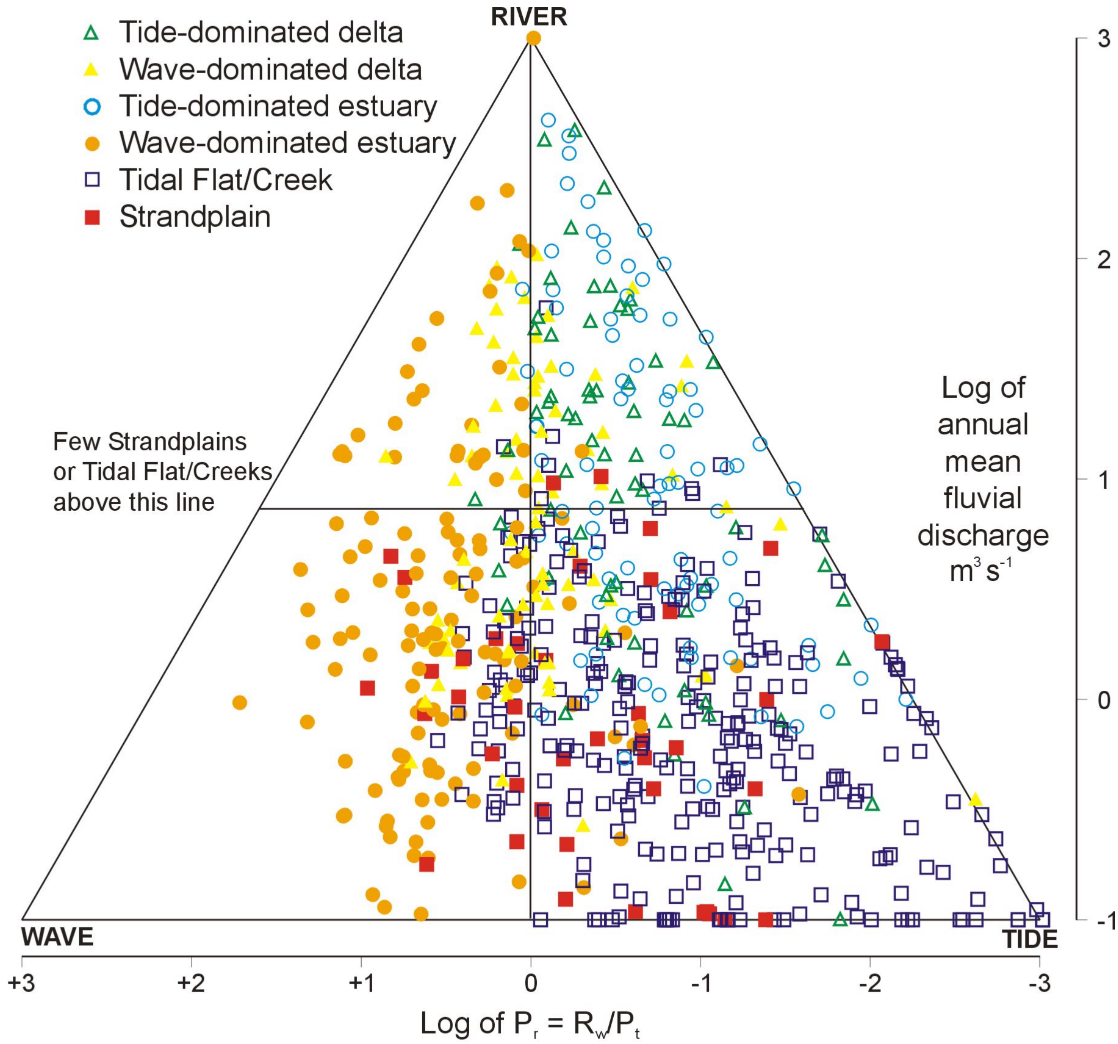


Figure 3. Total energy distribution plot for 780 estuaries and coastal waterways contained in the AED. The coloured symbol allocated to each coastal system represents the type of subclass as defined by geomorphology.

Table 2. Table listing the frequency of subclasses; percentage of the overall number of coastal systems represented by each subclass; and mean and standard deviation of wave/tide energy and fluvial discharge.

Coastal System Subclass	Frequency	Percent of total no. of systems	Mean wave/tide energy ($J\ m^{-2}\ s^{-1}$)	Fluvial Discharge ($m^3\ s^{-1}$)
Tide Dominated Estuary (TDE)	90	11.5	0.18 ± 0.30	38.1 ± 74
Tide Dominated Delta (TDD)	68	8.7	0.39 ± 0.75	33.9 ± 68
Wave Dominated Estuary (WDE)	128	16.5	24.10 ± 47.70	26.8 ± 181
Wave Dominated Delta (WDD)	78	10	3.10 ± 7.80	16.9 ± 23.3
Tidal Flat/Creeks (TC)	274	35.1	0.42 ± 0.77.	1.69 ± 4.2
Strandplain (SP)	41	5.3	2.56 ± 5.60	1.7 ± 2.4
Others	101	12.9	-	-

The distribution of subclass types around the country (Figure 4) shows that most wave-dominated subclasses and tide-dominated subclasses are found in the southern and northern half of the country, respectively. This is also shown in Table 3 in which the frequency of the different subclasses in each state is presented.

NT and QLD overwhelmingly contain the highest number of tide-dominated coastal systems in Australia. In contrast NSW, VIC and TAS contain almost no tide-dominated systems and are characterised by a wave-dominated coastline. South Australia is dominated tidal flat/creeks due to the arid climate and therefore the lack of significant fluvial discharge. The distribution of coastal system subclasses in WA is more evenly balanced than for all other states, having a ratio of tide-dominated to wave-dominated systems of 2:1; the tide-dominated systems occur in the north of the state, whilst the wave-dominated systems occur in the southwest.

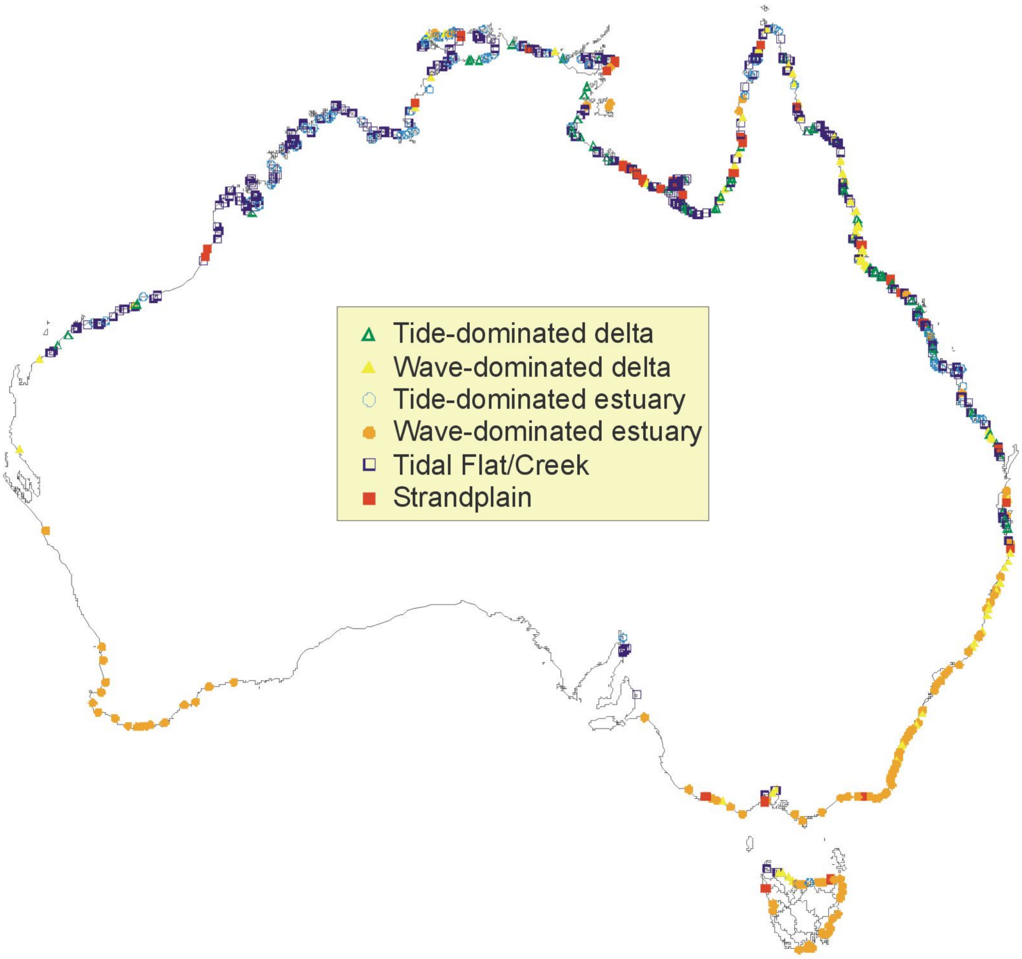


Figure 4. Map of Australia showing the classification of 780 estuaries and coastal waterways contained in the AED into subclasses based on their geomorphology.

Table 3. The number of coastal systems in each subclass type.

Coastal System Subclass	NSW	NT	QLD	SA	TAS	VIC	WA
Wave Dominated Delta (WDD)	18	7	44	2	10	5	7
Wave Dominated Estuary (WDE)	57	6	8	2	32	21	31
Strandplain (SP)	9	12	19	-	5	10	5
Tide Dominated Delta (TDD)	1	16	50	1	1	-	4
Tide Dominated Estuary (TDE)	-	28	38	1	3	1	24
Tidal Flat/Creek (TC)	3	54	140	10	3	2	73

2.4.2. Geomorphic Conceptual Models

Conceptual models illustrate the basic form of a system, and highlight important processes and linkages. The models may be used to classify coastal systems from around Australia, and to develop specific indicators that can assist with measuring ecosystem health. AGSO have developed geoscience conceptual models for four of the six coastal system subclasses based on "idealised" wave- and tide-dominated facies models presented in Dalrymple *et al.* (1992). The models have been modified for Australian conditions using the results of the energy and geomorphic classifications. The numbered points refer to numbers on the figures. Full details of the geomorphic and sedimentary characteristics of each facies in the models is given in Appendix C.

Wave-dominated Estuaries

1. Wave-dominated estuaries (Figure 5) are distinguished by relatively high wave energy at the mouth compared to tide energy.
2. Near the mouth, total energy is high due to the summation of high wave and tide energies.
3. Near the head, total energy is high due to high river energy. River energy declines downstream due to a reduction in downstream hydraulic gradient.
4. In the middle of the estuary, total energy is low because waves can not penetrate the estuary, and because tidal energy is dissipated on the ebb- and flood-tide deltas.
5. Waves transport sediment from the sea towards the estuary and build a barrier at the mouth. Tidal currents transport sediment into the estuary to form flood and ebb tidal deltas that extend seaward and landward of the inlet.
6. Landward of the barrier and flood/ebb tide deltas is a low-energy relatively deep central basin. The central basin is the main sink for fine sediment.
7. Waves and tidal currents deposit fine sediment on the edge of the central basin to form intertidal flats, and saltflats/saltmarshes. Mangroves are common along margins. Sandy beaches can also form.
8. Sediment from the catchment is deposited in the main channel, on the floodplain, and can be transported into the estuary to form a fluvial bay-head delta that extends into the central basin.

Examples of wave-dominated estuaries include Lake Illawarra (NSW) and Swan River (WA).

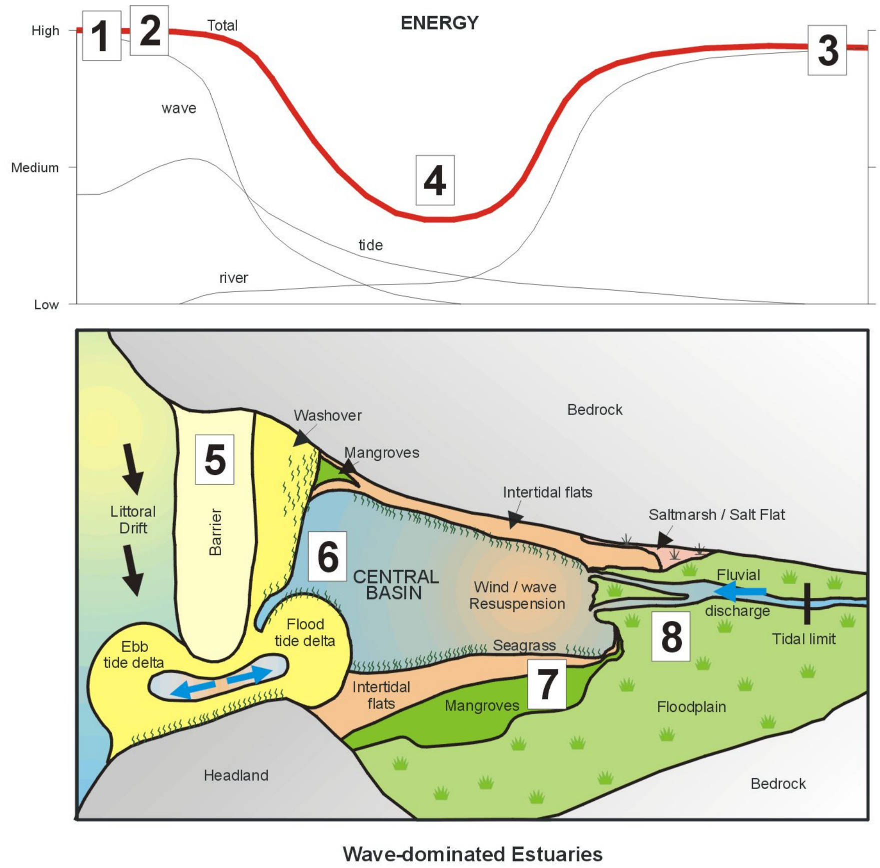


Figure 5. Geomorphic and sedimentary facies model of wave-dominated estuaries in Australia.

Tide-dominated Estuaries

1. Tide-dominated estuaries (Figure 6) are distinguished by relatively high tidal energy at the mouth compared with wave energy.
2. Near the mouth, total energy is high because both tidal energy is high and wave energy is moderate.
3. Inside the estuary, wave energy is reduced over extensive tidal sand banks, thus decreasing total energy.
4. Total energy rises to a maximum where the difference between the effects of constriction by the funnel-shaped entrance (tidal-amplification) and effects of dissipation by sediment shoals is greatest.
5. Further headward, total energy falls to a minimum because friction created by the sediment shoals becomes greater than tidal amplification.
6. Total energy rises in the river-dominated zone because of constriction at the head.
7. In the funnel-shaped mouth, strong tidal currents transport coarse sediment into the estuary and build elongate tidal sand banks that extend to the zone of maximum total energy.
8. Near the tidal limit, where the channel is characterised by a sinuous river channel pattern, total energy is at a minimum. Sediment of mixed river and marine origin accumulates here.
9. Intertidal flats, mangroves, and saltflat/saltmarshes occur extensively along the sides of the estuarine channel (Woodroffe *et al*. 1989).
10. Tide-dominated estuaries are naturally turbid because of the strong tidal currents.

Examples of tide-dominated estuaries include the Ord River (WA) and Broad Sound (QLD).

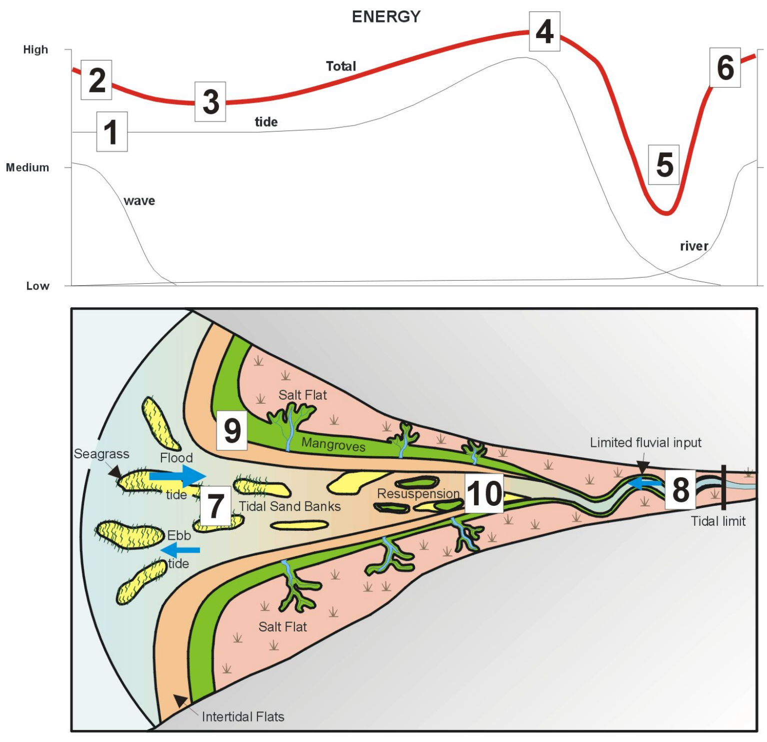


Figure 6. Geomorphic and sedimentary facies model of tide-dominated estuaries in Australia.

Wave-dominated Deltas

1. Wave-dominated deltas (Figure 7) are characterised by relative high wave energy at the mouth compared to tide energy, and are distinguished from wave-dominated estuaries by high river energy.
2. Total energy at the mouth is high because of high wave energy at the coast.
3. Total energy declines immediately landward of the mouth because wave energy is dissipated on the barrier. The dominance of river energy further landward means total energy is relatively high along the channel.
4. Maximum tidal energy occurs in the constricted inlet mouth.
5. At the mouth, waves transport sediment towards the entrance and build a sub aerial barrier.
6. Sediment transported from the catchment by the river is deposited on the floodplain, forming levees and back swamps, and in the main channel.
7. River sediment is transported directly to the mouth because the channel connects the river's catchment with the ocean.
8. Relatively strong river energy causes net seaward-directed sediment transport. Coarse sediment deposited near the inlet forms flood/ebb tide deltas.

Examples of wave-dominated deltas include the Manning River (NSW) and Yarra River (VIC).

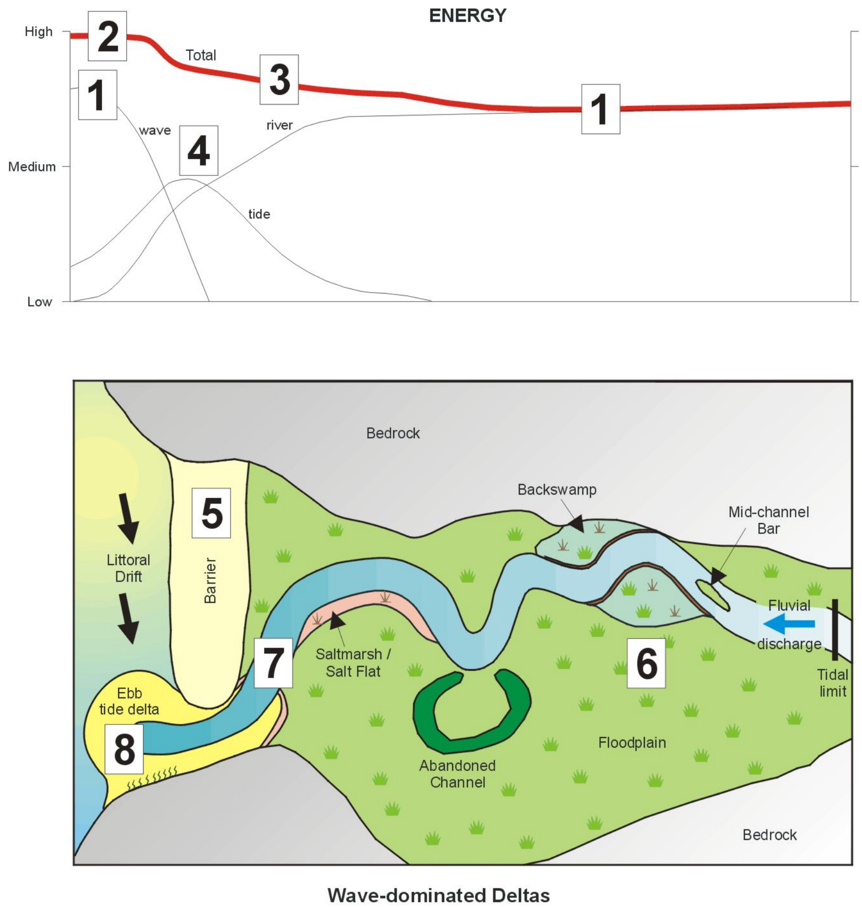
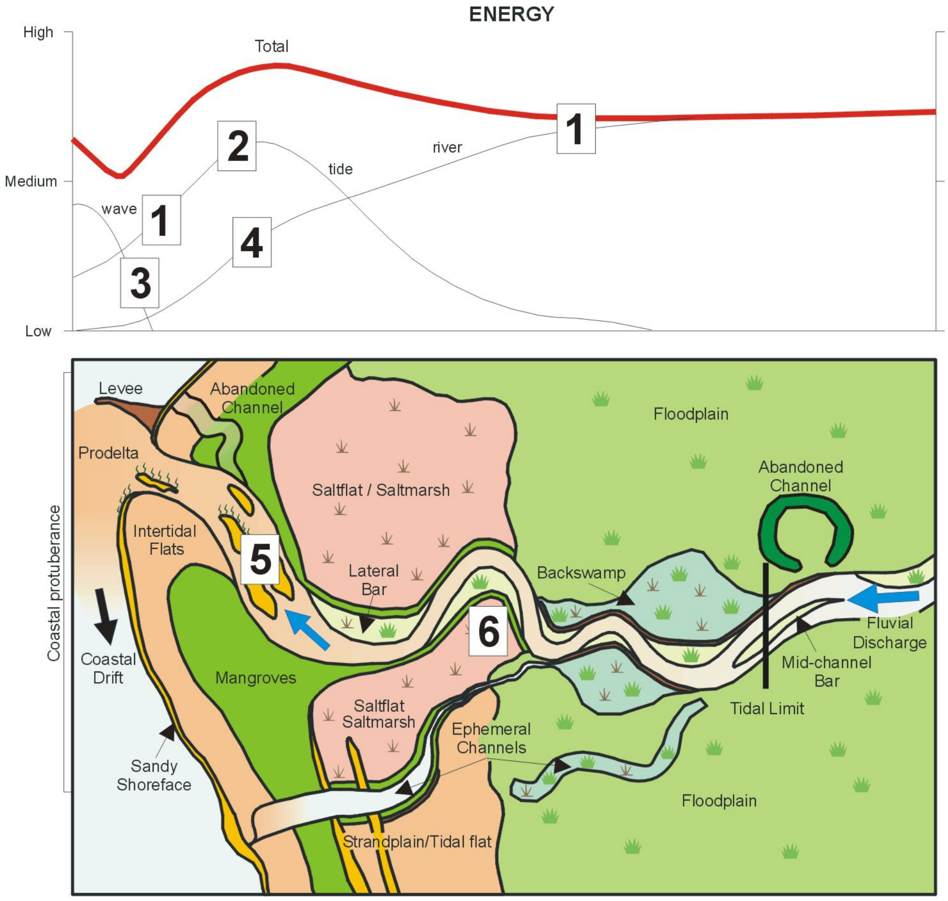


Figure 7. Geomorphic and sedimentary facies model of wave-dominated deltas in Australia.

Tide-dominated Deltas

1. Tide-dominated deltas (Figure 8) are characterised by relatively high tide energy at the mouth compared with wave energy, and are distinguished from tide-dominated estuaries by high river energy.
2. Tidal energy is greatest slightly landward of the mouth due to constriction by the funnel shaped mouth.
3. Wave energy is dissipated on shoals seaward of the mouth, and declines rapidly landwards.
4. River energy remains moderate to high along the channel, but drops off significantly as the channel widens towards the mouth.
5. Inside the mouth, moderately-strong tidal currents transport coarse sediment into the channel from offshore and build elongate tidal sand banks. These banks only extend a short distance into the channel because tidal energy is dissipated by channel friction.
6. Extensive areas of intertidal flats, mangroves, and saltflat/saltmarshes occur along the sides of the channel.

Examples of tide-dominated deltas include the Macarthur River (NT) and Burdekin River (QLD).



Tide-dominated Deltas

Figure 8. Geomorphic and sedimentary facies model of tide-dominated deltas in Australia.

2.5. Application of Conceptual Facies Models

The four conceptual facies models are useful for two important reasons:

1. they offer fundamental insights into the behaviour of estuaries and coastal waterways around Australia; and
2. they provide environmental managers with important information about the form and functioning of individual or groups of estuaries and coastal waterways (Figure 9).

The conceptual facies models do not, however, allow a direct comment to be made about ecosystem health. Rather, they should be viewed as a means of providing the geological framework within which individual systems can be compared.

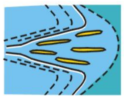
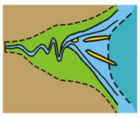
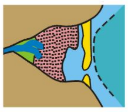
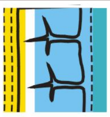
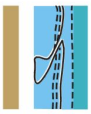
Type of Coastal Environment	Sediment Trapping Efficiency	Turbidity	Circulation	Habitat Loss due to Sedimentation
 Tide-dominated Delta	Low	Naturally High	Well Mixed	Low Risk
 Wave-dominated Delta	Low	Naturally Low	Salt Wedge/ Partially Mixed	Low Risk
 Tide-dominated Estuary	Moderate	Naturally High	Well Mixed	Some Risk
 Wave-dominated Estuary	High	Naturally Low	Salt Wedge/ Partially Mixed	High Risk
 Tidal Flats	Low	Naturally High	Well Mixed	Low Risk
 Strand Plains	Low	Naturally Low	Negative/ Salt Wedge/ Partially Mixed	Low Risk

Figure 9. Plan view maps showing types of coastal systems in relation to some key management implications.

The maps illustrate key morphological features and diagnostic criteria for each type of coastal system.

2.5.1. Sediment Trapping Efficiency

The fate of most particle-associated contaminants in coastal environments is directly linked with the dispersal and deposition of fine-grained sediment. Thus, the ability of a system to trap fine sediment is important for management in terms of toxicants, heavy metals and particle-associated contaminants.

Wave-dominated Estuary (WDE)

The trapping efficiency of wave-dominated estuaries is high because they contain a low-energy central basin from which very little sediment escapes. The low-energy conditions in the central basin means that this region is the primary repository for fine material and particle-associated contaminants (e.g. Hodgkin & Hesp 1998; Heggie & Skyring 1999). Strandplains and Coastal Lakes/Lagoons (i.e. wave-dominated estuaries cut off from the ocean by a sandy barrier) will trap 100% of all river inputs until such time as a flood event cuts a new inlet through the wave-built barrier and flushes the estuary. However, unless these flood events are extremely large, they may not dislodge contaminants trapped within fine grained sediment deposited in the central basin. The sediment trapping efficiency of wave-dominated estuaries is thus high (Figure 9).

Tide-dominated Estuary (TDE)

The trapping efficiency of tide-dominated estuaries is moderate because in general they are highly energetic and turbid systems (Figure 9). Fine material is continually resuspended in the water column and very little accumulation takes place in the main tidal channels. Most of the fine material is deposited by tidal currents along the edges of the estuary, including seawards of the mouth, forming intertidal flats and saltflats/saltmarshes. In tide-dominated estuaries with tidal ranges of >4 m, the presence of strong tidal currents causes movement of turbid estuarine water seawards of the mouth so that some of the sediment may be lost to the system.

Wave- and Tide-dominated Deltas (WDD/TDD)

The sediment trapping efficiency of wave- and tide-dominated deltas is low (Figure 9) because:

1. they are characterised by net seaward-directed sediment transport; and
2. they contain few environments that are able to trap sediment.

Wave-dominated deltas do not have a low-energy central basin and thus contain very little room for sediment deposition, except during relatively infrequent major flood events where sediment may be deposited on the floodplain. In tide-dominated deltas, strong tidal currents continuously rework fine sediment along the length of the estuarine channel until the load is flushed offshore by flood events.

2.5.2. Turbidity

Turbidity is often considered a problem for the management of estuaries and coastal waterways because significant suspended material in the water column limits photosynthesis (which impacts seagrass habitat and phytoplankton viability).

The presence of strong tidal currents in tide-dominated estuaries and deltas means that these systems are naturally turbid (Figure 9). Total suspended solids may normally attain several grams per litre in many macro-tidal systems. In contrast, turbidity inside a wave-dominated estuary is usually low (Figure 9) because it is protected from vigorous wave action by a barrier at the mouth, and tidal currents are relatively weak in the low-energy central basin. An exception to this situation occurs where a wave-dominated estuary contains a relatively shallow central basin, where internal wind waves are able to resuspend fine sediment, resulting in significant turbidity inside the estuary.

A zone of turbid water known as a “turbidity maximum” is commonly found in coastal waterways with significant riverine input. This naturally occurring phenomenon is caused by the flocculation of fine particles resulting from the mixing of fresh and saltwater. In general, persistent and relatively high turbidity throughout a wave-dominated estuary or delta might be an indicator of anthropogenic impact.

2.5.3. Habitat Change

Habitat changes are important for management purposes because they affect productivity and species diversity in a system. Primary production in estuaries is directly related to the distribution of estuarine flora, which then directly and indirectly determines the nature of benthic and fish communities (Roy *et al.* submitted). Given time, the sedimentary facies in all estuaries and coastal waterways will change as part of the natural evolution of the system. Environmental managers must differentiate between these natural changes and changes resulting from anthropogenic activities.

An important point to recognise is that the distributions of facies generally change relatively slowly over decades to centuries. Given sea level stability over this time, changes in wave-dominated estuaries may include:

1. reduction in the size/area of the central basin;
2. reduction in the size/area of flood/ebb tidal deltas;
3. increase in size/area of the fluvial bay-head delta; and/or
4. increase in the size/area of the fluvial floodplain.

The overall facies distribution (thus habitats) in wave-dominated systems can alter significantly, making it a high-risk system for habitat change. In contrast, in tide-dominated systems all tidal facies will tend to migrate seaward, and because there is not necessarily a major change in the distribution of facies, these systems have a low risk of habitat change.

Given enough time and available sediment, estuaries will develop into deltas. Biological productivity increases as wave-dominated estuaries evolve towards deltas, and then declines when the delta stage is in place (Roy *et al*. submitted). This is due to a reduction in intertidal habitats, with sediment infilling. Tide-dominated estuaries and deltas are likely to have similar facies distributions.

Potential activities that result in accelerating this natural process of habitat loss or redistribution due to infilling include: increased sedimentation due to catchment disturbances or activities, and the construction of breakwaters.

3. Geometry

3.1. Introduction

The physical dimensions of 909 of Australia's estuaries and coastal waterways were collected as part of the NLWRA's inventory.

The geometric indices were compiled to meet the needs of the estuarine modellers (CSIRO), and to provide a simple, standard spatial data set for a large number of Australia's estuaries and coastal waterways, for which no data currently exist. The geometric data represent part of the geoscience component of the NLWRA database.

The data will be applied in the modelling of marine exchange (tidal prism), fluvial flushing time (residence time), water and sediment quality, and for the quantification of shoreline and estuarine habitat.

3.2. Methodology

Up to six geometric indices were collected for each estuary, these were estuarine water area (km^2), perimeter of shoreline (km), total length of the estuary to the tidal limit (km), entrance width (km), entrance length (km), and maximum basin width (km).

Full geometric measurements have been made for 909 NLWRA defined estuaries and coastal waterways. These are broken down according to State in Table 4.

Table 4. Frequency of estuaries and coastal waterways completed for which geometry data available by state.

State	Total Number	Number Completed
NSW	134	133
NT	140	139
QLD	313	299
SA	38	36
TAS	116	85
VIC	63	59
WA	171	158
TOTAL	**975**	**909**

Geometric indices were derived from measurements taken from Landsat TM satellite imagery, which allows rapid appraisal of geographical features in a consistent manner. AGSO has a large database of Landsat TM scenes covering most of the Australian coastline. Additional Landsat TM 5 and 7 images were acquired from ACRES to fill gaps in the estuary coverage. Images were processed for the enhancement of estuarine features (Appendix D.1). Hardcopies of the Landsat TM scenes, in combination with reference materials (air photos, topographic maps), were then used to interpret and define the geometric indices (Appendix D.2).

Data were captured using GIS digitising techniques (Appendix D.3). A brief explanation of each of the indices is given in Table 5, and full explanations of each geometric database field are given in (Appendix D.4.).

Table 5. Table of geometric data indices.
(Full explanations of each index are presented in Appendix D.4)

Geometric Index	Type	Units	Description
Water Area	area	km^2	Area of estuary to the high-tide limit, defined by water area and intertidal facies
Perimeter	length	km	Length of shoreline habitat defined by the region used to measure water area
Total Length	length	km	Distance between the upstream limit of estuarine facies, and the marine boundary
Maximum Width	length	km	Maximum width of the estuarine 'basin', if present, perpendicular to the total length
Entrance Width(s)	length	km	Width of the estuary at the mouth(s) or constricted point at the entrance (up to 3)
Entrance Length	length	km	Length of the constricted section of the entrance channel, joining the basin to the sea
Entrance Location	lat./long.	decimal degrees	Mid point of the main entrance or mouth of the estuary

3.3. Key Findings

Descriptive statistics for each of the different geometric indices are presented in Table 6. Median values for each index, in each of the different estuarine subclasses (eg. wave-dominated estuaries (WDE), wave-dominated deltas (WDD), strandplains (SP), tide-dominated estuaries (TDE), tide-dominated deltas (TDD), and tidal flat/creek (TC)), are presented in Table 7. Medians and percentiles are used in these tables in preference to means and standard deviations, because the data distributions for these parameters were non-normal.

Table 6. Descriptive statistics for estuarine geometric indices for the total Australian-wide data set

	Water Area (km^2)	Perimeter (km)	Total Length (km)	Max. Width (km)	Entrance Length (km)	Total Entrance Width (km)
Maximum	9567.1	1427	139.46	53.63	26.56	95.5
Minimum	0.1	2.3	0.1	0.06	0.2	0.1
Median	1.89	20.9	6.93	0.93	1.4	0.29
50% Range[1]	0.4 - 10.8	8.1 - 54.7	3.4 - 14.9	0.4 - 3.2	0.6 - 3.1	0.08 - 1.1

1. The 50% range (which includes 50% of the observations) ranges between the 75th and 25th percentiles.

Table 7. Median values of geometric indices in each of the different subclasses.
WDD = wave-dominated delta' WDE = wave-dominated estuary; SP = strandplain; TDE = tide-dominated estuary; TDD = tide-dominated delta; and TC = tidal creeks.

TYPE	WDD	WDE	SP	TDD	TDE	TC
Water Area	1.1	4.1	0.26	3.6	19.5	1.3
Perimeter	20.1	24.2	6.7	45.3	79.2	16
Total Length	7.5	7.6	3.5	17.4	20.5	5
Maximum Width	0.4	1.4	0.2	N/A	3.1	0.65
Entrance Width	0.2	0.1	0.07	0.5	2.5	0.6
Entrance Length	1.9	1.5	1.0	N/A	N/A	N/A

Table 7 values highlighted in red are comparatively high by the standards of the data set, i.e. these medians are higher than the 75th percentile for the overall the data set (Table 6). Values highlighted in yellow are moderate, eg. these medians fall within the 50% range of all the data (Table 6). Values highlighted in blue are comparatively low i.e. these medians are lower than the 25th percentile of the overall data set (Table 6)

From the data presented in Table 7, it is evident that there are clear differences in the size and shape of the different subclasses, particularly between wave-dominated and tide-dominated subclasses.

Tide-dominated subclasses (TDE, TDD, and TC) tend to have relatively large entrances with no constricting channel, and thus tend not to feature large central basins. The occurrence of some Maximum Widths that are larger than entrance widths (in these typically “funnel” shaped systems) is generally due to bedrock valleys enclosing the systems. The total length of tide-dominated systems is relatively large, is indicative of significant inland penetration of tidal waters. Long perimeters indicate that these systems generally feature complex shoreline, and consequently may contain a large amount of potential habitat space for mangroves and saltflat/saltmarshes.

Wave-dominated subclasses (WDE, WDD, and SP) tend to have narrow, constricted entrance channels, and often have basins in which both vertical and horizontal mixing of the water column can occur (large maximum width relative to entrance width). The total length of these systems is medium to small, suggesting limited penetration of tidal waters inland. Medium to small perimeter measurements indicates that shoreline habitats are less complex than those observed in tide dominated systems.

3.4. Application of Data

Synthesis of data sets such as the estuarine geometry data can provide important information for managers interested in addressing environmental issues in estuaries and coastal waterways (Table 8). While data are by no means comprehensive for each estuary, the Australia-wide perspective gained can provide a basic framework within which estuary types and “functions” might be compared and assessed.

Table 8. Synthesis of geometry-geomorphic relationships and some estuary management issues.

Estuary Type	Marine Exchange (Tidal Prism)	Volume	Risk to Water & Sediment Quality	Space for Shoreline Habitat
WDD	Very Small	Moderate	Moderate	Small
WDE	Small	Moderate	High	Moderate
SP	Very Small	Very Low	Very High	Small
TDD	Large	High	Low	Large
TDE	Very Large	Very High	Low	Large
TC	Large	Moderate	Low	Variable

3.4.1. Marine Exchange (Tidal Prism)

Large estuarine entrances are conducive to the exchange of tidal waters, as is a lack of an entrance-constricting channel. These features are common to tide-dominated subclasses, thus, the data suggest that tidal systems generally exchange large amounts of water with the marine environment each tidal cycle (also depending on local tidal range). Wave-dominated subclasses inherently have very small entrances (relative to tide dominated systems), and thus undergo relatively little tidal marine exchange.

Strong marine exchange and tidal currents influence the distribution of facies found within the entrances of estuaries and coastal waterways. This may result in the frequent occurrence of tidal sand bank (TSB) facies within tide-dominated systems. A large tidal prism may also be related to the extent of intertidal habitats within the system, and also have implications for the marine infilling of estuarine basins.

3.4.2. Residence Time

Water residence times of estuaries and coastal waterways are potentially important ecological indicators because they are a guide to the amount of time materials spend within an estuary or coastal waterway. This in turn provides an indication of the likelihood of this material being trapped, or utilised (in the case of nutrients) within the estuary or coastal waterway. Thus, waterways with short residence times are likely to export much of their catchments loads to the ocean, whereas waterways with long residence times are likely to utilise much of the nutrients added (through primary production) and to trap sediments and toxicants within depositional facies.

There are a large number of methods by which residence time of water within an estuary or coastal waterway may be calculated (Solis & Powell, 1999). Most measures of residence time represent an attempt to determine the average amount of time freshwater runoff remains within a waterway. All measurements of residence time require estimates of one or more of the following: estuarine area, average depth, freshwater runoff, salinity or tidal influx.

The data collected for the Audit do not allow us to make even the simplest estimate of residence time (estuary volume/freshwater runoff). However, the area measurement undertaken for the audit provides some indication of the likelihood that an estuary will be rapidly flushed.

Tide-dominated estuaries are clearly the largest class of coastal system in Australia with a median water area of 19.5 km^2, compared to 4.1 km^2 for the next largest class of coastal system (wave-dominated estuary) (Table 7). Clearly, tide-dominated estuaries will need very large fluvial flow rates or tidal influxes to flush catchment inputs from the estuary, compared to smaller wave-dominated subclasses.

3.4.3. Water & Sediment Quality

If we accept that a large physical size, a high degree of complexity and diversity within an estuary will increase an estuary’s ability to absorb stresses, such as nutrient and toxicant inputs, then we can use estuarine geometry to assess the relative resilience or robustness of coastal systems.

Typically tide-dominated estuaries are physically large and have a high degree of complexity (long shore-line). They also have large tidal influxes that promote exchange of water within the estuary. Wave-dominated estuaries, deltas and other coastal classes tend to be of smaller physical size, less diverse and have less tidal exchange. Geometric data suggest that, in general, wave-dominated coastal systems, strandplains and tidal deltas may be more susceptible to a deterioration in water and sediment quality than tide-dominated estuaries.

3.4.4. Shoreline Habitat Space

Potential shoreline habitat for estuaries and coastal waterways can be directly determined from the perimeter geometric indices. Shoreline habitat measurements represent the total amount of space for flanking estuarine habitats such as intertidal flats, mangroves, saltmarshes and saltflats, for a given water area. Thus, systems with highly convoluted shorelines tend to have the largest perimeters. The data indicate that tide-dominated subclasses generally have a much longer shoreline, and thus may contain more habitat space than wave-dominated subclasses. This is probably due to the convolute nature of tidal drainage across broad coastal areas.

3.5. Recommendations

AGSO recommend that:

- the geometric data are used to group estuaries and coastal waterways for comparison;
- potential relationships between geometry and flushing characteristics be explored with the goal of developing useful proxies;
- relationships between geometry and facies be explored to better understand habitat space; and
- the geometric data are considered for use in ecosystem models.

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4. Facies Mapping

4.1. Introduction

Sedimentary facies provide the substrate for habitats. Mapping geomorphic and sedimentary facies in coastal systems permits a quantitative assessment of the variability in habitats between systems, and can be used to indicate significant deviation from a pristine state. Eight estuarine facies were chosen that were easily identified and are found across all coastal system types in Australia. The facies are:

- barrier and back barrier;
- central basin;
- fluvial bayhead delta;
- flood and ebb tide delta;
- intertidal flat;
- mangrove;
- saltflat/saltmarsh; and
- tidal sand banks.

Channel facies was also mapped by default. The following habitats were also mapped, and will be considered facies for the purpose of this report:

- Bedrock (perimeter);
- Coral Reef; and
- Rocky Reef.

Full descriptions of the facies are provided in Appendix F.

4.2. Methodology

4.2.1. Mapping

The spatial distribution of facies was mapped for 405 of the 497 estuaries and coastal waterways classified by the NLWRA as modified in some way. Definitions of how each facies was interpreted and mapped can be found in Appendix G. Briefly, aerial photographs ranging in scale from 1:5 000 to 1:80 000 were used to interpret the facies and the facies boundaries were mapped onto hard copies of 1:15 000 to 1:50 000 scale Landsat TM images. These boundaries then were digitised using the "heads up" approach onto AGSO's library of Landsat TM imagery or, where imagery was unavailable, digital 1:100 000 topographic maps. Full details of the digitising methodology are presented in Appendix E.

4.2.2. Analysis

The probability of occurrence of a given facies in an estuary subclass was determined using the spatial coverage. The strength of the association of each facies with each of the different subclasses was then calculated from the probability distribution, using descriptive statistics (i.e. by comparing the measured probability with the 25^{th} and 75^{th} percentile range of all the probabilities for a facies). We also used Cluster Analysis to organise the facies data (expressed as percentages of the total system area), into meaningful groups that reflect commonality of increasing or decreasing percentage cover. Most types of Cluster Analysis are undertaken using two steps: (i) measures of similarity are computed between pairs of objects; and (ii) objects are amalgamated into larger groups on the basis of increasing dissimilarity.

We applied Ward's Method for amalgamation to a Euclidean distance matrix using STATISTICA™ (StatSoft Inc., 1995). In this approach, an Analysis of Variance is used to minimise the sum of the squares between clusters at each step in the procedure. Descriptive statistics (sample sizes, maximums, minimums, medians, and percentile ranges) for facies (percentage area) are used to assign dominant facies to each of the subclasses.

4.3. Key Findings

4.3.1. Probability Analysis

The probability (F) of a facies occurring within a particular subclass is indicated numerically in Table 9. The strength of the association of each facies in each estuary type is further indicated by a colour-code (see caption). The key findings from the probability analysis are:

- with a few exceptions, all facies are associated with all subclasses;
- the probability of a system containing barrier/back-barrier and central basin is highest for wave-dominated estuaries;
- the probability of a system containing coral reef and bedrock is low for all subclasses;
- the probability of a system containing intertidal flats and mangroves is very high for all subclasses;
- barrier/back-barrier, central basin, fluvial bayhead delta and flood/ebb-tide delta are most strongly associated with wave-dominated subclasses; and
- intertidal flats, mangrove, saltmarshes, and tidal sand banks are most strongly associated with tide-dominated subclasses.

Table 9. Probability of occurrence (numbers) and degree of association (colours) of each facies with each of the six coastal sedimentary environments.
BBB = barrier and back barrier; BED = bedrock (BED); CB = central basin; COR = coral reef; FBD = fluvial bayhead delta; FED = flood and ebb tide delta; IF = intertidal flats; MAN = mangrove; RR = rocky reef (RR); SM = saltflat/saltmarsh; TSB = tidal sand banks; WDD = wave-dominated delta' WDE = wave-dominated estuary; SP = strandplain; TDE = tide-dominated estuary; TDD = tide-dominated delta; and TC = tidal creeks.

Subclass	BBB	BED	CB	COR	FBD	FED	IF	MAN	RR	SM	TSB
WDD	0.68	0.04	0.09	0.06	0.15	0.75	0.91	0.83	0.25	0.77	0.57
WDE	0.83	0.018	0.82	0	0.72	0.87	0.91	0.31	0.55	0.71	0.3
SP	0.82	0	0.12	0	0	0.65	0.82	0.65	0.24	0.59	0.41
TDE	0.14	0.07	0.04	0	0.07	0.29	0.93	0.93	0.46	0.96	0.89
TDD	0.06	0.03	0	0.03	0.03	0.64	0.94	0.97	0.12	1	0.61
TC	0.18	0.02	0.04	0.02	0	0.61	0.95	0.89	0.2	0.95	0.43
Percentile range [1]	0.14 – 0.82	0.02 – 0.40	0.04 – 0.12	0.02 – 0.03	0.03 – 0.15	0.61 – 0.75	0.91 – 0.94	0.65 – 0.93	0.20 – 0.46	0.71 – 0.96	0.41 – 0.61

[1] The strength of association for each facies was determined by comparing the measured probabilities (F) to the 25th – 75th percentile range of the probability distribution for each facies: white = no association (F = 0); yellow = weak association (F < 25th percentile); blue = moderate association (25th percentile < F > 75th percentile); red = strong association (F > 75th percentile); and grey =very strong association (F = 1).

4.3.2. Cluster Analysis

The cluster analysis identified two main groups in the data (Figure 10):

- tide-dominated *Group 1* is characterised by an association of saltmarsh, mangrove, tidal sand banks, intertidal flats and flood/ebb-tide delta; and
- wave-dominated *Group 2* is characterised by an association of fluvial bayhead delta, central basin, and barrier/back-barrier.

The cluster analysis also revealed the following.

- Close association between saltmarsh and mangroves. This is not surprising since the probability of them occurring together is high for all subclasses (Table 9).
- Close association between tidal sand banks and intertidal flats. This may reflect increasing relative tidal influence. Strong tidal currents and large tidal ranges form tidal sand banks and large areas of intertidal flats, respectively, in coastal systems where the tidal range is >4 m (i.e. macrotidal systems).
- Close association between fluvial bayhead delta and central basin. This almost certainly reflects the high probability of these facies occurring in wave-dominated estuaries (Table 9). Barrier/back-barriers also cluster with these facies. However, barriers are also moderately associated with wave-dominated deltas and strandplains (Table 9).
- Although, flood/ebb-tide deltas occur most frequently in wave-dominated estuaries (Table 9), they cluster with *Group 1* (Figure 10) because they have larger percentage areas in tide-dominated subclasses.

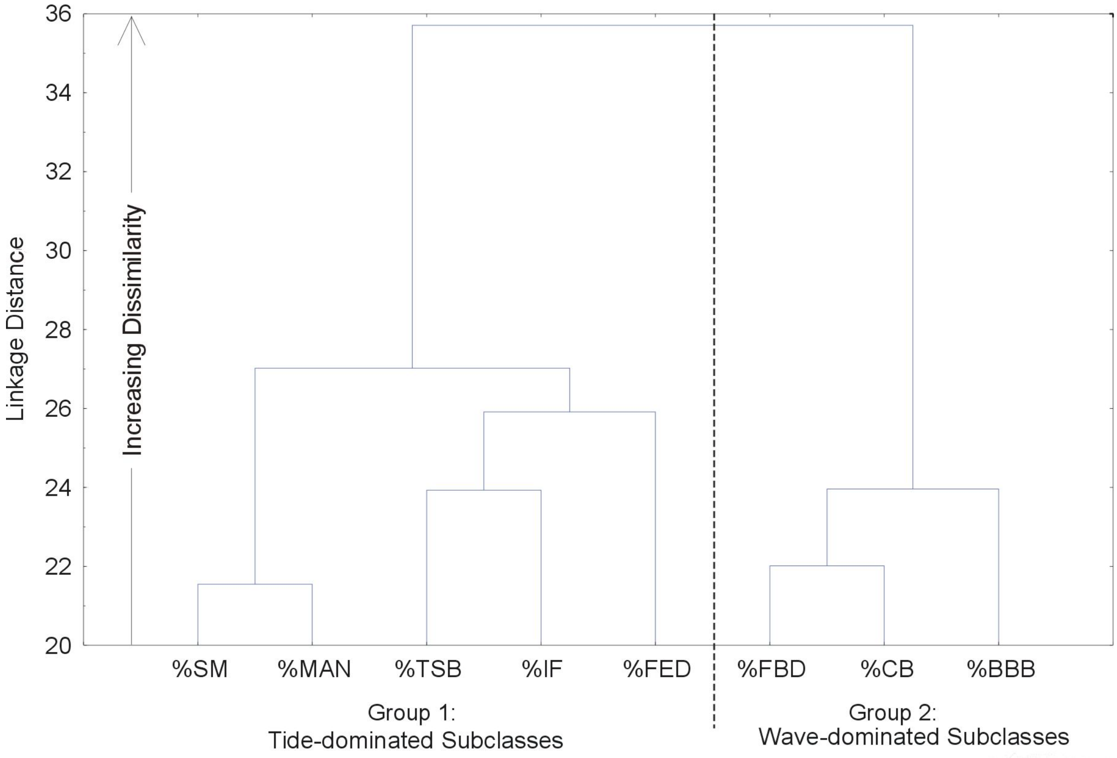

Figure 10. Cluster analysis dendrogram of facies percentage area data.
Most dissimilarity is shown in groups containing facies associated with wave-dominated subclasses and tide-dominated subclasses. SM = saltflat/saltmarsh; MAN = mangrove; TSB = tidal sand banks; IF = intertidal flats; FED = flood and ebb tide delta; FBD = fluvial bayhead delta; CB = central basin; and BBB = barrier and back barrier.

4.3.3. Descriptive Statistics

The probability analysis and the cluster analysis demonstrate that tide-dominated subclasses and wave-dominated subclasses each have diagnostic facies suites. Using the percentage area data (Table 10), it is possible to assign dominant facies to each of the different subclasses (indicated by blue text in Table 10). Dominant facies may be targeted in assessments of overall system health (see for example Table 16 and Table 17). They include the following:

- the central basin is the dominant facies in wave-dominanted estuaries;
- mangroves and channels are the doiminant facies in wave-dominated deltas;
- intertidal flats, barrier/back barriers and channels are the dominant facies in strandplains;
- mangroves, saltmarsh and channels are the dominant facies in tide-dominated estuaries;
- mangroves are the dominant facies in tide-dominated deltas; and
- mangroves and saltmarsh are the dominant facies in tidal creeks.

Table 10. Sample sizes (n), maximums (max), medians, and 25th – 75th percentile ranges (50% range) of %facies data for the different subclasses and the total data set (All Data). Minimum values (min) = 0 unless otherwise indicated. Dominant facies are indicated in blue text.

Facies	Wave-dominated Estuaries	Wave-dominated Deltas	Strandplains	Tide-dominated Estuaries	Tide-dominated Deltas	Tidal Creeks	All Data
% Intertidal Flats	n = 104 max = 62.2 median =3.1 50% range = 1.3 – 9.7	n = 48 max = 42 median =5 50% range =1.4 – 9.5	n = 14 max = 71.5 median=10.2 50% range =1.8 – 19.4	n = 26 max = 23.7 median= 4.7 50% range =0.6 - 9.0	n =31 max = 64.4 median=4.6 50% range = 2.4 – 9.7	n = 53 max =82.8 median=8.9 50% range = 2.6 – 25.1	n = 276 max = 82.9 median=4.5 50% range =1.4 – 11.5
% Mangrove	n = 35 max 41.8 median=0 50% range = 0 – 0.5	n = 44 max = 90 median=19 50% range =4.7-39.5	n = 11 max = 73 median = 7.4 50% range = 0 – 27.3	n = 26 max = 49.6 median=30.8 50% range =22.2-38.8	n =32 max = 71.7 median=29.8 50% range =16.3- 42.4	n = 50 max = 80.1 median=27.5 50% range =15.1 –38.1	n = 198 max = 89.8 median=10 50% range = 0 – 30.9
% Saltmarsh	n = 81 max = 64.6 median = 1.7 50% range = 0 – 9.5	n = 41 max = 69.8 median =4.9 50% range =0.2-17.2	n = 10 max = 22.6 median = 4.8 50% range = 0 - 11.7	n = 27 max = 52.1 median=21.8 50% range =12 – 32.9	n = 33 max = 79.1 median=12.4 50% range = 4.2 –42.1	n = 53 max = 84.2 median=24.7 50% range = 10.3-37.6	n = 245 max = 84.2 median=7.8 50% range = 0.9 – 24.2
% Barrier/ Back-Barrier	n = 95 max = 70.4 median=10.3 50% range = 1.6 – 23.1	n = 36 max = 38.9 median=2.2 50% range = 0 –5.6	n = 14 max = 89 median = 9.6 50% range = 4.1 – 46.3	n = 4 max = 11.9 median = 0 50%range = 0.0 – 0.0	n = 2 max = 2.9 median = 0 50%range = 0.0 – 0.0	n = 10 max = 28.1 median = 0 50%range = 0.0 – 0.0	n = 161 max = 89.6 median=0.8 50% range = .0 – 10.9
% Central Basin	n = 93 max = 97.5 median=31.3 50% range =9.9 – 55.1	n = 5 max = 5.9 median = 0 50%range = 0.0 – 0.0	n = 2 max = 42.5 median = 0 50%range = 0.0 – 0.0	n = 1 max = 10.2 median = 0 50%range = 0.0 – 0.0	n = 0	n = 2 max = 15.3 median = 0 50%range = 0.0 – 0.0	n = 103 max = 97.5 median =0 50% range = 0 – 19.2
% Flood/Ebb Tide Delta	n = 99 max = 51.8 median=4.8 50% range =1.6 – 9.3	n = 40 max = 54.4 median=3.6 50% range =.9 – 14.1	n = 11 max = 31.4 median =1.9 50% range = 0 – 6.4	n = 8 max = 23.4 median =0 50% range = 0 – 1.7	n = 21 max = 55.9 median=8.1 50% range = 0 – 20.1	n = 34 max = 58.4 median=5.5 50% range = 0.0 – 15.1	n =213 max = 58.4 median= 4.1 50% range = 0 - 12
% Fluvial Bayhead Delta	n = 82 max =64.3 median=6.5 50% range = 0 – 15.2	n = 8 max = 74.2 median = 0 50% range = 0.0 – 0.0	n = 0	n = 2 max = 53.9 median = 0 50% range = 0.0 – 0.0	n = 1 max = 3 median = 0 50% range = 0.0 – 0.0	n = 0	n = 93 max = 74.2 median =0.0 50% range = 0.0 – 3.0
% Channel Facies	n = 110 max =94.2 median=8.6 50% range = 4.5 – 18.4	n = 53 max = 95.2 min = 2 median=19.5 50% range = 10 – 37.3	n = 16 max = 78 median=13.4 50% range = 9.3 – 26.8	n = 28 max = 72.2 min = 4.4 median=20.2 50% range = 10.1 - 28	n = 33 max = 82.2 min = 0.3 median=13.8 50% range = 6.9 – 20.2	n = 51 max = 100 median =5.7 50% range = 2.7 – 11.5	n = 291 max = 100 median=11.4 50% range = 5.6 – 21.9
% Tidal Sand Banks	n = 34 max =20.3 median=0 50% range = 0 – 0.25.	n = 30 max = 8 median=0.31 50% range = 0 – 3.5	n = 7 max = 1 median =0 50% range = 0 – 1.32	n = 25 max = 40.6 median = 7.6 50% range = 1.9 – 14.5	n = 20 max =17 median=1.6 50% range = = 0 – 5.5	n = 24 max = 65.2 median = 0 50% range = 0 – 1.9	n = 139 max = 65.2 median=0 50% range = 0.0. – 2.7
% Bedrock	n = 2 max = 7.2 median = 0 50%range = 0.0 – 0.0	n = 2 max = 6.5 median = 0 50%range = 0.0 – 0.0	n = 0	n = 2 max = 0.51 median = 0 50%range = 0.0 – 0.0	n = 2 max = 0.6 median = 0 50%range = 0.0 – 0.0	n = 1 max = 0.14 median = 0 50%range = 0.0 – 0.0	n = 8 max = 7.2 median =0 50% range = 0.0 – 0.0
% Rocky Reef	n = 63 max = 24.5 median=0.08 50% range =0 – 0.72	n = 13 max = 26.8 median = 0 50% range = 0.0 – 0.0	n = 4 max = 10.4 median = 0 50% range = 0.0 – 0.0	n = 13 max = 5.4 median =0 50% range = 0 – 0.26	n = 4 max = 1.4 median =0 50% range = 0 – 0.0	n = 11 max =7.7 median =0 50% range = 0 – 0.0	n = 108 max = 26.8 median =0 50% range = 0 – 0.3
% Floodplain	n = 4 max = 21.8 median = 0 50% range = 0.0 – 0.0	n = 4 max = 21.8 median = 0 50% range = 0.0 – 0.0	n = 2 max = 3.4 median = 0 50% range = 0.0 – 0.0	n = 15 max = 11.1 median =.14 50% range = 0 – 4.4	n = 11 max =14.3 median=0 50% range = 0 – 2.5	n = 1 max = 7.3 median = 0 50% range = 0.0 – 0.0	n = 57 max =28 median = 0 50% range = 0.0 – 0.0
% Coral Reef	n = 0	n = 3 max = 46.4 median = 0 50% range = 0.0 – 0.0	n = 0	n = 0	n = 1 max = 29.5 median = 0 50% range = 0.0 – 0.0	n = 1 max = 3.8 median = 0 50% range = 0.0 – 0.0	n = 5 max =46.4 median=0.0 50% range = 0.0 – 0.0

4.4. Application of Data

The data collected by AGSO represents the first comprehensive quantitative geoscience inventory for estuaries and coastal waterways ever produced in Australia. The work documents facies areas, including mangroves, saltmarsh/saltflats and intertidal flats, which are key habitats for State of Environment Reporting (Ward *et al.* 1998). While the facies assessment only includes total area data and not floristics, the data should form a comprehensive baseline for assessment and preservation of these habitats around the Australian coastline. Furthermore, the strong association between facies and subclass has allowed for the development of an index to assess the degree of deviation from an ideal or normal state.

4.4.1. A Deviation Index for Australia's Modified Estuaries and Coastal Waterways

The occurrence of facies, and the application of an index that quantifies the presence and/or absence of diagnostic facies can assist resource managers with identifying the following:

1. the coastal system subclass (Figure 1), which is crucial to the understanding of how the system functions (see Section 2), and is also the basis for comparing systems when allocating resources;
2. systems that are significantly perturbed from a pristine state (as defined by conceptual models in Section 2);
3. systems that warrant further investigation because they may be significantly modified or degraded; and
4. substrate/habitat distribution and abundances for measures of productivity, biodiversity and habitat condition.

Because each subclass contains a particular suite of facies, individual systems can also be assessed at a national scale.

AGSO have developed a Deviation Index that uses the presence and absence of facies to assist with the quantification of habitat integrity for 405 of Australia's estuaries and coastal waterways deemed to be modified in some way by the NLWRA. As only non-pristine systems have been mapped, facies in the four conceptual models for Australian conditions (Section 2.4.2), derived from idealised facies models presented in Dalrymple *et al.* (1992) are used as the basis for comparison to pristine systems. The greatest habitat integrity is assumed to occur in a system that has an idealised facies distribution. The degree to which the facies distribution in an estuary and coastal waterway differs from this idealised distribution is a measure of its deviation. This Deviation Index then can be incorporated with other indicators for an overall assessment of the habitat integrity for the purposes of resource management.

Distinctive facies suites representing the pristine situation were identified for each coastal subclass and used as the basis for allocating a deviation score between 0 and 8 for each system, with 0 representing no deviation and 8 representing maximum deviation. Full details of the allocation of the facies and rules for applying the deviation score are presented in Appendix H. Deviation scores for each system can also be found in Appendix H, and will be made available in the OZESTUARIES database (www.agso.gov.au/ozestuaries).

A total of 277 estuaries and coastal waterways have a deviation score of between 0 and 2. A visual inspection of these systems indicates that these deviations are mostly due to natural variations based on regional characteristics in the nature of facies. Those systems with a deviation score of 3 (n = 84) show deviations due to either natural or anthropogenic activities. Any system that has a deviation score of >3 is thus flagged for further investigation into the reasons (natural or otherwise) for the high deviation score. For example, the Nerang River (QLD), a wave-dominated delta, has a deviation score of 5. A visual inspection of the facies indicates that this system does not contain a barrier, flood/ebb tidal deltas, mangroves and saltflat/saltmarsh, but does contain tidal sand banks. The loss of facies and habitats in this system is due to the intense development of canal estates. This development is likely to have had significant impacts on ecosystem function such as nutrient cycling, species diversity and physico-chemistry (turbidity and salinity), thus compromising ecosystem integrity.

4.5. Recommendations

- AGSO recommends that the facies (habitat) data contained within the OZESTUARIES database be utilised as a baseline to assess the current status of key coastal habitats (e.g. mangroves, saltmarsh/saltflat, and inter-tidal flats) for their monitoring and management.
- AGSO also recommends that the Deviation Index be used to:

    1. identify severely deviated systems for further investigation (i.e. those systems with a deviation score >3);
    2. rank all systems for comparative analysis between subclasses; and
    3. describe substrate abundance based on facies occurrence and areas, which then can be translated into a proxy for habitat integrity.

4.5.1. Refinement and Development of Deviation Index

In order to compare modified systems with pristine systems, a select group of pristine estuaries and coastal waterways that encompasses all subclasses should be mapped to capture the variability of geomorphic and sedimentary facies distributions of these systems. This will enable a reappraisal of the "cut off" score that currently distinguishes severely deviated systems from less deviated systems by placing it into a context that encompasses the variability in pristine systems. We strongly recommend that this is undertaken because the natural variability in pristine systems is currently unknown, and may vary significantly from the "idealised" situation as depicted in the four conceptual models.

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5. Sediment Geochemistry

5.1. Introduction

The sediments of estuaries and coastal waterways are the ultimate recipients of all materials discharged into them, including those from natural and anthropogenic sources. There are two main components of coastal waterway sediments: (1) materials sourced from the catchment, including terrestrial plants (organic matter), soil and mineral particles; and (2) *in situ* materials including minerals and organic matter (algal, macrophytes and other organic debris) formed during phototrophic growth. Decaying organic matter in sediments of coastal waterways is a potential source of nutrients. This is important because sediment-sourced nutrients may drive algal blooms in the overlying water column leading to eutrophication.

This component of the geoscience Audit was focussed on eutrophication. The parameters outlined here are required for ecosystem models, as indicators of key processes controlling eutrophication, and as sedimentary indicators of incipient eutrophication. Toxicants such as heavy metals, petroleum hydrocarbons and pesticides are not considered. AGSO was contracted to undertake the collection of geochemical data as part of NLWRA Theme 7, Tasks 2, 3 & 5. The following sediment geochemical data was collected and collated.

1. Sediment denitrification rates.
2. Sediment denitrification efficiencies.
3. Sedimentation rates.
4. Total organic carbon (TOC) total nitrogen (TN) and total phosphorus (TP) concentrations in sediment.

5.1.1. Definitions and Rationale

Denitrification Rates

Nitrogen is probably the most important nutrient controlling phototrophic growth in Australian estuaries and coastal waterways. Denitrification - the microbial conversion of N to nitrogen gas (N_2) within the sediment - is a self-cleansing mechanism by which water bodies can rapidly rid themselves of N derived from point- and non-point sources within the catchment (Berelson *et al.* 1998; Heggie *et al.* 1999a; Fredericks *et al.*, 2000). Nitrogen gas, produced in this way, is generally unavailable biologically, and is vented to the atmosphere.

The denitrification rates [DR] are calculated from the following equation.

$$DR = TDIN_p - DIN_m$$

Where $[TDIN]_p$ = predicted total dissolved inorganic nitrogen liberated during organic matter degradation and $[DIN]_m$ = the measured dissolved inorganic nitrogen liberated into overlying waters. Denitrification rates are reported in units of mmole m^{2} day $^{-1}$

Denitrification rates are important in the assessment of N budgets for coastal waterways. However, sediment denitrification efficiencies have far greater implications for management.

Denitrification Efficiencies

The sediment denitrification efficiency (DE%) is the sediment denitrification rate divided by total N remineralised in sediments (Berelson *et al.* 1998; Heggie *et al.* 1999a). Simply stated, the denitrification efficiency is the percentage of N liberated from the sediments as N_2 gas compared to the total N released from degrading organic matter. The N remineralised in sediments is computed as the product of the rate of carbon respiration and the C/N ratio of the organic matter being decomposed. The organic matter metabolised in the sediment is generally assumed to consist mainly of diatomaceous phytoplankton, which has a C:N:Si:P ratio of 106:16:17:1 (Redfield, *et al.* 1963; Froelich *et al.* 1979; Brzezinski, 1985). The C:N:P ratio is commonly referred to as the Redfield Ratio or the Redfield stoichiometry. Recent work on several estuaries by AGSO has confirmed that diatoms are the most abundant source of organic matter being recycled (Berelson *et al.* 1998; Heggie *et al.* 1999a; Fredericks *et al.* 2000).

Denitrification efficiencies (DE%) were calculated from the following equation.

$$(DE\%) = =[TDIN_p - DIN_m] * 100 / TDIN_p$$

The denitrification efficiency is emerging as a new process-indicator of sediment quality, and has implications for overlying water quality, and thus, for ecosystem health. For example, the Port Phillip Bay Environmental study found that denitrification efficiencies decreased with increased carbon respiration rates (Berelson *et al.* 1998; Heggie *et al.* 1999a). Where N loading to the sediments was high, most N was liberated as biologically available ammonia. AGSO have made similar observations elsewhere.

Sedimentation Rates

The sedimentation rate is the rate at which sediments accumulate in estuaries. It is expressed in units of cm yr^{-1} in this report. Sedimentation rates have implications for estuarine infilling, and are used in calculations of sediment, carbon and nutrient accumulation and burial rates. Sedimentation rates are important for modellers in assessing sediment and nutrient mass balances.

Sediment TOC, TN and TP

The TOC (total organic carbon), TN (total nitrogen) and TP (total phosphorus) concentrations in sediment are indicators of organic content of sediments. These “solid phase” nutrients may be used on their own, or in conjunction with denitrification efficiencies, to investigate risks to water quality. TOC, TN and TP are expressed in units of mg kg^{-1} in this report - division of this unit by 10,000, converts these mg kg^{-1} measurements to the more conventional unit of percent weight (%wt). The atomic ratios C:N and C:P were computed from the solid phase data in cases where the parameters were measured contemporaneously. Organic rich sediments have high TOC, TN & TP and are found in environments characterised by high productivity, little oxidation of organic matter by aerobic processes, and rapid burial and preservation of organic matter. These data, along with total sulphur (TS) in sediments, are indicators of the oxic/anoxic status of the environments.

5.2. Methodology

Denitrification rates and efficiencies, sedimentation rates, and sediment TOC, TN and TP concentrations were collated from data within AGSO, literature searches, and contributed by colleagues and the State authorities (Table 11 and Table 12). These data are included in the geoscience database OZESTUARIES. The methods used for collection and analysis are available in the designated reports or publications. Users of OZESTUARIES are advised to consult original data sources if they wish to use data for their own applications (see AGSO disclaimer).

Briefly, most data used in the computation of denitrification rates and efficiencies were derived from the benthic chamber studies of AGSO and those provided by MAFRI (Marine and Freshwater Resources Institute, Victoria). The latter data are from Westernport Bay, Gippsland Lakes, and Port Phillip Bay. Stoichiometric denitrification rates (mmol m^{-2} d^{-1}) were calculated using benthic flux data for DIN (dissolved inorganic nitrogen), as well as benthic flux data for one or other of total carbon dioxide (TCO_2), dissolved oxygen (O_2) or silicate (SiO_4) (Table 11 and Table 12). Silicate is a proxy for N from diatomaceous phytoplankton. Recent analysis of data from the Port Philip Bay (Murray & Parslow, 1999), has shown that a denitrification efficiency of about 40%, is indicative of escalating ammonia fluxes from the sediments in comparatively poorly flushed systems. We believe, a denitrification efficiency of 40% or less is indicative of a high risk of eutrophication. This interpretation is briefly described in Palmer *et al.* (2000a).

Sedimentation rates were measured by various methods, including ^{210}Pb, ^{137}Cs and ^{14}C dating. The methods often did not yield comparable results because of the different assumptions used in the model calculations.

The methods used for measuring TOC, TN and TP vary. However, only data from wet chemical methods or ignition techniques were included. Loss on ignition data (LOI) were not included because they are sometimes unreliable estimators of TOC (CSIRO Huon Estuary Study Team, 2000). The TOC, TN and TP data summarised in this report are average concentrations from the top 20-cm of sediment. This interval incorporates about 100 years of sediment accumulation at a typical sedimentation rate of 0.2 cm yr^{-1} (Table 13). Some of the data were from 1-2 cm slices of sediment, while others were bulk samples which integrated larger sediment slices.

We have included some data on TS concentrations in sediments. TS were not required by the NLWRA. However, TS is an indicator of sulfate reduction in sediments, which is related to the organic content in the environment and also has important implications for denitrification efficiencies.

Table 11. Summary of sediment data collated from Focus Estuaries ■ = data available

Focus Estuaries	Abbrvn	State	Type[1]	Denit.Rate[2]	Denit Efficiency[3]	TOC	TN	TP	Sed Rate
Broke Inlet		WA	WDE						
Brunswick River		NSW	WDD						
Burnett River	BU	QLD	TDD			■		■	
Clarence River		NSW	WDE						
Lake Alexandrina	LA	SA	WDE			■	■		■
Daintree River		QLD	TDD						
Darwin Harbour	DH	NT	DRV			■	■		
Derwent River		TAS	DRV						
Durras Lake	DL	NSW	WDE	■ a,d	■ a,d	■	■		
Embley River		QLD	TDE						
Fitzroy River		WA	TDD						
Gippsland Lakes	GL	VIC	WDE	■ a	■ a		■	■	
Hopkins River		VIC	WDD						
Huon River Estuary	HE	TAS	DRV			■	■		
Northern Spencer Gulf	SG	SA	TDE			■			
Ord River		WA	TDE						
Port River – Barker Inlet	POR	SA	TC			■			
Smiths Lake		NSW	CL						
Wilson Inlet	WI	WA	WDE	■ a	■ a	■	■	■	■
Yarra River		VIC	WDD						

[1]WDE = wave-dominated estuary; WDD = wave-dominated delta; TDE = tide-dominated estuary; TDD = tide-dominated delta; TC = tidal channel; DRV = drowned river valley; CL = coastal lagoons; CS = continental shelf; WW = waterway; and Bay = embayment

[2] Denitrification Rate = rate of N released as N_2 gas (moles N m^{-2} day^{-1}) estimated as follows:

a Denitrification rate = 16/106 * TCO_2 flux - DIN flux
(assumes a Redfield ratio of 106C:16N);

b Denitrification rate = 17/16 *Si flux - DIN flux
(assumes a diatomaceous source with 17Si:16N);

c Denitrification rate = 16/138 * O_2 flux – DIN flux
(assumes a Redfield ratio of 106C:16N and all NH_4^+ converted to NO_3-); and

d Denitrification rate = N_2 flux
(direct measurement)

Those data which had small TCO_2 fluxes (< 5 mmol m^{-2} d^{-1}) with large (~ 100%) error terms were excluded from the dataset prior to analysis. Because denitrification is a respiratory process, the benthic flux data, which were indicative of benthic production, were also eliminated. Data indicative of benthic production had one or more of the following: (i) benthic oxygen fluxes that were positive; (ii) benthic TCO_2 fluxes that were negative; or (iii) negative dissolved inorganic nitrogen (DIN) fluxes.

[3] Denitrification Efficiency = [N_2 flux/TIN flux * 100]. TIN = ammonia + oxidised N + N_2 gas (all expressed as moles of N).

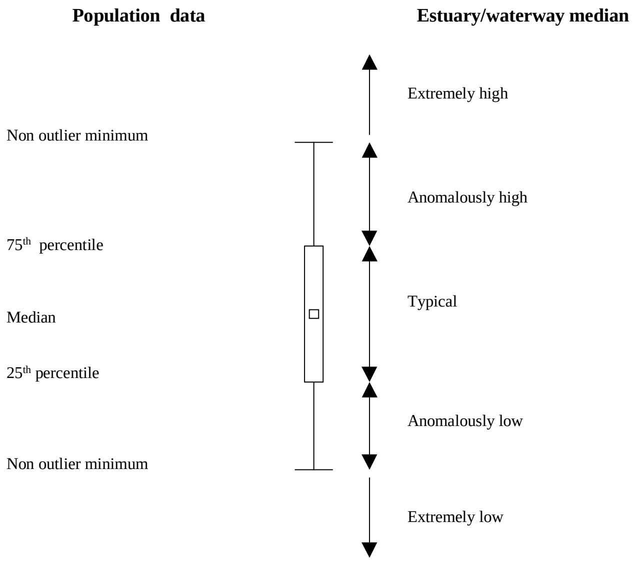
Table 12. Summary of sediment data collated from Non-Focus Estuaries ■ = data available

Non-focus estuaries	Abbrvn[1]	State	Type[2]	Denit.Rate[3]	Denit Efficiency[4]	TOC	TN	TP	Sed Rate
Albert Catchment	AR	QLD	TDD			■		■	
Beaufort Inlet	BI	WA	WDE			■	■	■	
Bega River Estuary	BE	NSW	WDE						■
Bowling Green Bay	BGB	QLD	BAY	b	b				
Burrill Lake	BL	NSW	WDE			■	■	■	
Canning	CAN	WA	WDE			■	■	■	
Clyde River	CRBB	NSW	DRV			■	■	■	
Cockburn Sound	CS	WA	WW				■	■	
Crookhaven River	CR	NSW	WDD			■	■	■	
GBR Shelf	GBRS	QLD	CS	b	b				
Gordon Inlet	GI	WA	WDE			■	■	■	
Hammersly Inlet	HI	WA	WDE			■	■	■	
Hardy Inlet	HAI	WA	WDE			■	■	■	
Harvey Estuary	HARV	WA	WDE						■
Hinchinbrook Channel		QLD	WW	d	d	■	■	■	
Irwin Inlet	II	WA	WDE			■	■	■	
Johnson River	JR	QLD	TC					■	
Lake Illawarra	LI	NSW	WDE			■	■	■	
Maroochy River	MARO	QLD	WDE			■		■	
Mary River	MARY	QLD	TDE			■		■	
Moore River Inlet	MRI	WA	WDD			■	■	■	
Moreton Bay	MB	QLD	WDE	a	a	■	■	■	
Moruya River	MOR	NSW	WDD			■	■	■	
Myall Lakes	MYL	NSW	WDE	a,d	a,d	■	■	■	■
Oldfield Inlet	OI	WA	WDE			■	■	■	
Parry Inlet	PI	WA	WDE			■	■	■	
Peel Inlet	PEEL	WA	WDE						■
Port Phillip Bay	PPB	VIC	BAY	a	a	■	■	■	■
Rock'ham/Missionary Bay	RMB	QLD	BAY	c	c	■	■	■	
Scott River	SCR	WA				■	■	■	
Shoalhaven River	SR	NSW	WDD			■	■	■	
St. Georges Basin	SGB	NSW	WDE			■	■	■	
St. Mary's	STM	WA	WDE			■	■	■	
Swan River	SWR	WA	WDE	a	a	■	■	■	■
Tomaga River	TR	NSW	WDD			■	■	■	
Torbay	TOR	WA	WDE			■	■	■	
Tuggerah Lakes	TL	NSW	WDE			■	■	■	■
Walepole Nornalup	WN	WA	WDE			■	■	■	
Wallis Lake	WL	NSW	WDE	a,d	a,d	■	■	■	
Warnbro Sound	WS	WA	WW				■	■	
Wellstead Inlet	WELI	WA	WDE			■	■	■	
Western Port	WP	VIC	BAY	a	a				

5.3. Key findings from the Sediment Geochemical Data Compiled in OZESTUARIES

We have undertaken a simple statistical analysis (maximums, minimums, medians, and percentiles) of the geochemical data (Table 13). Medians and percentiles were used in preference to means and standard deviations because most of the data were skewed.

We have developed some simple parameters that may assist managers assess "risk" to habitat integrity. The sediment characteristics of each estuary may be classified as being either typical, anomalous or extreme by comparing the data for each estuary or from each site to the entire range of values recorded in the database as follows:



With this approach, we can identify those estuaries and waterways which have atypical characteristics compared to the other water-bodies within the database. Ideally we should compare coastal waterways of the same class to identify outliers, however, the data set is too small for this at present. As a result of this, some types of coastal waterways (such as wave dominated estuaries) will be identified as atypical because of the presence/dominance of key facies.

In some instances we believe we can establish a link between sediment characteristics and risks to water quality (i.e. sediment denitrification) and can further establish specific values which represent significant risk to water quality. In other instances we have simply identified atypical estuaries and sites for further investigation.

Table 13. Summary of denitrification rates, denitrification efficiencies, sedimentation rates, TOC, TN & TP concentrations in sediment, and C:N and C:P ratios in sediment.

Data and Units	Estuaries[1] & waterways (n =)	Measurements (n =)	Max	Non-outlier Max[2]	Min	Median	50% range[3]
Denitrification rates (mmol m^{-2} d^{-1})	12	887	41.9	9.6	-7.7	2.8	1.5 - 4.8
Denitrification efficiencies (%)	12	887	134.4	135	-152	72	47.7 - 90.0
Sedimentation rates (cm yr^{-1})	8	31	1.75	0.85	0.01	0.2	0.11 - 0.43
TOC (mg kg^{-1})	36	2340	234,300	51,000	68	10850	3100 – 22600
TN (mg kg^{-1})	34	2369	13,000	3,600	6	840	230 – 1600
TP (mg kg^{-1})	36	2223	2,358	940	0	260	120 – 450
C:N	30	2267	474	45	0.5	13.6	10.1-24.3
C:P	31	2069	2,884	430	2	79.4	46.2-201.3

[1] Estuaries and coastal waterways (see Table 11 and Table 12).

[2] The non-outlier maximum. Outliers were determined by protocols outlined in STATISTICA™ (Statsoft Inc., 1995), using a default outlier coefficient (o.c.) value of 1.5. They include (i) data points > upper box value (UBV) + o.c. * (UBV – LBV) or (ii) data points < lower box value (LBV) – o.c. * (UBV – LBV). Upper box value and lower box values refer to the 75th and 25th percentiles respectively. Anomalous high values lie beyond the 75th percentiles.

[3] The range between the 25th and 75th percentiles that includes 50% of the data.

5.3.1. Denitrification Rates and Efficiencies

A summary of the denitrification rate data is presented in Figure 11a. A key finding from the analysis is that values from 1.5 to 4.8 mmol m^{-2} day^{-1} constitute the typical range for Australian estuaries and waterways (Table 13). Moreton Bay data is anomalously high in measured rates (median > 75% of all data). High rates were measured (but with large errors) in both seagrass and mangrove sites. The data from seagrass sediments suggest that these sandy sediments are robust, and efficiently turnover C and N in the sediments. This is because the plants pump oxygen into the sediments and the high permeabilites and mobility of these sandy sediments facilitate ventilation of sediments with oxygenated bottom waters. Therefore, sandy sediments of seagrass sites are characterised by high aerobic oxidation rates and low preservation rates of organic matter in sediments.

A summary of the denitrification efficiency data is presented in Figure 11b. Note that in this figure we have not plotted the usual statistical parameters. Rather, values of 40% and lower were identified as a “high risk” to sediment and water qualities (Palmer *et al.* 2000a), and values > 70% were indicative of “low risk”. The following observations were made from Figure 11b.

- While no estuaries or coastal waterways had median values <40%, there are six waterways (Bowling Green Bay, Gippsland Lakes, Myall Lakes, Durras Lake, Swan River Estuary and Westernport Bay) in which 25% of the measured denitrification efficiencies were less than 40%.

- Four of the six waterways with relatively low denitrification efficiencies are classified as wave-dominated estuaries (e.g. Gippsland Lakes, Myall Lakes, Durras Lake and Swan River Estuary; Table 11 and Table 12). The other environments are Bays.
- Two of the waterways with relatively low denitrification efficiencies (Gippsland Lakes and Swan River Estuary) have recognised problems with anthropogenic eutrophication, including toxic algal-blooms.
- Myall Lakes has low denitrification efficiencies in the mud facies and a salinity of <2ppt, at the time of sampling, and may be considered as a freshwater ecosystem.
- Durras Lake is classified as a pristine estuary but had some low denitrification efficiencies and was not eutrophic. However, the estuary was temporarily stratified and had anoxic bottom waters (Palmer *et al.* 2000b).
- Six estuaries have median denitrification efficiencies greater than 70% and are classed as at low risk (Great Barrier Reef Shelf, Port Philip Bay, Wilson Inlet, Missionary Bay, Wallis Lakes and Moreton Bay).

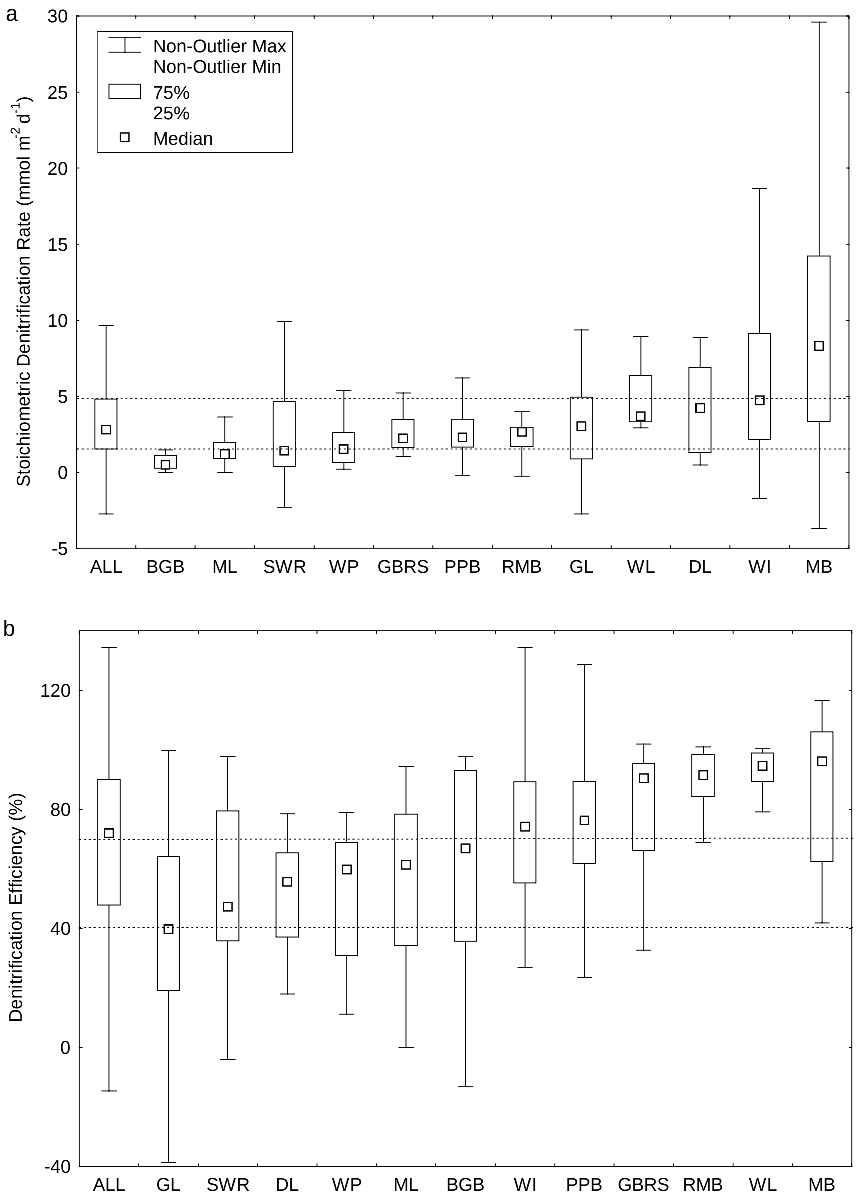


Figure 11. (a) Calculated denitrification rates and (b) efficiencies for Australian estuaries and coastal waterways.

The dotted lines in (a) mark the 25th and 75th percentiles of the total data set (all data), and the range within which 50% of the data lies. In (b) the dotted lines mark efficiencies of 40% (high risk) and 70 % (low-risk) respectively noted in Palmer *et al.* (2000a). Abbreviated names are: Bowling Green Bay. (BGB); Myall L. (ML); Swan River (SWR); Western Port (WP); Great Barrier Reef Shelf (GBRS); Port Phillip Bay (PPB); Rockingham/Missionary Bay (RMB); Gippsland L. (GL); Wallis L. (WL); Durras L. (DL); Wilson Inlet (WI) and Moreton Bay (MB).

5.3.2. Sedimentation Rates

A summary of the sedimentation rate data is provided in Figure 12. Key findings from the analyses are that the median sedimentation rate was 0.2 cm yr^{-1}, typically ranging between 0.11 to 0.43 cm y^{-1} (Table 13; Figure 12). There is no direct link between sedimentation and risks to sediment water quality. However, we note that Myall Lakes have anomalously high sedimentation rates and that a significant number of sites in the Swan Estuary have anomalously to extremely high sedimentation rates compared to other coastal waterways.

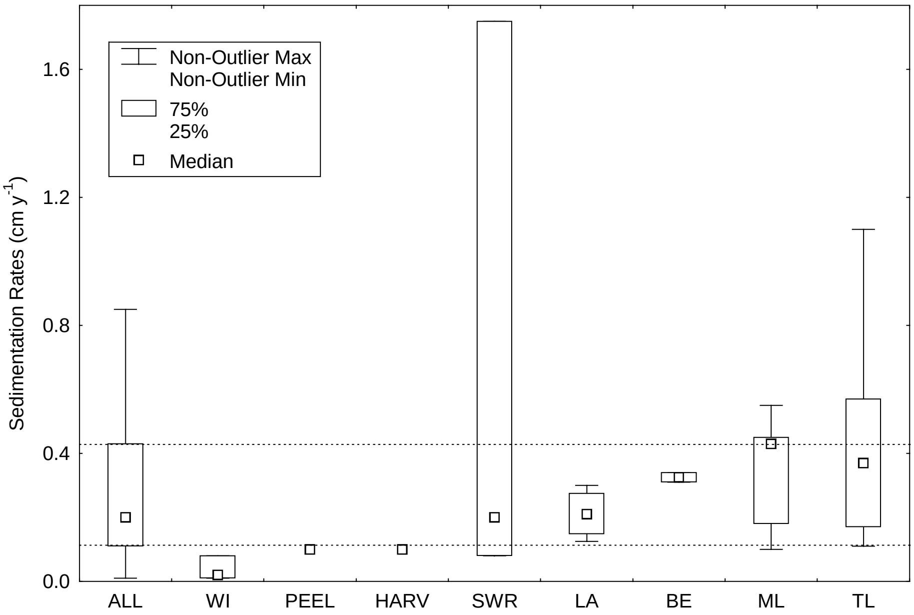


Figure 12. Sedimentation rates from Australian coastal systems.
The dotted lines mark the 25th and 75th percentiles of the total data set (ALL), and is the range within which 50% of the data lies. Abbreviated names are as follows: Wilson Inlet (WI); Peel Inlet (PEEL); Harvey Estuary (HARV); Swan River Estuary (SWR); Lake Alexandrina (LA); Bega River (BE), Myall Lakes (ML) and Tuggerah Lakes (TL).

5.3.3. TOC, TN & TP in Sediment

A summary of TOC, TN and TP data is presented in Figure 13. The typical ranges for solid phase parameters (Table 13) are as follows:

- TOC = 3,100 – 22,600 mg kg^{-1};
- TN = 230 –1600 mg kg^{-1}; and
- TP = 120 and 450 mg kg^{-1}.

Most of the waterways with anomalously high to extremely high values for TOC, TN and/or TP were wave-dominated estuaries, probably reflecting the accumulation of organic rich mud in central basin facies (Section 4). Estuaries and individual sites with high values of TOC, TN and TP are worthy of further investigation.

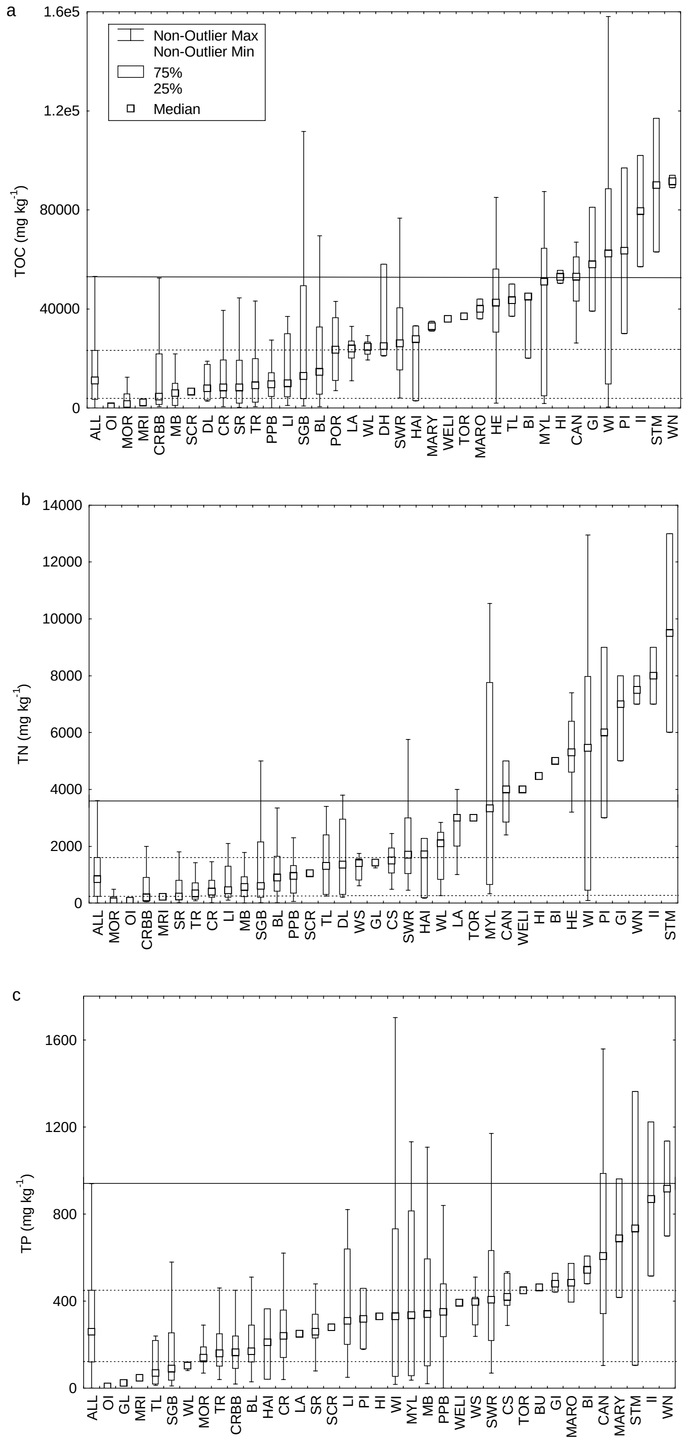


Figure 13. Sediment TOC (a), TN (b), and TP (c) from Australian estuaries and waterways. The dotted lines mark the non-outlier 25th and 75th percentiles respectively of the total data set, and include the range within which 50% the data lies. Medians falling above this zone are anomalously high. The solid line marks the non-outlier maximum of the total data set (ALL). Values found above these lines are extreme. Abbreviated names are as follows: Oldfield I. (OI); Moruya R. (MOR); Moore R. (MRI); Clyde River (CRBB); Moreton B. (MB); Scott R. (SCR); Durras L (DL); Crookhaven R. (CR); Shoalhaven R. (SR); Tomaga R. (TR); Port Phillip B. (PPB); L. Illawarra (LI); St. Georges B. (SGB); Burrill L. (BL); Port R. (POR); L. Alexandrina (LA); Wallis L. (WL); Darwin H. (DH); Swan R. (SWR); Hardy I. (HAI); Mary R. (Mary); Wellstead S. (WELI); Torbay (TOR); Maroochy R. (MARO); Huon R. (HE); Tuggerah L.: Beaufort I (BI); Myall L (MYL); Hammersley I (HI); Canning R. (CAN); Gordon I (GI); Wilson I. (WI); Parry I. (PI); Irwin I. (II); St. Mary's (STM); Spencer Gulf (SG); Burnett R. (BU); (TL); Walepole Nornalop (WN); Cockburn S (CS); and Warnbro S. (WS).

5.3.4. C:N and C:P Ratios in Sediment

The C:N and C:P data are summarised in Figure 14. The C:N ratio in sediments reflects a combination of the source of organic matter and the preferential loss of N during diagenesis. Fifty percent of the C:N observations fell in the range from 10.1 to 24.3; the median C:N ratio was 13.6, compared to the Redfield ratio for marine phytoplankton of 6.6 (Table 13; Figure 14a).

Sediments with low values of C:N (6.6 to 10) probably reflect a mainly phytoplankton source for the organic matter preserved in the sediment. Estuaries with higher C:N ratios probably reflect a greater input of organic matter from aquatic plants (such as seagrasses and macroalgae) and/or terrestrial material. Sediments with very high C:N ratios probably reflect a large input of terrestrial organic matter (e.g. lignin and cellulose) from terrestrial macrophytes which have high C:N ratios (Atkinson & Smith, 1983). Several southern NSW waterways, mostly wave dominated classes, have median C:N ratios of ~24, and probably have large proportions of terrestrial organic matter in their sediments.

Fifty percent of the C:P ratios fell in the range from 46.2 to 201.3 (Table 13; Figure 14b); the median ratio was 79.4 compared to the Redfield ratio for marine phytoplankton of 106. Only about 30% of the data are close to the Redfield stoichiometery. Another 30% of the data show enrichment of P in sediments relative to C (e.g. C:P <106:1).Two coastal waterways in particular (Moreton Bay and Moruya River) have anomalously low C:P ratios (median values <25th percentile of population) that may warrant further investigation. Low C:P ratios imply the presence of a large pool of potentially available phosphorus within the sediments.

There are at least two reasons why phosphorus may be enriched in sediment relative to the Redfield stoichiometry. First, P is particle reactive and diagenetic reactions between P and Fe have been shown to trap P within surficial oxic layers of marine sediments (Heggie *et al.* 1999b). This fractionation at the sediment water interface between C and P enriches P in near surface sediments while C is released to the overlying waters as TCO_2. Second, P is transported from catchments to estuaries mainly in particulate phases, adsorbed to iron oxyhydroxides and other oxidised Fe species, and when buried represents a catchment source of P that is not derived from in situ organic matter degradation (Norrish & Rosser, 1993).

More than 50% of the data are relatively depleted in phosphorus compared to the P contents of typical marine organic matter. This tendency is particularly exaggerated in data from some NSW wave-dominated estuaries (St Georges Basin, Wallis Lake and Tuggerah Lakes) and WA wave-dominated estuaries (Hardy, Gordon and Parry Inlets, Walepole Nornalup, and St Mary's River).

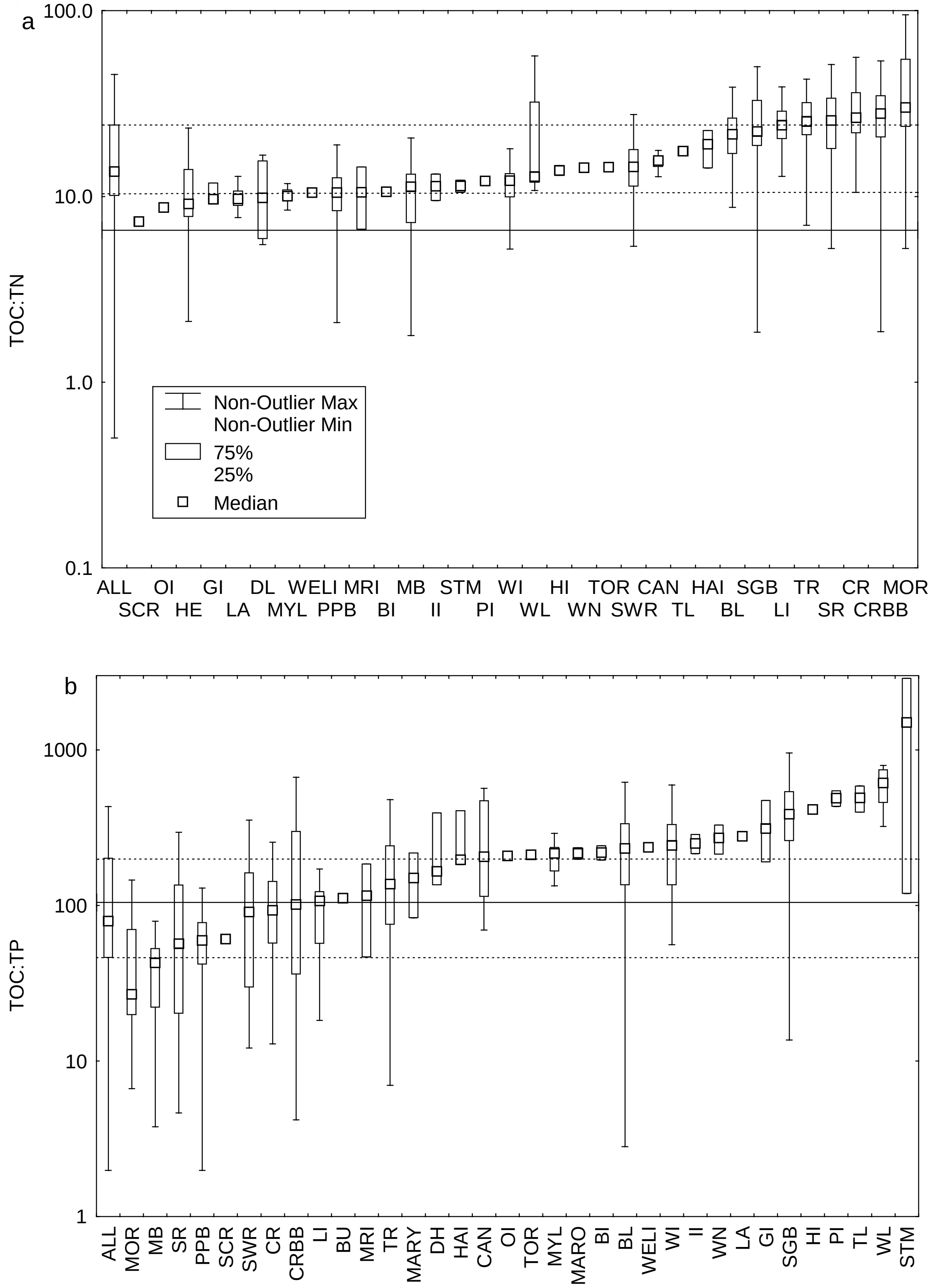


Figure 14. C: N ratios (a) and C: P ratios (b) for Australian estuaries.
The dotted lines mark the 25th and 75th percentiles of the total data sets (e.g. ALL), and the range within which 50% of the total data falls lies. The solid lines show the Redfield stoichiometry (e.g. C: N = 6.6 (a) and C: P =106 (b)). Abbreviated names are as follows: Scott R. (SCR); Oldfield I. (OI); Huon R. (HE); Gordon I (GI); Durras L (DL); Myall L (MYL); Wellstead S. (WELI); Port Phillip B. (PPB); Moore R. (MRI); Beaufort I (BI); Moreton B. (MB); Irwin I. (II); St. Mary's (STM); Parry I. (PI); Wilson I. (WI); Wallis L. (WL); Hammersley Inlet (HI); Torbay (TOR); Swan R. (SWR); Canning R. (CAN); Tuggerah L. (TL); Hardy I. (HAI); Burrill L. (BL); St. Georges Basin (SGB); L. Illawarra (LI); Tomaga R. (TR), Shoalhaven R. (SR); Crookhaven R. (CR); Clyde River (CRBB); Moruya R. (MOR); Walpole Nornalup (WN); L. Alexandrina (LA); L. Mary R. (Mary); Burnett R. (BU); Darwin H. (DH); and Maroochy R. (MARO).

5.4. Applications

5.4.1. A framework, and indicators, to assess sediment and water qualities

We believe some potential indicators of sediment and water qualities emerge for the prediction and understanding of eutrophication and nuisance algal occurrences. However, these data are most applicable to wave-dominated classes of estuaries and waterways. There are insufficient data to test their application for the tide-dominated classes.

We assemble data in Table 14, to demonstrate a proposed framework for this type of assessment. The data is constructed according to simple statistical analysis of the geochemical dataset and assigns colours according to the following protocols.

1. Denitrification efficiencies of <40% are highlighted in red and are believed to be indicative of a high risk to water quality and habitat integrity. Denitrification efficiencies between 40% and 70% are indicative of a "moderate" risk to water quality and are highlighted in yellow. We have nominally chosen a denitrification efficiency of >70% as a low risk to water quality. These low-risk data are highlighted in blue

2. Estuaries with median values of TOC, TN and TS (total sulphide measured in sediment) in excess of the non-outlier maximum for the total data sets (see Table 13) are highlighted in red, and are deemed extreme values. Median concentrations that are in excess of the 75th percentile of all the data, and less than the non-outlier maximum concentration, are highlighted in yellow as anomalous concentrations. Medians falling within the 25th and 75th percentiles of all data are typical and are highlighted in blue.

3. We have also included in the table observations of the presence of nuisance algal occurrences including blue-green algal blooms, dinoflagellates and swimming closures.

The occurrence of low denitrification efficiencies within the sediments of an estuary is the most important indicator of water-quality risk, as there is a direct link between this parameter and the recycling of plant available nitrogen. There is a less direct link for other sediment parameters, however, sediments with high carbon, nitrogen and sulphur are often associated with highly productive environments with anoxic sediments. High concentrations of organic carbon, nitrogen, and phosphorus and TS in sediments are therefore considered as indicators of an elevated risk to water quality.

Table 14. Example of how % denitrification efficiency and select sediment parameters may be used to assess ‘risk’ to water quality and habitat integrity

Variable	GL	SWR	WP	DL	ML	WI	PPB	WL	MB	GBR Shelf	RMB
Denitrification efficiency (%)	39	47	59	56	61	74	76	94	96	90	91
TOC (mg kg^{-1})		15850		7950	51000	62350	9535	24701	6000		
TN (mg kg^{-1})		1700		1350	3331	5788	980	2102	554		
TS (mg kg^{-1})		6780			9700	23700		2608	15200		
Observations*	BG, D	BG, D, SC			BG, D, SC	D	LBG	D	BG		

* Based on our own observations: BG= Blue-green algae, D = dinoflagellate occurrences; SC = swimming closures; and LBG = local blue green algae (additional inputs from local authorities would be helpful).

Abbreviated names refer to Gippsland Lakes (GL), Swan River (SWR), Western Port (WP), Durras Lake (DL), Myall Lakes (ML), Wilson Inlet (WI), Port Phillip Bay (PPB), Wallis Lake (WL), Moreton Bay (MB), Great Barrier Reef Shelf (GBR), and Rockingham-Missionary Bay (RMB).

The indicated concentrations are the median concentrations found in the different estuaries.

5.4.2. Integrated Assessments.

The previous sections outline a preliminary framework to assess estuarine risk to nuisance algal bloom occurrences and eutrophication. The dataset for some estuaries is incomplete and a complete assessment cannot be made from these limited data. In general, a combination of red-yellow colourations in Table 14 indicates poor sediment conditions and we believe high to medium risk for nuisance algal blooms and eutrophication; yellow to blue combinations represent medium to low risk, while blues represent typical values of these estuarine parameters and represent low risk. Despite the incompleteness of these data to date, some features emerge.

The Gippsland Lakes have a median denitrification efficiency less than the critical value of 40% that we have identified. Although there are not data available for the sediments, they are reported to be fine-grained black muds smelling of hydrogen sulphide. The low denitrification efficiencies combined with anoxic sediments and large pools of TOC, TN and TS in sediments suggest a high risk scenario.

The Swan River also has relatively low denitrification efficiencies and already experiences nuisance blooms. While the pool size of carbon and nutrients in the Swan are ranked as typical and anomalous respectively, the denitrification efficiency is in the medium risk category. The low denitrification efficiencies may reflect overlying water stratification and oxygen limitation to the sediments, which controls N cycling.

The Myall Lakes has a predominance of yellow-red combinations and is ranked medium-high risk. The Bombah Broadwater section of the Myall lakes has been experiencing blue-green algal blooms and areas have been closed to swimming for a year or more. Similarly, Wilson Inlet is dominated by a combination of yellow-red occurrences and is also ranked medium – high risk. Wilson Inlet presents extreme values of carbon and nitrogen concentrations, however, the denitrification efficiency indicates that nitrogen is recycled from the sediments primarily as N_2 gas. Seasonal data showed low denitrification efficiencies occurred at some times of the year. Overall, the variable denitrification efficiency, large nutrient pools present in the sediments indicate that Wilson Inlet is at medium to high risk.

Data for Wallis Lake is highlighted by a combination of yellow-blue colourations (Table 14), suggesting medium to low risk scenarios. Wallis Lake has anomalous levels of TOC and TN in sediments, but the denitrification data indicate that N is being recycled primarily as N_2 gas.

Only Port Philip Bay and Moreton Bay were dominated by blue colourations, which represent low risk scenarios. Port Phillip Bay has been found to have good water quality and this has been maintained by efficient recycling of N in sediments. Furthermore, there have been few nuisance algal blooms but exotic species have made appearances in the Bay (Harris *et al.* 1996). Moreton Bay has recently experienced blue-green algal blooms, but these are probably driven by runoff events and not by nutrients derived from processes operating in the sediments.

5.5. Recommendations

The recommendations summarised here represent a distillation of the key findings, literature searches, viewpoints of colleagues, and from our own research.

5.5.1. Denitrification Efficiencies

Denitrification efficiencies are evolving into useful indicators of sediment- and water quality, and therefore of habitat integrity, in wave-dominated ecosystems (e.g. those dominated by seagrasses and phytoplankton). We recommend the following as denitrification efficiency protocols:

- if denitrification efficiencies are <40% then water quality is 'at risk';
- if denitrification efficiencies are > 40% and < 70% then sediment quality and water quality are at 'moderate risk'; and
- If denitrification efficiencies are > 70% then sediment and water quality are 'good', with little risk of degradation under current and existing conditions.

Potential threats to efficient denitrification include the following and should be monitored:

- water column stratification;
- low dissolved oxygen in the water column, specifically the bottom waters;
- high and easily metabolised TOC and TN loads (e.g. high TCO_2 fluxes);
- poor ventilation of sediments by physical and bioactive processes;
- sulphate reduction (Joye and Hollibaugh, 1995: evidence includes high pore-water ammonia; sediment TS); and
- sewage and toxicant impacts including heavy metal pollution (Sakadevan *et al.* 1999).

However, there is a deficit of knowledge regarding denitrification efficiencies on an Australian-wide basis, and in systems other than wave-dominated estuaries and embayments. For example, only 13 coastal systems were found to have suitable data to estimate this parameter (Table 11 and Table 12). More data is needed from individual facies (Section 4) and across the full range of subclasses (Section 2), so that baseline conditions appropriate to the individual systems can be established.

We recommend further research into denitrification and its usefulness as a potential indicator of sediment and water quality. Furthermore, the examination the 'nitrogen cycle' in sediments, N fixation – denitrification balances in estuaries, and the effects of salinity on denitrification efficiencies are also warranted.

5.5.2. Easily Measured Indicators (or proxies) of Estuarine Sediment Conditions

We recommend the further collection of those data already compiled, across the different facies types (Section 4), since they are easily measured indicators of estuarine sediment conditions.

- TOC and TN contents are indicators of organic rich vs. organic poor environments .
- TOC:TN ratios are a crude indicator of the source of organic matter in sediments (terrestrial, macrophytic vs. marine algal).
- TP contents and TOC:TP ratios may be indicators of P enrichment in sediments, efficient P trapping by sediments or catchment inputs of P.
- TS is an indicator of sulphate reduction which affects denitrification efficiency and TS is also an indicator of organic rich vs. organic poor environments.
- Sedimentation rates should also continue to be compiled. As more data are collected, rates characteristic of the different subclasses may emerge and serve as useful guides to managers in assessing infilling rates, including catchment erosion rates and infilling from the sea.

Furthermore we recommend the collection of additional data, to supplement those above, so that a more robust suite of indicators of sediment conditions can be established. These include the following.

- The presence of dissolved oxidised N (nitrate + nitrite, NO_x) in sediment pore-waters is indicative of oxic to suboxic conditions and denitrification, while undetectable NO_x is indicative of suboxic to anoxic conditions.
- Low ammonia concentrations in pore-waters are generally indicative of oxic to suboxic conditions, while high levels are indicative of anoxic conditions and sulphate reduction.
- Biomarkers of rural and urban runoff should be included and used as aids to identify sources of anthropogenic pollutants.
- The relationship between carbon and nutrient loads to an estuary and solid phase TOC, TN and TP in the sediment should be quantified.
- Sediment carbon and nutrient accumulation and burial rates should be compiled.

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6. Conceptual Models of Estuarine Function

6.1. Introduction

AGSO was contracted to undertake the development of conceptual models under Tasks 2 & 3 of the contract document between AGSO and the CSIRO/NLWRA. The two-dimensional models in Section 2 (Figure 5 to Figure 8) illustrate the basic form of wave-dominated estuaries, wave-dominated deltas, tide-dominated estuaries, and tide-dominated deltas. The mapping and statistical analyses in Section 4, shows quantitatively, that the different subclasses of estuaries and coastal waterways have distinct facies suites as a function of different balances of physical forces (e.g. wave-, tide- and river-energies). In this section, three-dimensional conceptual models illustrating facies (habitat) and both sediment transport and nitrogen cycling pathways have been developed for each of the above subclasses. The nutrient terms, and some discussion pertaining to the importance of nitrogen dynamics in Australian coastal waterways are provided in Section 5.

The conceptual models were constructed through reviews of literature (Section 8.4) and through fruitful discussions with colleagues. They were developed as management tools to demonstrate links between form (geomorphology) and function (biogeochemical processes) in Australian estuaries and deltas. Each of the subclasses may be susceptible to different kinds of stresses because of intrinsic differences. Therefore, by integrating both physical and biological processes, the conceptual models present a simple, yet holistic picture of these coastal systems, and a foundation through which to custom-build indicators of integrity. The models are preliminary, and we anticipate that they will facilitate discussion between managers, environmental officers and scientists. They are intended to be living documents that will evolve with feedback, and we encourage this.

6.2. Key Findings

Three-dimensional conceptual models illustrating sediment transport processes and nitrogen cycling through the facies suites of a wave-dominated estuary, a wave-dominated delta, a tide-dominated estuary, and a tide-dominated delta are presented in Figure 15 to Figure 22.

Two-dimensional models depicting nitrogen and phosphorus recycling under conditions of high- and low- nutrient loadings, in the central basin facies, are also provided in Figure 23 to Figure 26. Summary tables describing habitats and key processes operating in each facies are presented in Table 15 and Table 16.

6.2.1. Wave-Dominated Estuary – 3D Sediment Model

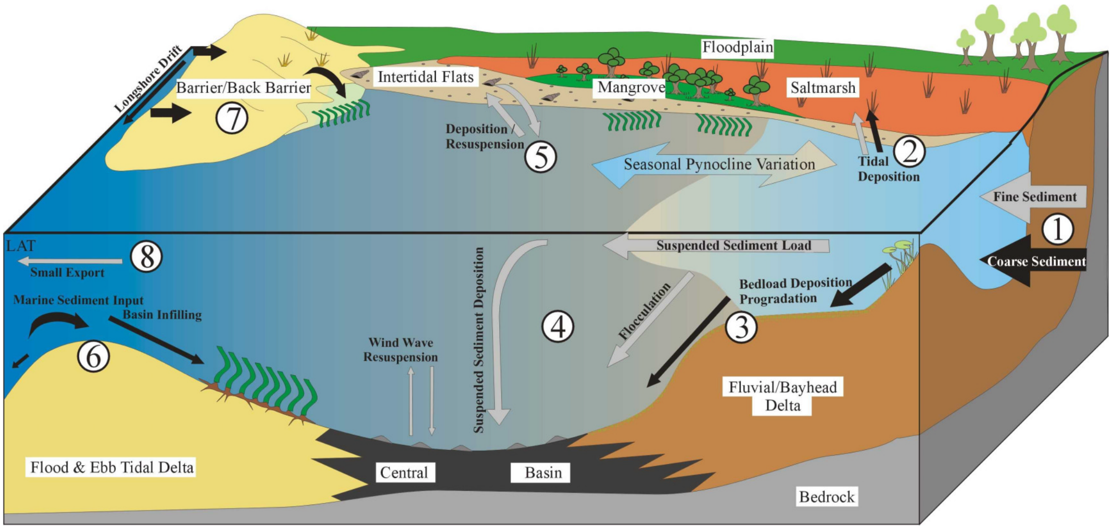

Figure 15. Wave-dominated estuary – 3D Sediment Model.

1. Fine and coarse sediment enter the estuarine system from the catchment, depending on river flow and sediment supply
2. Some deposition of fine sediment occurs on flanking saltmarshes, due to the baffling effect of saltmarsh vegetation. Coarser sediment also accumulates here during flood/high flow conditions.
3. As a result of a rapid decrease in transport capacity (flow velocity), the majority of coarse material is deposited within the fluvial-bayhead delta facies. The bayhead delta gradually progrades into the central basin of the estuary.
4. Fine suspended sediment is transported into the central basin, where deposition occurs, depending on wave conditions and tidal energy with the estuary. Flocculation (particle aggregation due to changes in salinity) is also an important process here, allowing fine particles to settle from the water column. Some resuspension of the fine sediment can occur.
5. Fine sediment undergoes both deposition and erosion in intertidal flats environments, aided by biological activity such as burrowing. A general trend of slow growth of intertidal flats is seen in most wave-dominated estuaries.
6. In the entrance of the estuary, sedimentary processes are dominated by infilling with coarse sediment from a marine source. This coarse sediment builds out into the central basin. Export of some suspended sediment into the marine environment also occurs, particularly during flood/high flow conditions.
7. Coarse sediment derived from the marine environment is driven along the coast by strong wave energy, forming a distinctive barrier at the entrance. Washover deposits of coarse sediment from the barrier into the central basin occurs during storm events.
8. Almost all coarse sediment, and the majority of fine sediment is trapped and deposited within the estuary.

6.2.2. Tide-Dominated Estuary – 3D Sediment Model

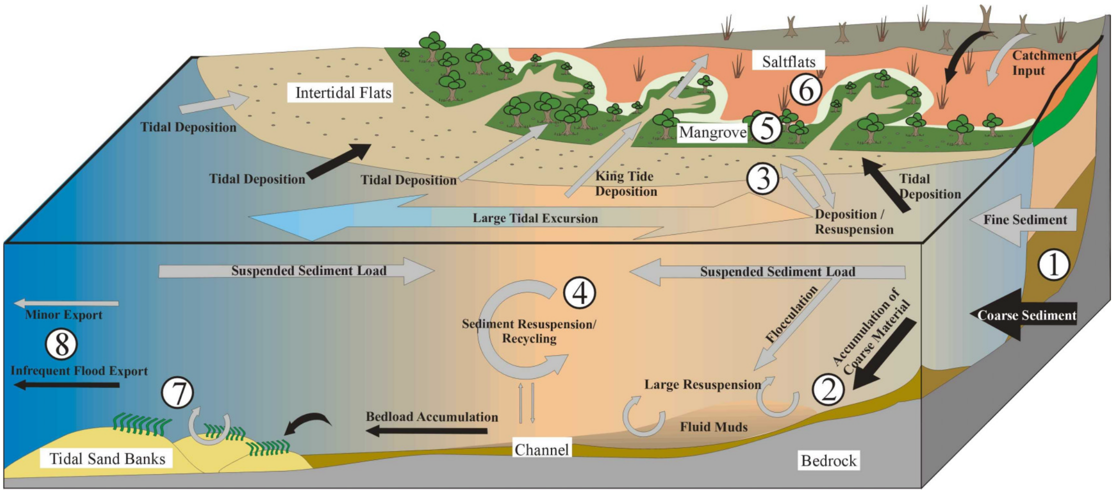

Figure 16. Tide-Dominated Estuary – 3D Sediment Model.

1. Fine and coarse sediment enter the estuary from the catchment, depending on river flow and sediment supply
2. The majority of coarse material is deposited at the head of the estuary, due to a reduction of river flow velocity and therefore sediment transport capacity. Some reworking and redeposition of material by tidal currents also occurs.
3. Fine sediment undergoes both deposition and erosion in intertidal flats, aided by biological activity such as burrowing. Coarser material is also deposited on flanking environments by tidal currents and flood events. A general trend of slow growth of intertidal facies is observed.
4. Large quantities of suspended sediment are characteristic of tide dominated estuaries, and a dynamic relationship exists between deposition, flocculation, resuspension and transport of sediment. Quantities of fine and coarse sediment can pool temporarily within the channel.
5. Mangrove facies, with interspersed tidal drainage channels, commonly flank tide-dominated estuaries, and serve as a depocentre for fine and flocculated sediment. Tidal asymmetry (high energy flood and lower energy ebb), baffling by vegetation, and percolation of tidal water through animal burrows result in the deposition of fine sediment, and allow for the replacement of intertidal flats by mangroves.
6. Saltflat facies experience inundation by king tides, and some deposition of fine sediment can occur. Ebb tide waters often flow through tidal drainage channels. Quantities of fine and coarse sediment can also be derived from the catchment and deposited during storm events.
7. Accumulation of coarse bedload material can occur within the mouth of the estuary, forming tidal sand banks. This material tends to be unstable and is redistributed in large quantities during storms. Seagrasses are able to colonise and fix the sediment to an extent, also mangrove colonisation can occur on larger sand banks.
8. Very little sediment is exported from the estuary overall, due to net landward transport driven by tidal action. The majority of sediment export occurs during flood events.

6.2.3. Wave-Dominated Delta – 3D Sediment Model

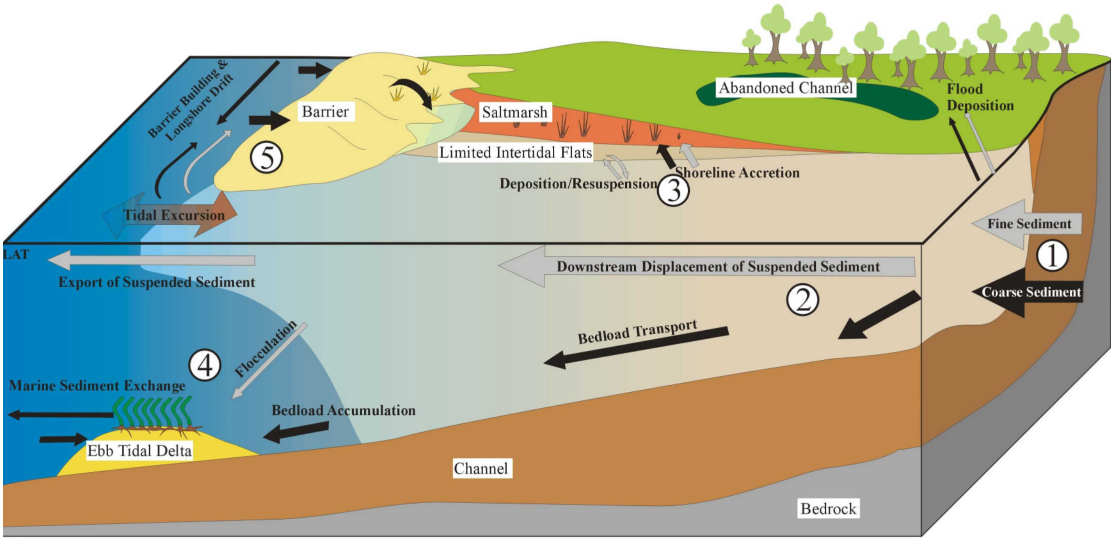

Figure 17. Wave-Dominated Delta – 3D Sediment Model.

1. Fine and coarse sediment enter the estuarine system from the catchment, depending on river flow and sediment supply.
2. Suspended fine sediment, and coarse sediment is moved along the bottom of the channels downstream (as bedload), due to unimpeded river flow within the delta. Some lateral deposition of both types of sediment can occur, including the development of coarse sediment point bar deposits, and deposition of fine sediment (during flood events) on the floodplain.
3. Limited deposition and resuspension occurs on intertidal flats and saltmarshes if present.
4. The majority of deposition occurs at the mouth of the delta, and results in the export of sediment into the marine environment. Fine suspended sediment is generally exported, with some flocculation occurring over the salinity gradient. Bedload accumulation of coarser sediment can occur, and may form an ebb tidal delta within the entrance of the estuary.
5. High wave energy results in the distribution of sediment along the coastline proximal to the delta, forming a barrier bar.

6.2.4. Tide-Dominated Delta – 3D Sediment Model

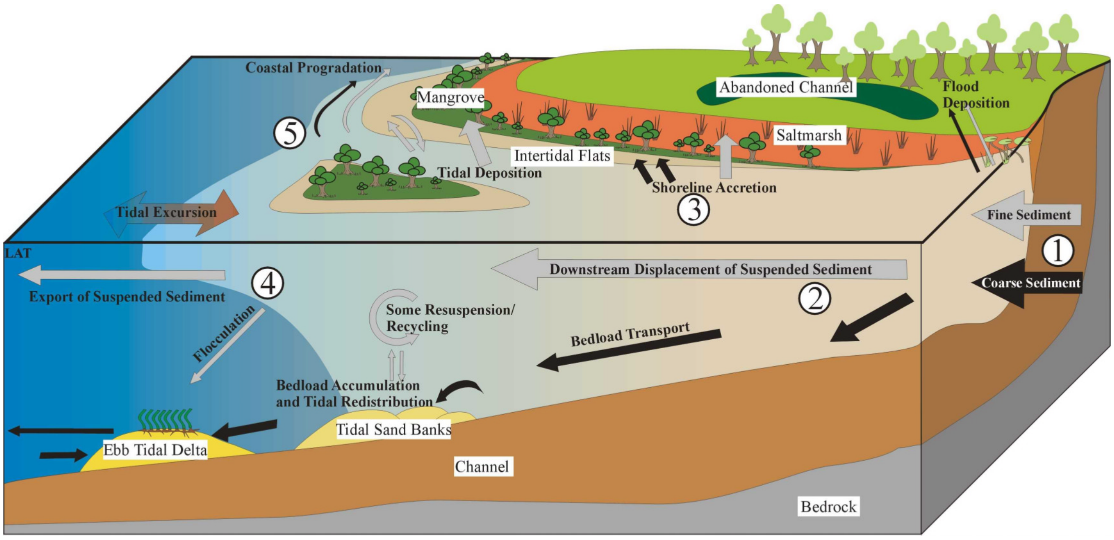

Figure 18. Tide-Dominated Delta – 3D Sediment Model.

1. Fine and coarse sediment enter the estuarine system from the catchment, depending on river flow and sediment supply.
2. Suspended fine sediment, and coarse sediment (as bedload) are transported downstream. Some lateral deposition of both types of sediment can occur, including the development of coarse sediment point bar deposits, and floodplain deposition of fine sediment (during flood events).
3. Fine and coarse sediment are deposited onto the flanking intertidal flats, mangrove and saltmarsh environments, in a similar manner to processes described for tide dominated estuaries.
4. The majority of deposition occurs at the mouth of the delta, and results in the export of sediment into the marine environment. Fine suspended sediment is generally exported, with some flocculation occurring over the salinity gradient. Bedload accumulation of coarser sediment can occur, and may form an ebb tidal delta within the entrance of the estuary, and tidal sand banks may form due to sediment resuspension and recycling.
5. Sediment transported by tidal currents accumulates on the delta front, causing the gradual progradation of the delta.

6.2.5. Wave-Dominated Estuary – 3D Nitrogen Model

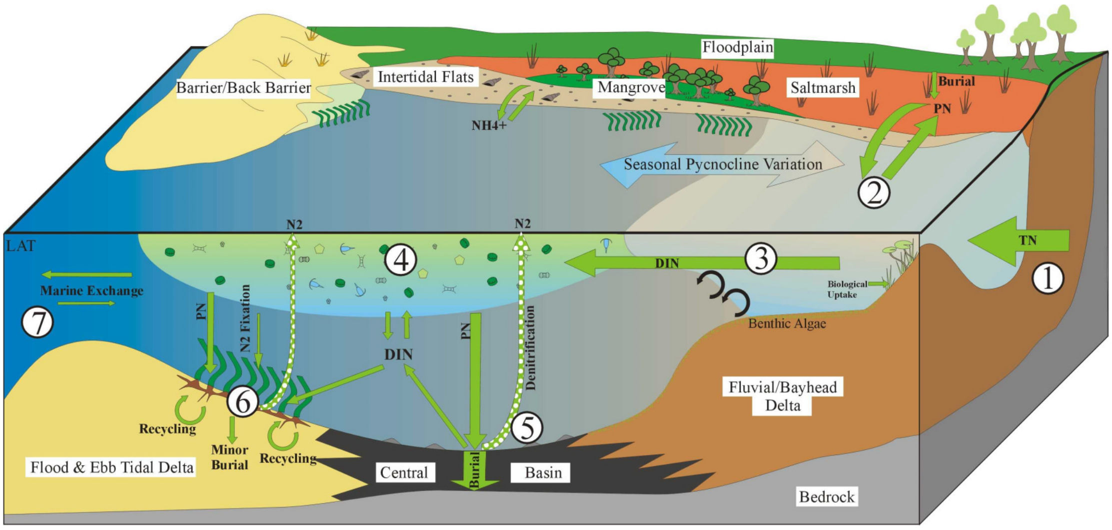

Figure 19. Wave-Dominated Estuary – 3D Nitrogen Model.

1. Nitrogen (particulate and dissolved; TN) enters the estuarine system from point- and non-point sources from within the catchment.
2. Some deposition and burial of particulate nitrogen (PN) occurs on flanking saltmarshes, due to the baffling effect of saltmarsh vegetation. Burial and resuspension of PN and dissolved inorganic nitrogen (DIN) can also occur within intertidal flats. Some PN may be deposited and buried within the fluvial bayhead delta.
3. The DIN is transported into the central basin of the estuary, with biological uptake (phytoplankton, seagrass and macrophytes) occurring along the way if residence times are long enough, and if temperature and light levels are suitable.
4. PN is deposited in the sediment as phytoplankton and faecal pellet debris.
5. Decomposition of organic matter within the sediment produces dissolved inorganic nitrogen (potentially available for further plant/phytoplankton growth). Denitrification within the sediment converts nitrate to N_2 gas. The N_2 escapes from the system to the atmosphere. Some of the PN deposited into the central basin sediment is buried.
6. Seagrasses take up DIN from the water column, and from the sediment pore-waters. The pore-water DIN is derived from the metabolism of phytoplankton, seagrass and other organic matter debris. The seagrass debris therefore, in part, is “recycled” back to the plants. N-fixation occurring in the root-zone contributes additional DIN to this pool. Denitrification is an important process in seagrass meadows. Sandy sediments are permeable, hence can be ventilated by oxygen-rich overlying waters resulting in efficient remineralisation of organic debris (mostly by denitrification) with little preservation of organic matter.
7. Where residence times are long, only very small quantities of the TN load are exported to the marine environment. Export may be significant during flood events.

6.2.6. Tide-Dominated Estuary – 3D Nitrogen Model

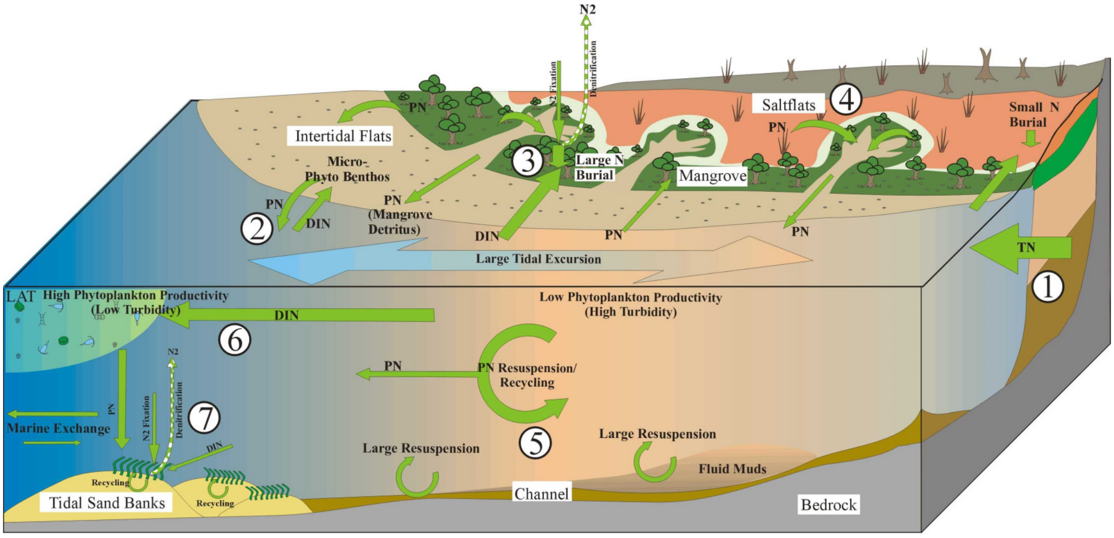

Figure 20. Tide-Dominated Estuary – 3D Nitrogen Model.

1. Nitrogen (particulate and dissolved; TN) enters the estuarine system from point- and non-point sources from within the catchment.
2. Tidal movements on the flanks of the estuary transport particulate nitrogen (PN) and dissolved inorganic nitrogen (DIN) onto the intertidal flats, where some of the DIN is converted to PN through the activity of benthic micro-algae.
3. Mangrove sediment is a net sink for DIN and PN. Nutrient uptake is driven by high rates of plant growth and microbial activity. N-fixation is active in the root-zone and contributes to the DIN pool. Some N is liberated to the atmosphere as N_2 gas through denitrification. PN is processed by biota such as crabs, or it is exported to the coastal waters as leaf litter and fine particulate matter. In the coastal waters it may be redistributed during ebb tides.
4. Small amounts of PN are buried in saltflats during king tides. Most PN is exported back into the estuarine channel during the ebb tide.
5. PN and DIN exist within the water column. However due to turbidity, phytoplankton productivity is limited. Circulation and re-suspension of PN occurs in this zone. PN is probably reworked during the resuspension process, and DIN can be remineralised to the water column.
6. A proportion of the DIN reaches the less turbid zone at the mouth of the estuary where phytoplankton convert it to PN.
7. Seagrasses, which colonise the tidal sand banks near the mouth of the estuary, also process DIN, in the same manner as that described for wave dominated estuaries.
8. Typically, only moderate quantities of the TN load are exported to the marine environment, however, this may be significant during flood events.

6.2.7. Wave-Dominated Delta – 3D Nitrogen Model

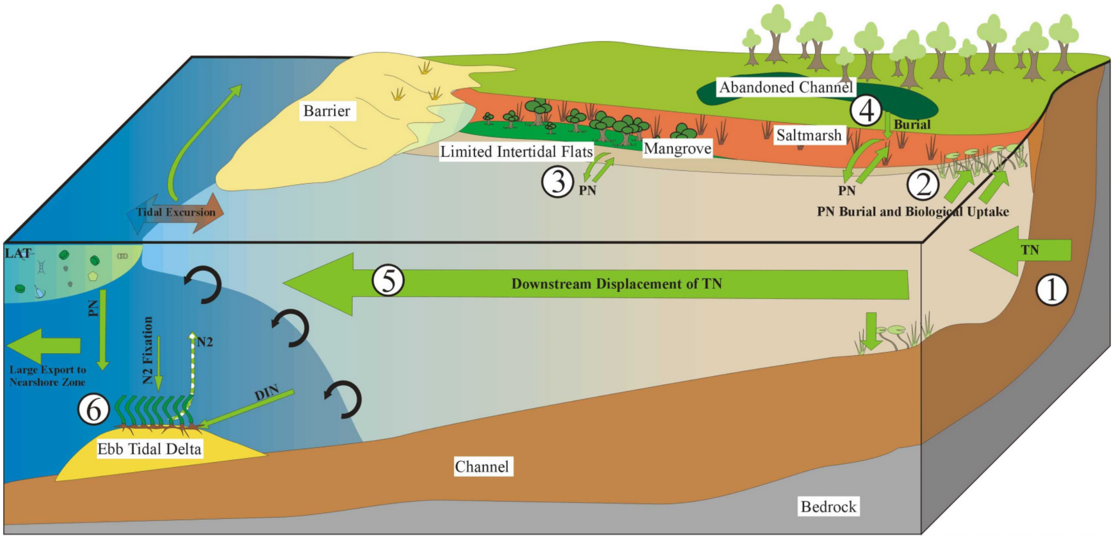

Figure 21. Wave-Dominated Delta – 3D Nitrogen Model.

1. Nitrogen (particulate and dissolved; TN) enters the estuarine system from point- and non-point sources from within the catchment.
2. Biological uptake (plants) of dissolved inorganic nitrogen (DIN) occurs on the flanks of the river channel.
3. Intertidal flats and mangrove facies often occur, and can influence nutrient dynamics as per tide-dominated estuaries. However, they may play a smaller role.
4. Particulate nitrogen (PN) is buried in saltmarsh facies during king tides, or during periods of high fluvial flow. Some PN is exported back into the estuarine channel during the ebb tide.
5. The majority of the river-borne TN is transported from the delta by strong downstream displacement. Lower turbidities allow for its assimilation by phytoplankton in the marine environment. DIN uptake by seagrass growth may occur at the mouth of the delta (see also wave dominated estuary).

6.2.8. Tide-Dominated Delta – 3D Nitrogen Model

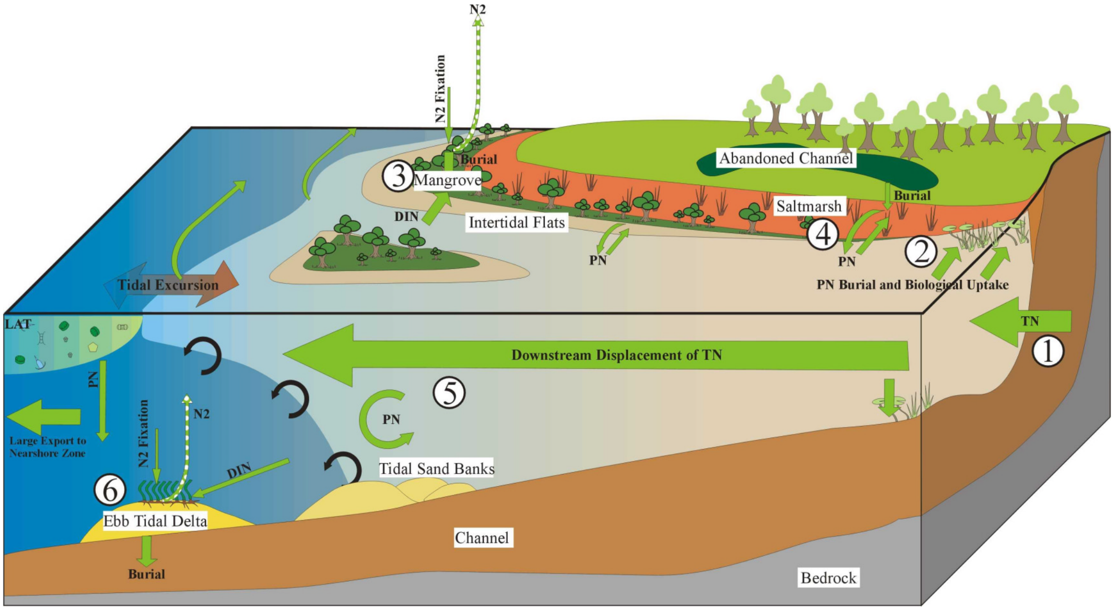

Figure 22. Tide-Dominated Delta – 3D Nitrogen Model.

1. Nitrogen (particulate and dissolved; TN) enters the estuarine system from point- and non-point sources from within the catchment.
2. Biological uptake (plants) of dissolved inorganic nitrogen (DIN) occurs on the flanks of the river channel and may be an important sink for N within the delta.
3. Intertidal flats and mangrove facies influence nutrient dynamics in a similar way to that described for tide-dominated estuaries.
4. Particulate N (PN) is buried in saltmarsh facies during king tides, or during periods of high river flow. Some PN can be exported back into the estuarine channel during the ebb tide.
5. The majority of the TN load is transported from the delta by strong downstream displacement. Lower turbidities allow for its assimilation by phytoplankton in the marine environment. Some circulation and re-suspension of nutrients also occurs.
6. DIN uptake by seagrass growth may occur at the mouth of the delta (see also wave dominated estuary).

6.2.9. Estuarine Function and Nutrient Loadings in Wave-Dominated Estuaries

Conceptual models of nitrogen (N) and phosphorus (P) dynamics in wave-dominated estuaries under low and high nutrient loadings are presented in Figure 23 to Figure 26. Nitrogen is thought to be the most important nutrient limiting primary productivity and phototrophic growth in Australia's estuaries and coastal waterways. Key nitrogen transformations in coastal waterways include:

1. fixation or assimilation by phototrophs;
2. degradation of biomass in the sediment;
3. remineralisation in the sediments by ammonification; and
4. sedimentary nitrification (the conversion of ammonia produced by microbial decomposition of organic matter to nitrate) and denitrification (the loss of N to the atmosphere; Section 5).

Microbial degradation of organic matter with available oxygen and aerobic nitrification are prerequisites for anaerobic denitrification. Denitrification acts as an escape mechanism for anthropogenic N inputs to a coastal waterway. Efficient nitrification and denitrification are consistent with low N loads (Figure 23). High N loads to coastal waters are, in part, known to result in low denitrification efficiencies and the recycling of N as ammonia. Recycling of nitrogen as ammonia results in enhanced productivity, potential eutrophication, and degraded water and sediment qualities (Figure 24).

Phosphorus is also an essential element for life. Key transformations of phosphorus in wave-dominated estuaries (Figure 25 and Figure 26) are:

1. assimilation by phototrophs and/or adsorption by clay;
2. degradation of biomass and the remineralisation of phosphate;
3. phosphate trapping by ferric iron in well-aerated sediment; and
4. release of phosphate into the water column when sediment becomes anoxic.

Phosphorus is not thought to be limiting for primary producers in most impacted Australian estuaries and coastal waterways.

Nitrogen recycling in mud facies of a wave-dominated Australian estuary under a low nutrient load

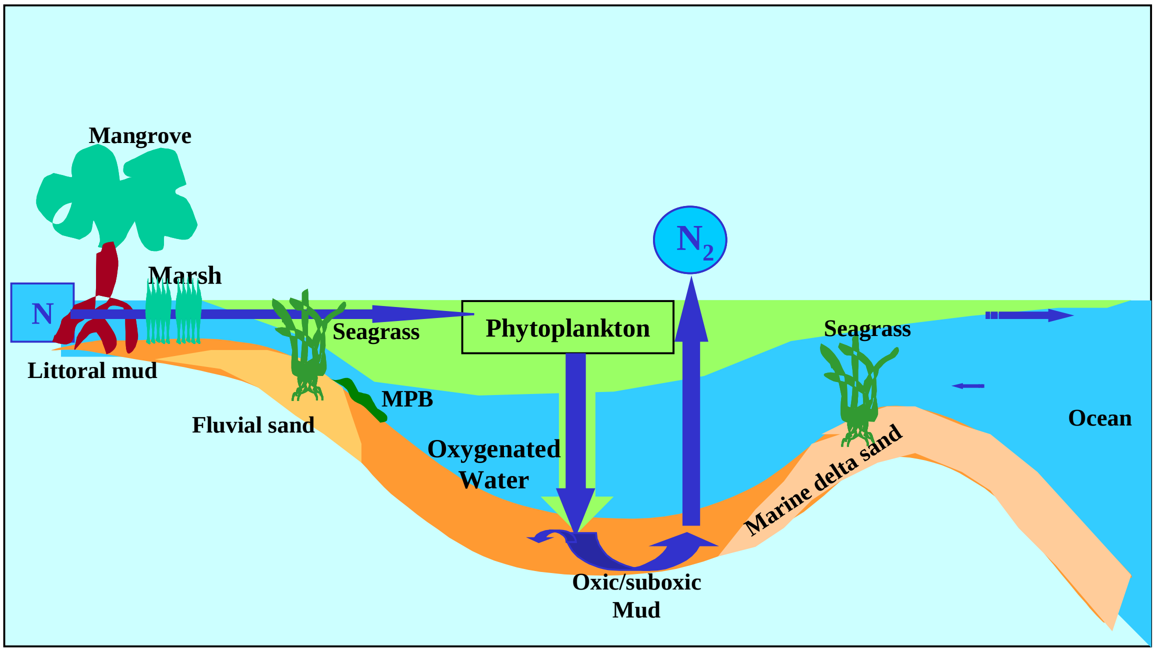

Figure 23. A low nutrient load: Nitrogen recycling in mud facies of a wave-dominated Australian estuary

1. Sedimentary nitrification and denitrification are tightly coupled.
2. Denitrification dominates N cycling; Denitrification efficiencies are high.
3. Little N recycling from sediment as ammonia to enhance external nutrient loadings.
4. Rapid loss of external N inputs as nitrogen gas
5. Organic-poor sediments, low TOC & TN probably characterise this environment.

Note: MPB refers to microphytobenthos.

Nitrogen recycling in mud facies of a wave-dominated Australian estuary under a high nutrient load

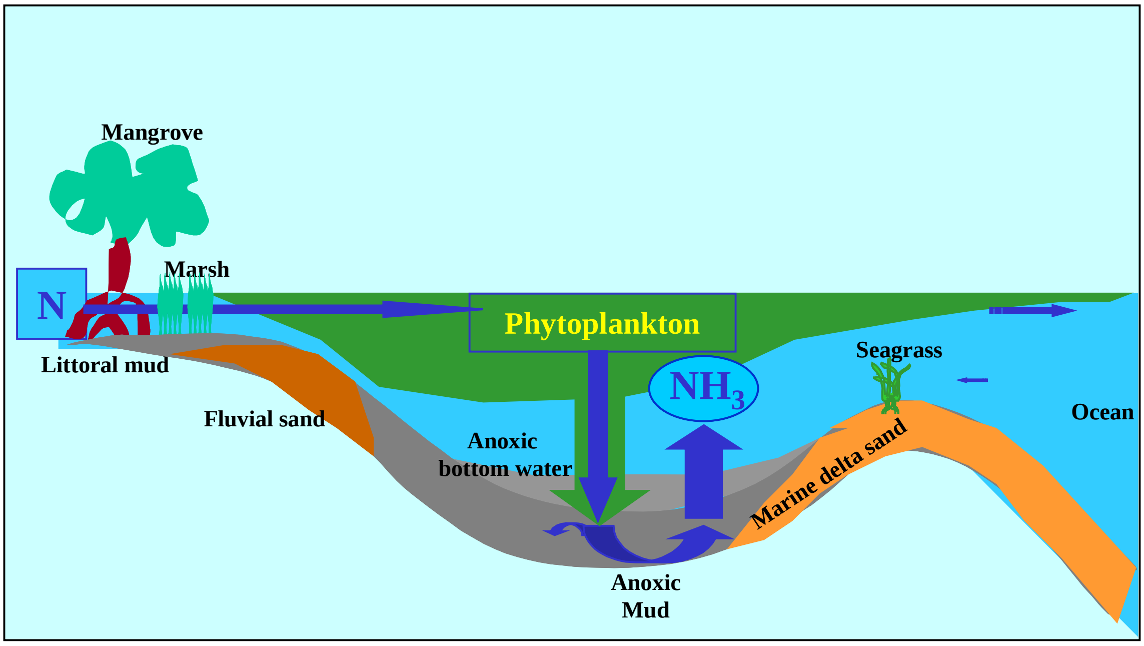

Figure 24. A high nutrient load: Nitrogen recycling in mud facies of a wave-dominated Australian estuary

1. Nitrification (microbial conversion of ammonia to nitrate) is inhibited or stops altogether.
2. Ammonification (biological generation of ammonia) dominates N cycling in the mud; ammonia (NH_3) concentrations are high in porewater and NH_3 is recycled from the sediment, which enhances external loading.
3. Denitrification efficiencies are low or zero.
4. Sulphate reduction may liberate H_2S at the sediment-water interface to lower denitrification efficiencies.
5. Organic-rich sediments (high TOC, TN & TS) characterise this environment.

Phosphorous recycling in mud facies of a wave-dominated Australian estuary under a low nutrient load

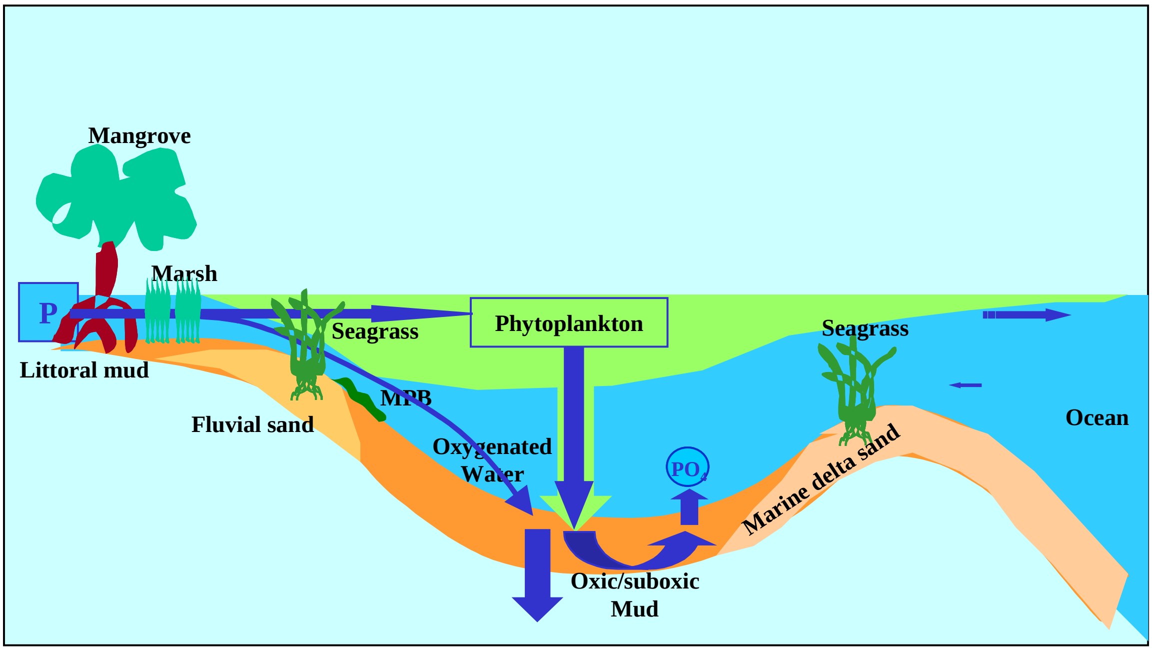

Figure 25. Phosphorous recycling in mud facies of a wave-dominated Australian estuary under a low nutrient load

1. Low phosphate concentrations in porewaters.
2. Most phosphate is trapped in the oxic upper layers of the sediment.
3. Little P recycling from sediment to enhance external loading.

Phosphorous recycling in mud facies of a wave-dominated Australian estuary under a high nutrient load

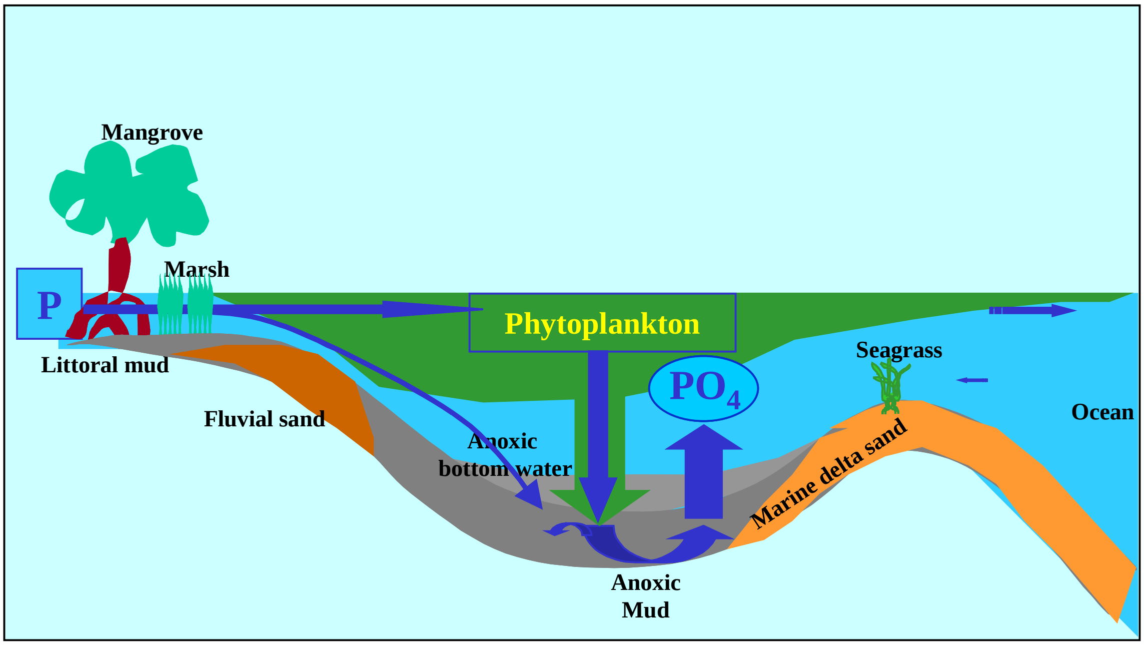

Figure 26. A high nutrient load: Phosphorous recycling in mud facies of a wave-dominated Australian estuary

1. High phosphate concentrations in porewaters.
2. Phosphate is remineralised in the sediment.
3. Stratification and high oxygen demand of sediments results in anoxic bottom waters.
4. Phosphate is recycled from the sediment to enhance external loading.

6.2.10. Tables Supporting 3D Conceptual Models

Table 15. Descriptive sedimentology and sediment geochemistry of Estuarine and Waterway facies.

Facies	Physical Transport (Water, Nutrients, Sediment)	Sediment	Sedimentary Processes	Organics	Oxygen Conditions water	Oxygen Conditions sediment
Saltflats/ Saltmarsh	Tides, groundwater exchange / Tides baffled by vegetation	Poorly sorted mud & sand	Slow spring tide driven accretion / Vegetation controlled accretion	Some algal production / Very high organic production & deposition of terrestrial organic matter	Infrequent inundation	Suboxic to anoxic
Intertidal Flats	Varied strength tidal currents	Cohesive mud to sand	High tide deposition, low water scouring	High autochthonous deposition	Infrequent inundation	Suboxic to anoxic
Fluvial-Bayhead Delta (subaqueous)	Downstream flow only	Poorly sorted terrigenous sediment and organic matter	Flood dominated deposition	High proportion of terrigenous organics	Oxic	Variable
Central Basin	Riverine discharge, marine tidal exchange, wind induced mixing	Mud, flocculated clay and organic matter	Depth controlled deposition & resuspension	High autochthonous & allochthonous deposition	Oxic (stratification dependant)	Anoxic to suboxic
Flood/Ebb Tide Delta	Strong tidal currents	Well sorted sand and gravels	Sediment mobility controlled by tidal velocity	Low	Oxic	Oxic to suboxic
Tidal Sand Banks	Very strong tidal currents	Fluid mud, mud to gravels	Erosion, resuspension, localised deposition controlled by tidal velocities	Low	Oxic	Suboxic
Barrier/Back Barrier (subaqueous)	Wave driven longshore currents, tides	Well sorted sand	Storm dominated accretion	Low	Oxic	Oxic to suboxic
Mangroves	Flood tide dominated currents	Cohesive mud, flocculated clay and organic matter	Vegetation controlled accretion	High autochthonous production & deposition	Infrequent inundation	Suboxic

Table 16. Facies habitats & features, carbon & nutrient dynamics, potential impacts and indicators of compromised integrity.

Facies	Habitats & Features	Carbon and Nutrient Dynamics	Potential Impacts	Indicators of compromised integrity
Saltmarsh/ Saltflat	-Saline porewaters and groundwater; salt crusts on saltflats -Highly productive communities of salt tolerant grasses in saltmarshes -Flooding is mainly during spring tides. -Important foraging area for fish; affords protection from predation -Feeding and roosting areas for birds	-Sulphate reduction is important for oxidising organic C and for releasing nutrients to porewaters in saltmarshes. -Net export of N and P from saltflats during ebb-tides. -Denitrification occurs mainly in creekbanks of saltmarshes where aeration facilitates the oxidation of DIN. -Saltmarsh plants are source of detritus to estuarine waters -Apparent P-uptake by sediment; soluble reactive P is apparently low in porewaters -High TOC, TN and TP (inferred) in sediment	- Land reclamation -Susceptible to wave erosion by boat traffic, oil pollution, grazing, and urban expansion	-Lowered recruitment of juvenile fish with fisheries implications -Acid-sulphate drainage -Increased sediment transport -Loss of bio-diversity -Reduction of habitat area
Intertidal Flats	-Sandflats or mudflats -Valued for intrinsic bio-diversity -Cyanobacteria and filamentous algae; burrowing animals; commercially valued pelagic macrofauna (during high tides) -Microbial and chemical zonation in sediment	-Oxygen reduction and sulphate reduction are important metabolic pathways for the oxidation of organic C -Denitrification is an important control on N budgets. -Oxic to sub-oxic conditions are maintained in interfacial sediment by tidal energetics and by the activity of burrowing animals. -Organic C burial rates can be high in mudflats	-Susceptible to pollution, bait-collecting and other fishing activities -Wave erosion from boat traffic -Land reclamation	-Loss of biodiversity -Reduction of habitat area
Fluvial Bayhead Delta	-Highly energetic, often with massive sediment deposition -Turbidity may limit phytoplankton growth and macrophyte establishment -Subject to saltmarsh/mangrove colonisation	-Probably comparatively low primary productivity -Permeable sediment and energetics promotes oxidation of organic matter and coupled nitrification-denitrification -Burial and preservation of some organic matter from catchment	-Changes in catchment sediment transport	-Changes in size of facies
Central Basin *Marginal photic zone (<~5m)*	-Seagrasses and associated epiphytes support high levels of primary productivity, detrital food chains (i.e. foraging areas for fish and crustaceans) -Seagrasses stabilise sediment and promote sedimentation	-Detrital plant matter drives early diagenesis -Ventilation of permeable sediment by plant roots and physical processes facilitate efficient organic C oxidation, nitrification, and denitrification. Oxygen reduction is most important for releasing nutrients. Burial is limited. -DIN and DIP is recycled back to the plants via porewaters	-Eutrophication -Turbidity -Susceptible to boat traffic	-Loss of seagrasses Spread of epiphytes Erosion/deposition of mud

Facies	Habitats & Features	Carbon and Nutrient Dynamics	Potential Impacts	Indicators of compromised integrity
Central Basin *ii. Deep, > 5m aphotic zones*	-Pelagic food chains with microbial loops in photic zone -Benthic communities process detrital pelagic organic matter on seafloor -Variable marine – brackish water communities depending on entrance conditions	-Sulphate reduction is most important for oxidising organic carbon and returns NH_4 to water column. -Denitrification is a major control on N budgets in estuaries where flushing times are long. -Most muddy sediment act as P-traps although P may be released during periods of anoxia, usually caused by stratification	-Excessive nutrient loads -Increased stratification with -bottom water anoxia -Construction of training walls	-Turbidity -Denitrification efficiencies < -Denitrification efficiencies <40% -Nuisance taxa (cyanobacteria and dinoflagellates). -Excessive algal growth -Fish kills
Flood/Ebb Delta	-Seagrasses in lower energy (lower turbidity) zones -Cyanobacteria on open sand -Benthic and pelagic fish communities	-See seagrass comments under Fluvial Bayhead Delta and marginal shallow water photic zone. -N-fixation may be more important in the N-budget. -High oxygen levels promote nitrification	-Dredging (navigation, sand mining) -Construction of break-waters and training walls with modification by long-shore drift	-Increased erosion/deposition
Tidal Sand Banks	-Shifting substrates -Similar to Flood/Ebb Tide Delta depending on turbidity and extent of tidal action	-Nutrient recycling not significant because of comparatively low primary production and redistribution of organic debris by tide action	-Sand mining -Dredging	-Loss/reduction of facies
Barrier/Back Barrier	-Sand -Seagrasses on sub-aqueous back barrier -Salt tolerant vegetation stabilise sub-aerial barrier	-Bird faeces and wrack are potential sources of recycled nutrients on barrier -Submarine groundwater discharge may be a significant source of nutrients to coastal waters in urbanised settings. -N-fixation/denitrification occur on the back-barrier	-Modification of long-shore drift -Sand mining -Construction of training walls, infilling for urban and industrial development -Groundwater is a major pathway for anthropogenic nutrients	-Increased erosion/deposition -Eutrophication of coastal waters
Mangroves	-More diverse and abundant in tropical than temperate settings -Significant sites for the recruitment of juvenile fishes and crustaceans -Cohabitation of marine and terrestrial biota -Mangroves dampen flushing in tidal estuaries and creeks and stabilise coastal sediment	-Facies is a sink for N and P -Nutrient uptake is driven by high rates of both plant growth and microbial activity (e.g. for decomposing litter with high C:N ratios). -Processing of organic matter by crabs influences sediment ammonium concentrations, and mangrove productivity -Macro-particles are a source of nutrients to coastal waters	-Land reclamation -Pollution (air and oil)	-Increased sediment transport -Lowered recruitment of juvenile fish with implications for commercial fisheries -Loss of biodiversity -Eutrophication of waters beyond the turbid zone

Table 17. Waterway and Estuarine type, dominant facies and ecosystem/habitat supported, key features risk to eutrophication and other risks, potential indicators and management actions.

Subclass	**Dominant facies (habitat) by area (Table 10)**	**Features (Figure 9)**	**Eutrophication Risk**	**Other Risks**	**Indicators of compromised integrity**	**Management Actions**
Wave-dominated deltas	Mangroves & Channels	Generally good flushing Low sediment trapping efficiency Naturally high turbidity Poorly mixed/saltwedge	Low because: (a) Low sediment trapping efficiency (b) High turbidity (c) Net seaward directed sediment transport	Removal of facies (e.g. dredging) Reclamation of Mangroves and Saltmarsh Stratification	Loss of mangrove/saltmarsh habitat Possible eutrophication beyond the turbid zone Shoreline erosion and style and rate of sedimentation is altered Bottom water anoxia and fish kills Turbidity	Limit catchment activity and soil loss. Maintain good flow Cost-benefit analysis on coastal development Shoreline development should avoid the mangrove fringe where possible
Wave dominated estuaries and coastal lakes	Central Basin (with phytoplankton and seagrasses)	Nutrients and fine-grained particles trapped year round Barrier/back-barrier restricts flushing and promotes stratification (partial mixing) Naturally low turbidity	High because: (a) Low turbidity (b) Poor flushing characteristics (c) Nutrient are trapped in central basin (d) Stratification	Increased turbidity (seagrasses) Boat traffic (seagrasses) Removal of facies (e.g. dredging)	Denitrification efficiency <40%, Biomarkers of STP or other contaminants Fish kills Toxic algal blooms Reduction of seagrass area Bottom water anoxia Turbidity	Control nutrient/sediment loads from catchment Exclude boat traffic or reduce boat speed near seagrasses Cost-benefit analysis on coastal development Increase flushing but ensure engineering works do not increase stratification
Strandplains	Channels, Intertidal Flats, and Barrier/back-barrier	Low sediment trapping efficiency Low turbidity Saltwedge/partially mixed Barrier/back barrier can be opened or closed	Moderate to high because (a) Low turbidity (b) Barrier can be closed thus increasing nutrient retention	Loss of facies (dredging/ erosion) Stratification Turbidity	Denitrification efficiency <40% Toxic algal blooms Reduction of seagrass area Bottom water anoxia and fish kills Turbidity	Control nutrient/sediment loads from catchment Limit boat traffic Increase flushing

Subclass	Dominant facies (habitat) by area (Table 10)	Features (Figure 9)	Eutrophication Risk	Other Risks	Indicators of compromised integrity	Management Actions
Tide-dominated deltas and tidal creeks	Mangroves, Saltmarsh and Channels	Low sediment nutrient trapping efficiencies; Fines accumulate in Mangroves Naturally high turbidity Well mixed	Low because: (a) High turbidity (b) Low sediment trapping efficiencies (c) Nutrient retention in Mangroves	Reclamation of Mangrove and Saltmarsh	Mangrove habitat loss Shoreline erosion and style and rate of sedimentation is altered Possible eutrophication beyond the turbidity front Acid-sulphate drainage	Cost-benefit analysis on coastal development Shoreline development should be away from the mangrove fringe
Tide-dominated estuaries	Mangroves, Saltflat/Saltmarsh and Channels	Sediment/nutrient trapping is moderate; accumulation in mangroves and saltmarsh Naturally high turbidity Well mixed	Low because: (a) High turbidity (b) Net nutrient retention in Mangroves	Reclamation of Mangrove and Saltmarsh Dredging/sand-mining	Mangrove/saltmarsh habitat loss Removal of tidal sand banks Shoreline erosion and style and rate of sedimentation is altered Possible eutrophication beyond the turbidity front Acid sulphate drainage	Cost-benefit analysis on coastal development Shoreline development should be away from the mangrove fringe

6.3. Applications

The conceptual models (Figure 15 to Figure 26) and supporting documentation (e.g. Table 15 to Table 17) are education guides to:

1. the key habitats and features of estuaries and deltas;
2. sediment transport modes within estuaries and deltas; and
3. nutrient dynamics within estuaries and deltas.

The models highlight for example, that central basin mud is a sink for carbon and nutrients, including phytoplankton derived from the water column and terrestrial-plant material derived from the catchment. They also illustrate that mangroves and saltflats/saltmarshes are the facies where mud accumulates, and where carbon and nutrients are recycled in tide-dominated estuaries. By comparison, they show that deltas (both wave- and tide-dominated), have little remaining accommodation space for fine sediment, and do not act as significant traps for sediment, nutrients or toxicants.

Using the conceptual models as a framework, it is possible to identify:

1. potential threats to the integrity of individual facies (habitats) (see Table 16); and
2. potential threats to the integrity of the subclasses as a whole (including eutrophication). These thoughts are summarised in Table 17, and in Table A of the Executive Summary.

6.4. Recommendations

- The sediment and nutrient conceptual models developed in this study should be widely circulated to stakeholders, including community groups, local authorities, environmental officers, and scientists for further discussion. Development of conceptual models as management tools is reliant upon feedback.
- Conceptual models should be constructed for strandplains and tidal creeks.

7. Estuarine Geoscience Database (OZESTUARIES)

> "*The need to consolidate existing information on Australian estuaries has been recognised. Of the more than 700 Australian estuaries, less than 50 estuaries have been extensively studied and more of these studies have been undertaken on impacted estuaries and very little on pristine and ecologically healthy systems. What is needed for Australian estuaries is an easy to understand inventory and categorisation based on the key driving processes that determine change from natural to modified systems. This will provide a framework to identify management requirements, prioritise management effort, define monitoring and assessment activities and structure data collection and presentation.*" NLWRA Project Brief – 7.17.7.3.1.

The National Land and Water Resources Audit (NLWRA) through Theme 7 Project 3, Estuarine Health Assessment, have recognised the need for a National Database of Australian estuaries. AGSO's role in this project has been to collect data and develop a geoscience database. The following steps were taken to achieve the required outputs:

1. With input from States and NT, agree on the estuaries to be included in this project. Alert all State agencies to the need to provide data once the data framework is established.
2. Review existing estuarine and coastal catchment data sets (eg Digby *et al*. (AED)), Dalrymple *et al*. 1992. State and NT inventories), including data scale, frequency, recency, and accessibility.
3. Develop the spatial data framework to be used for an initial presentation of AED data within this Audit project. Ideally this framework should incorporate the digitised boundaries of all estuaries identified in point 1 and their catchments; at a minimum it should include the locations of the estuaries as geo-referenced points.
4. Assemble the AED data and enter into the spatial data framework. Add records for estuaries not included in AED but required under point 1.
5. Add other relevant catchment and estuarine data to the framework, obtained from the States and Territory agencies following point 1.

The data collected for the geoscience database has been described in detail in the previous sections. This section will explain specific aspects of the geoscience database and how it can be queried via the Internet. The AGSO Ozestuaries database was designed using features of the Australian Estuarine Database. Ozestuaries was expanded to incorporate additional data obtained from the States and the NLWRA. The additional data includes geochemical, geometric, geomorphic information, and new estuarine classifications.

7.1. Ozestuaries Database Development

The Ozestuaries database has been developed to incorporate The Australian Estuarine Database (AED) and data acquired for the NLWRA. The database has been created using Oracle version 7.3.4.4. Oracle is a relational database management system that enables the user to store, retrieve and modify data on request.

The AED was compiled in 1998 and incorporates spatial, geographic, morphological and climatic data for 780 Australian estuaries. The database was developed to enable a practical classification scheme for estuaries that can then be used as a resource management tool (Bucher and Saenger, 1991).

7.2. Accessing Ozestuaries

Access to the Ozestuaries database is via the AGSO Internet site, www.agso.gov.au/ozestuaries. A login name and password are required and these are available by contacting the NLWRA.

Once logged on, the following screen will display.

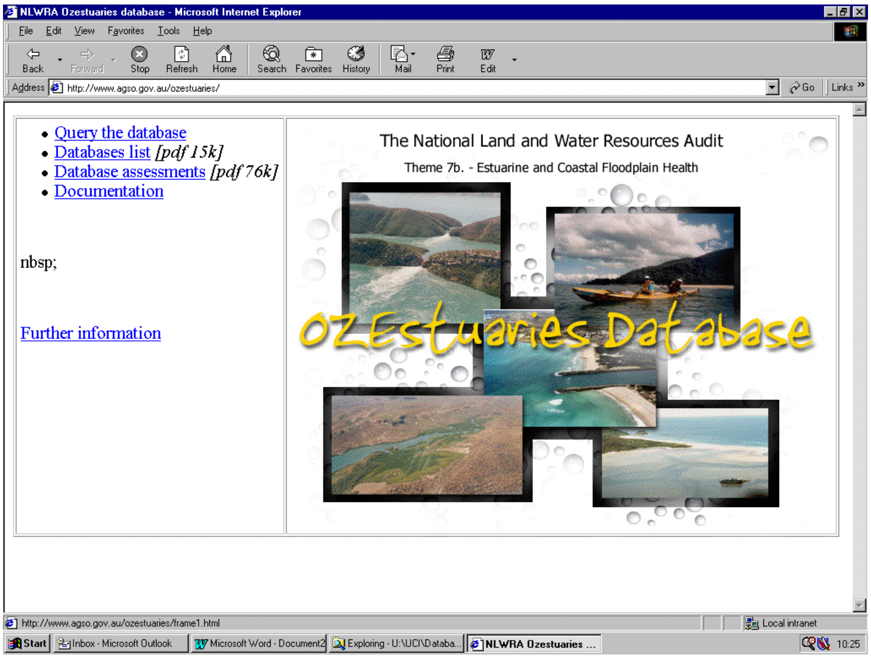

Figure 27. Ozestuaries Internet page.

AGSO had the task of reviewing existing data sets for the NLWRA. Click on Databases List to view the existing data sets. Click on Database Assessment for the assessment of these data sets.

To view the Final Report produced by AGSO click on documentation. You will then have the option to download the entire document or a particular section. All documentation will be in PDF format.

What to do if You Need Help With Ozestuaries

If you are having problems contact the Ozestuaries Administrator at AGSO. Details are as follows or click the Further information link.

Craig Smith

Telephone - 02 6249 9650

or via email - craig.smith@agso.gov.au

7.3. Estuary Search

Click on Query the database and the main Ozestuaries **Query/Map** window will display (Figure 28).

There are **two** ways to search **Ozestuaries**. Either:

Use the **Query** window **(left)** side of the screen

Or

Use the **Map** window **(right)** side of the screen

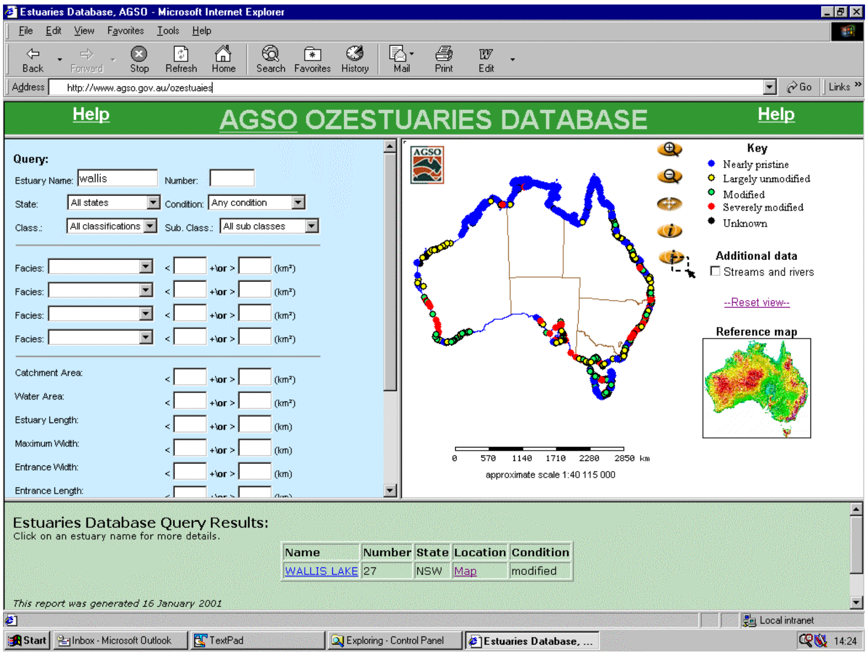

Figure 28. Ozestuaries Query/Map window.

7.3.1. Query Window (Left) Side of Screen

There are no **mandatory** fields in the **Query** window. You can fill in as many or as few fields as needed. If the **Submit** button is clicked with no fields entered, then a list of all estuaries will be displayed in the **Results** window.

Entire or part names can be used in the **Estuary Name** field. For example, entering WA into the **Estuary Name** field will search for all estuaries beginning with, or containing the letters WA. Alternatively, if the entire name is typed into the field only one estuary should be displayed in the **Results** window (unless more than one estuary has that name).

You can select a **Condition**, **Classification** or **Sub-Classification** option from the drop-down lists. For example, select **Wave-Dominated** from the **Classification** drop-down and click **Submit** to display all wave-dominated estuaries in the **Results** window.

Facies and **Geometry** data are presented as either areas or lengths. To search the database using this criteria you can either enter a range of values or enter one value in the greater than (>) or less than (<) box. If a range of values is entered and **Submit** clicked, all estuaries that lie within that range for the chosen field will be displayed in the **Results** window. You can also have returned all estuaries than have values greater than or less than an entered value by entering that value in either the greater than box **(>)** or the less than box **(<)**. Up to four facies can be selected using drop-down lists.

A **Geochemistry** check box has been added to the **Query** window. Geochemical information is not available for all estuaries in the database. If the box is checked and **Submit** clicked, then all estuaries that contain geochemical data will be displayed in the **Results** window. This button is located above the Sort Results button.

A **Sort results by** name, number, state or condition drop-down list is also available to further assist your query. This drop-down list is located above the Submit button.

Example

1. Select **NSW** from the **State** drop-down menu
2. Select **Mangrove** from the first **Facies** drop-down menu and enter 10 and 2 in the range boxes
3. Enter 150 and 50 in the range boxes adjacent to **Catchment Area**
4. Leave the **Geochemistry** box **unchecked**
5. Click on **Submit**

All **NSW** estuaries that have a **Mangrove** area between 2 and 10 km^2 and a **Catchment Area** between 50 and 150 km^2 will be displayed in the **Results**.

Click on the **Clear** button to begin a new search.

7.3.2. Map Window (Right) Side of Screen

This window enables you to select estuaries by location. You can use the navigation keys of this window to define a search area. Estuaries can be selected individually or areas can be selected. Notes on the function of each navigation key will be displayed when the mouse is moved over the keys, they include:

- zoom into an area
- zoom out
- centre map
- information on individual estuaries
- information on estuaries within an area

All chosen estuaries will appear in the **Results** window.

7.3.3. Results Window (Bottom) of Screen

The **Results** window (Figure 28) displays the results of a **Query** or **Map** defined search. Click on the required **Estuary Name**, for example, Wallis Lake and the **Estuary Details** window (Figure 29) will display the detailed results for that estuary. If Map is selected a triangular point (▲) will appear on the Australian map showing the location of the estuary.

7.3.4. Help Link

If you are having difficulty searching for estuaries, press the Help link in the top header bar (Figure 28) to display notes on how to use **Ozestuaries**.

7.3.5. Estuary Details Window

The **Estuary Details** window will display all the data relating to the chosen estuary on a separate window (Figure 29).

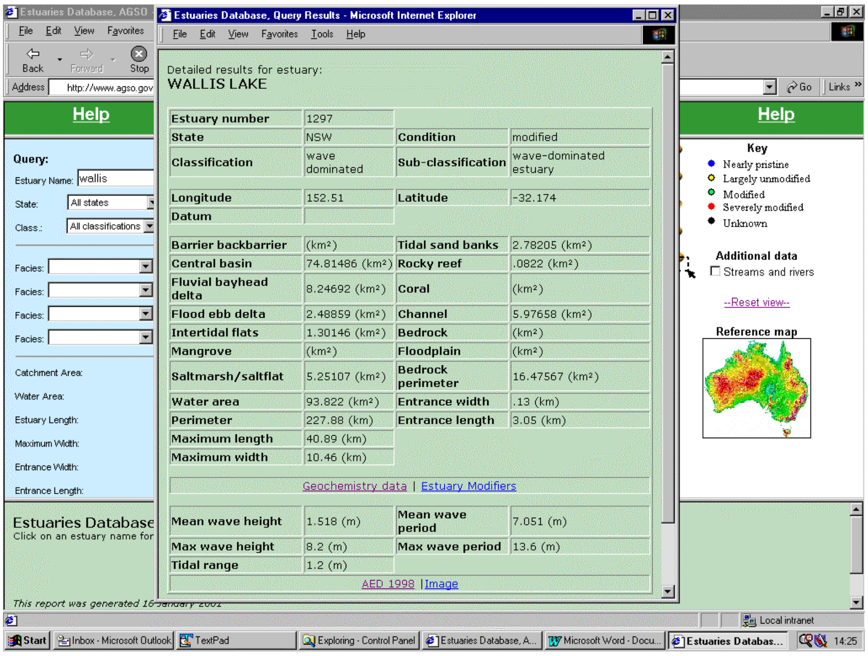

Figure 29. Estuary Details window.

If **Geochemical data** is available for the estuary then the Geochemistry data link will display. When the link is clicked the Geochemistry data will display in a separate window (Figure 30) as a Comma Separated Variable file (CSV). **NOTE:** This file can be saved using **File, Save As** (.txt) for use later in a variety of applications, for example, Microsoft Excel.

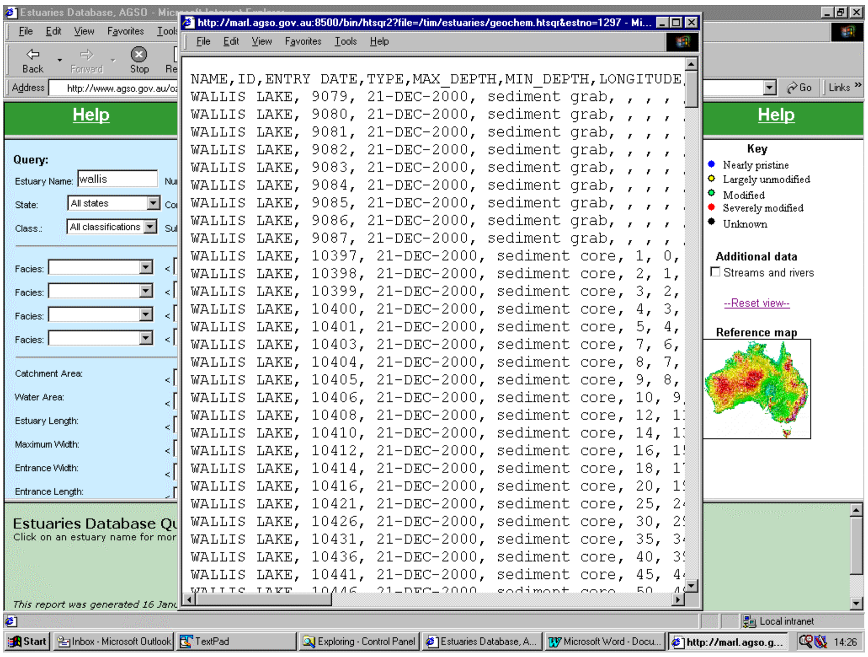

Figure 30. Geochemistry Data window.

If **Estuary Modifiers** data is available for the estuary, the Estuary Modifiers link will display. When the link is clicked, the Estuary Modifiers will display in a separate window (Figure 31).

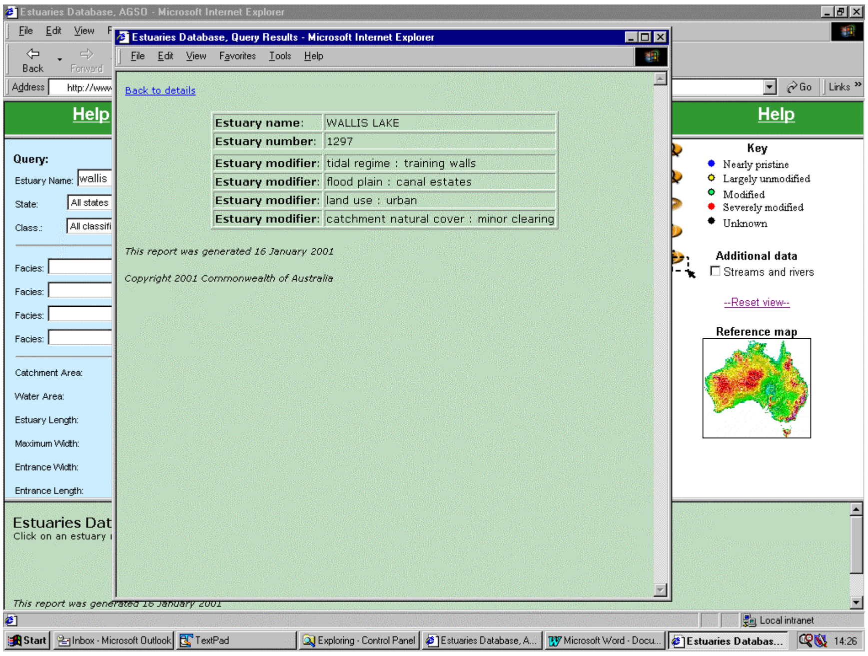

Figure 31. Estuary Modifiers window.

If **AED 1998** data is available for the estuary, the AED 1998 link will be displayed. When the link is clicked, data from the AED 1998 database will display in a separate window (Figure 32).

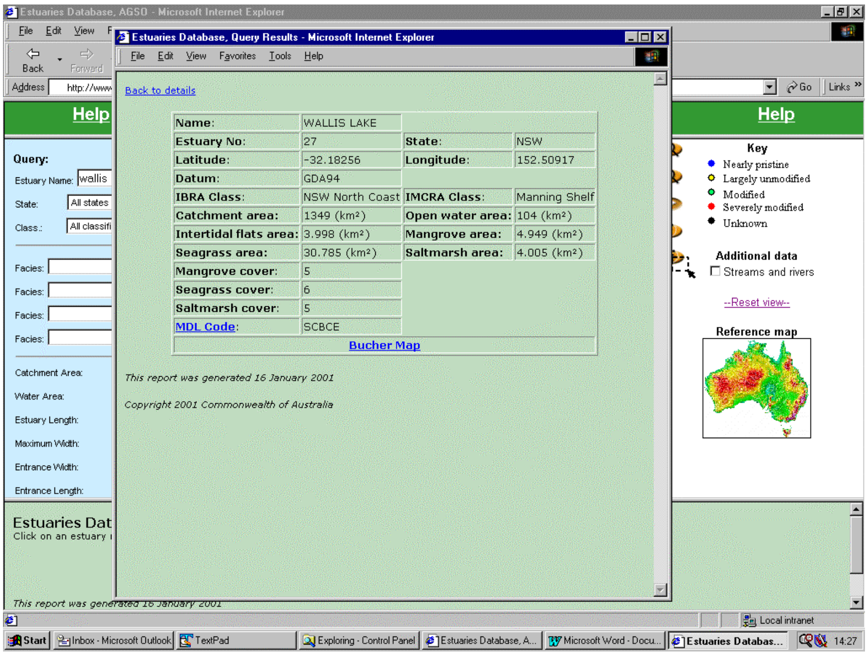

Figure 32. AED 1998 window.

To display a list of **MDL** (main drainage line) **Codes** for the estuaries, click the MDL Codes link. The MDL Codes were derived for use in the AED98 and are a way of categorising estuaries based on morphological attributes. The MDL Codes will display in a separate window (Figure 33).

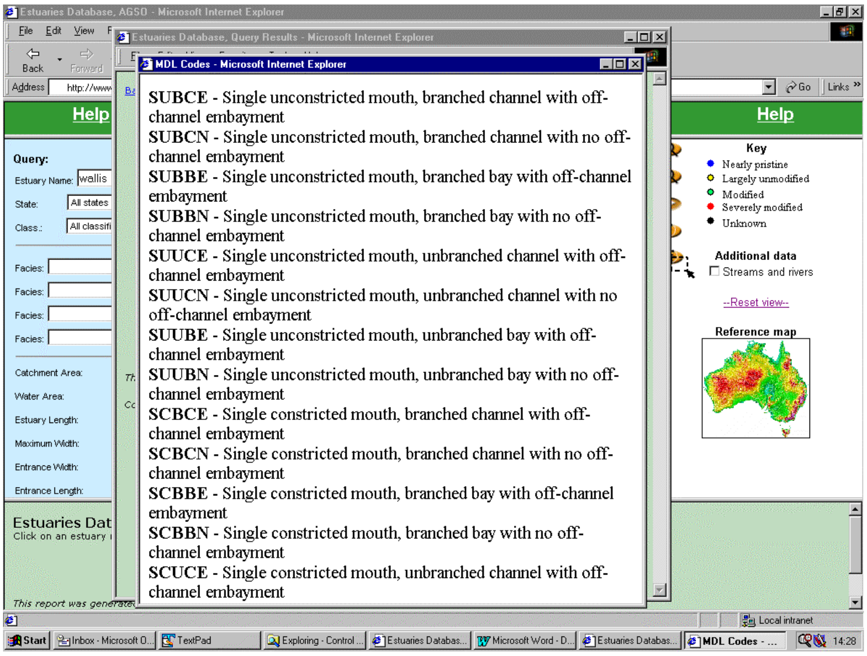

Figure 33. MDL Codes window.

To display the **Bucher Map** for the estuary, click the Bucher Map link. Bucher maps were produced by Bucher & Saenger (1991) as part of an inventory of Australian estuaries and enclosed marine waters. The Bucher Map will display in a separate window (Figure 34).

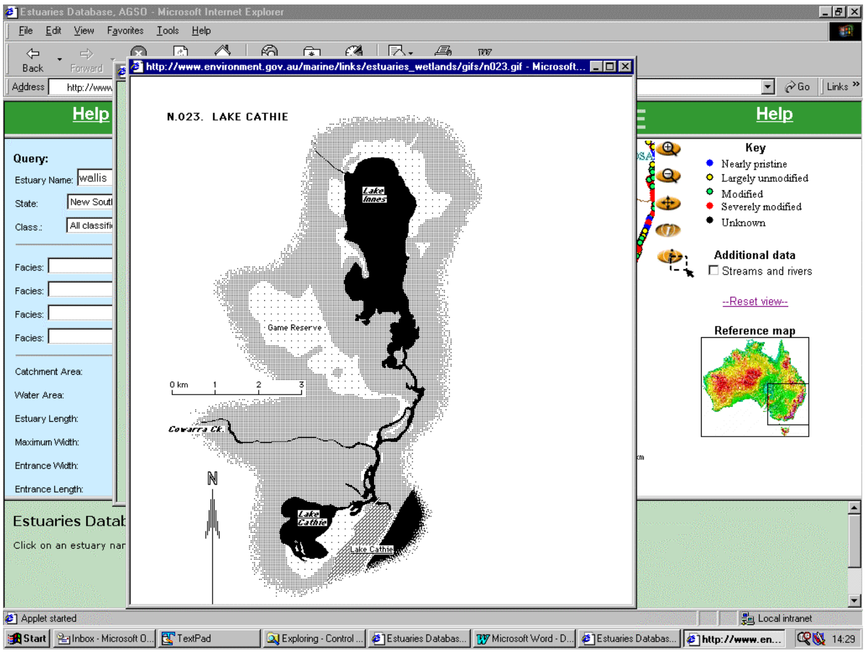

Figure 34. Bucher Map window.

If an **Image** is available for the estuary, then the Image link will display. When the link is clicked, a Landsat Thematic Image of the estuary will display in a separate window (Figure 35).

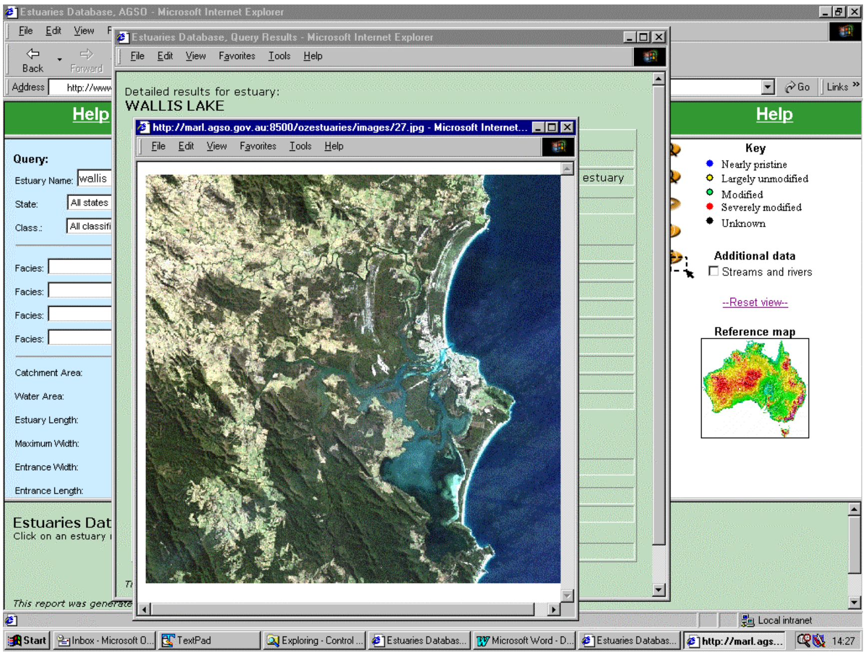

Figure 35. Landsat Image window.

8. References

8.1. References cited in text

Atkinson M.J. and Smith S.V. (1983). C:N:P ratios of benthic marine plants. *Limnology and Oceanography* **28 (3)**, 568-574.

Berelson, W. M., Heggie, D. T., Longmore, A., Kilgore, T., Nicholson, G., and Skyring, G. (1998). Benthic nutrient recycling in Port Phillip Bay, Australia. *Estuarine, Coastal and Shelf Science* **46**, 917-934.

Boyd, R., Dalrymple, R.W. & Zaitlin, B.A. (1992). Classification of clastic coastal depositional environments. *Sedimentary Geology* **80**, 139-150.

Brzezinski, M. A. (1985). The Si:C:N ratio of marine diatoms: Interspecific variability and the effect of some environmental variables. *Journal of Phycology* **21**,347-357.

Bucher, D. & Saenger, P. (1991). An inventory of Australian estuaries and enclosed marine waters: an overview of results. *Australian Geographical Studies* **29**, 370-381.

CSIRO Huon Estuary Study Team (2000). Huon Estuary Study: Environmental Research for Integrated Catchment Management and Aquaculture. Project No. 96/284, Final Report to the Fisheries Research and Development Corporation, p. 285.

Dalrymple, R.W., Zaitlin, B.A. & Boyd, R. (1992). Estuarine facies models: conceptual models and stratigraphic implications. *Journal of Sedimentary Petrology* **62**, 1130-1146.

Digby, M.J., Saenger, P., Whelan, M.B., McConchie, D., Eyre, B., Holmes, N. & Bucher, D. (1998). *A physical classification of Australian Estuaries* (Report Prepared for the Urban Water Research Association of Australia No. 4178). Southern Cross University, Centre of Coastal Management, Lismore, NSW, 47pp.

Fredericks, D. J. and Heggie, D. T. (2000). Are sediments a significant source of nutrients in Wilson Inlet. AGSO Professional Opinion 2000/04 Australian Geological Survey Organisation, Canberra.

Froelich, P. N., Klinkhammer, G. P., Bender, M. L., Luedtke, N., Heath, G. R., Cullen, D., Dauphin, P., Hammond, D., Hartman, B., and Maynard, V. (1979). Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic; suboxic diagenesis. *Geochimica et Cosmochimica Acta* Pergamon, Oxford. **43**, 1075-1090.

Harris, G., Batley, G., Fox, D., Hall, D., Jernakoff, P., Molloy, R., Murray, A., Newell, B., Parslow, J., Skyring, G., and Walker, S. 1996. Port Phillip Bay Environmental Study Final Report. CSIRO, Canberra, Australia.

Heggie, D. T., Skyring, G. W., Berelson, W. E., Longmore, A. R., and Nicholson, G. J. (1999a) Sediment-water interaction in Australian coastal environments: implications for water and sediment quality. *AGSO journal of Australian Geology and Geophysics* **17(5/6)**, 159-173.

Heggie, D. T., Skyring, G. W., Orchardo, J., Longmore, A. R., Nicholson, G. J., and Berelson, W M. (1999b). Denitrification and denitrifying efficiencies in sediments of Port Phillip Bay: direct determinations of biogenic N_2 and N-metabolite fluxes with implications for water quality. *Marine Freshwater Research* **50**, 589-596.

Heggie, D.T. & Skyring, G.W. (1999c). Flushing of Australian estuaries, coastal lakes and embayments: an overview with biogeochemical commentary. *AGSO Journal of Australian Geology and Geophysics* **17**, 211-225.

Hodgkin, E.P. & Hesp, P. (1998). Estuaries to salt lakes: Holocene transformation of the estuarine ecosystems of southwestern Australia. *Marine and Freshwater Research* **49**, 183-201.

Joye, B and Hollibaugh, J. T. (1995). Influence of sulfide inhibition of nitrification on nitrogen regeneration in sediments. *Science* American Association for the Advancement of Science., Washington, DC, United States. **270;** 5236, 623-625.

Murray, A. G. and Parslow, J. S. (1999). Modelling of nutrient impacts in Port Phillip Bay - a semi-enclosed marine Australian ecosystem. *Marine and Freshwater Resources* **50**, 597-611.

Norrish, K and Rosser, H. (1993). Mineral Phosphate. In Soils: An Australian Viewpoint (Division of Soils, CSIRO, CSIRO, Melbourne. 336-361.

Palmer, D, Fredericks, D., Smith, C. and Heggie, D.T. (2000a). Nutrients from sediments: Implications for algal blooms in Myall Lakes. *AGSO Research News Letter* **33**, 2- 4.

Palmer, D., Fredericks, D. J., Smith, C., Tindall, C., and Heggie, D. T. (2000b). A reconnaissance study of benthic fluxes in Durras Lake. AGSO Professional Opinion 2000/14 Australian Geological Survey Organisation, Canberra.

Redfield, A.C., Ketchum, B.H., and Richards, F.A. (1963). The influence of organisms on the composition of seawater. In The Sea, Vol. 2, (Ed. M.N. Hill), pp 26-79. (Wiley Interscience: New York).

Roy, P.S., Williams, R.J., Jones, A.J., Coates, B., Gibbs, P.J., Yassini, I., Hudson, J.P. & West, R.J. (submitted). Structure and function of southeast Australian estuaries. *Australian Journal of Earth Sciences*.

Solis, R.S., and Powell, G.L. (1999) Hydrography, Mixing Characteristics, and Residence Times of Gulf of Mexico Estuaries. In Bianchi, T.S., Pennock, J.R., Twilley, R.R.Biogeochemistry of Gulf of Mexico Estuaries.

Sakadevan, K., Zheng, H., and Bavor, H. J. (1999). Impact of heavy metals on denitrification in surface wetland sediments receiving wastewater. *Wat. Sci. Tech.* **40**, 349-355.

Statsoft Inc. (1995). STATISTICA for Windows (Volume III): Statistics (2^{nd} Edition), Tulsa, OK.

Ward, T., Butler, E., Hill, B. (1998). Environmental indicators for National State of the Environment Reporting, CSIRO Division of Marine Research, Commonwealth of Australia, pp. 84.

8.2. Additional Reading

Nichol, S.L., Zaitlin, B.A. & Thom, B.G. (1997). The upper Hawkesbury River, New South Wales, Australia: an example of an estuarine bayhead delta. *Sedimentology* **44**, 263-286.

Nunes Vaz, R.A., Lennon, G.W. & Bowers, D.G. (1990). Physical behaviour of a large, negative or inverse estuary. *Continental Shelf Research* **10**, 277-304.Roy, P.S. (1984) New South Wales estuaries: their origin and evolution. *In*: Thom, B.G. (ed.) *Coastal Geomorphology in Australia,* Academic Press, New York, pp. 99-122.

Thom, B.G., Shepard, M.J., Ly, C.K., Roy, P.S., Bowman, G.M. & Hesp, P.A. (1992). *Coastal Geomorphology and Quaternary geology of the Port Stephens-Myall Lakes area*. Australian National University, Department of Biogeography and Geomorphology, Monograph 6, 407pp.

Woodroffe, C.D. (1993). Late Quaternary evolution of coastal and lowland riverine plains of Southeast Asia and northern Australia. *Sedimentary Geology* **83**, 163-175.

Woodroffe, C.D., Chappell, J., Thom, B.G. & Wallensky, E. (1989). Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia. *Sedimentology*, **36**, 737-756.

8.3. References to Geochemical Data Used in the Sediment Geochemistry Database

Alongi, D. M. (1988). Microbial-meiofaunal interrelationships in some tropical intertidal sediments. *Journal of Marine Research* **46**, 349-365.

Alongi, D. M. (1989). Benthic processes across mixed terrigenous -carbonate sedimentary facies on the central Great Barrier Reef continental shelf. *Continental Shelf Research* **9**, 629-663.

Alongi, D. M. (1990). Effect of mangrove detrital outwelling on nutrient regeneration and oxygen fluxes in coastal sediments of the central Great Barrier Reef lagoon. *Estuarine, Coastal and Shelf Sciences* **31**, 581-598.

Alongi, D. M., Tirendi, F., Trott, L. A., and Brunskill, G. J. (1999). Mineralization of organic matter in intertidal sediments of a tropical semi-enclosed delta. *Estuarine and Coastal Shelf Science* **48**, 451-467.

Anderson, J. R., Storey, K. J., and Carolane, R. (1981). Macrobenthic fauna and sediment data for eight estuaries on the south coast of New South Wales. *Technical Memorandum 81/22* CSIRO Institute of Biological Resources, Division of Land Use Research, Canberra, p7.

Barnett, E. J. (1993). Recent sedimentary history of Lake Alexandrina and the Murray Estuary. School of Earth Sciences, Ph.D Thesis, The Flinders University of South Australia.

Barnett, E. J. (1994). A Holocene paleoenvironmental history of Lake Alexandrina. *Journal of Palaeolimnology* **12**, 259-268.

Bastyan, G., Latchford, J., and Paling, E. I. (1995). In *Macrophyte distribution and sediment chemistry in Wilson Inlet.* Institute for environmental science, Perth. MAFRA 95/8.

Bastyan, G. and Paling, E. I. (1995). Experimental studies on coastal sediment nutrient release and content (Report to CSBP). Institute for Environmental Science Report No. MAFRA 95/5 Murdoch University, 28p.

Beckett, R., Easton, A. K., Hart, B. T., and McKelvie, I. D. (1982). Water movement and salinity in the Yarra and Maribyrnong estuaries. *Australian Journal of Marine and Freshwater Research* **33**, 401-415.

Berelson, W. M., Heggie, D. T., Longmore, A., Kilgore, T., Nicholson, G., and Skyring, G. (1998). Benthic nutrient recycling in Port Phillip Bay, Australia. *Estuarine, Coastal and Shelf Science* **46**, 917-934.

Boto, K. G. and Wellington, J. T. (1984). Soil characteristics and nutrient status in a northern Australian mangrove forest. *Estuaries* **7**, 61-69.

Collett, L. C., Collins, A. J., Gibbs, P. J., and West, R. J (1981). Shallow dredging as a strategy for the control of sublittoral macrophytes: a case study in Tuggerah Lakes, New South Wales. *Australian Journal of Marine and Freshwater Research.* **32**(4)*, p 563-571*.

CSIRO Huon Estuary Study Team June (2000). Huon Estuary Study: Environmental Research for Integrated Catchment Management and Aquaculture. Project No 96/284 In *Final Report to the Fisheries Research and Development Corporation* 285.

EPA South Australia (2000). Heavy Metals and PCB's in Dolphins, Sediment and Fish. Special Survey of the Port River, p.33.

Gerritse, R. G. (1999). Sulphur, organic carbon and iron relationships in estuarine and freshwater sediments: effects of sedimentation rate. *Applied Geochemistry* **14**, 41-52.

Hancock, G. J. and Hunter, J. R. (1999). Use of excess ^{210}Pb and ^{228}Th to estimate rates of sediment accumulation and bioturbation in Port Phillip Bay, Australia. *Marine Freshwater Research* **50**, 533-545.

Hancock, G. J. and Murray, A. S. (1996). Source and distribution of dissolved radium in the Bega River estuary, southeastern Australia. *Earth and Planetary Science Letters* **138**, 145-155.

Herczeg, A. L., Smith, A. K., and Dighton, J. C. (2001). A 120 year record of changes in nitrogen and carbon cycling in Lake Alexandrina, South Australia: C:N, $\delta^{15}N$ and $\delta^{13}C$ in sediments. *Applied Geochemistry* **16**, 73-84.

King, R. J. and Hodgson, B.R. (1995). Tuggerah lakes system, New South Wales, Australia. In *Eutrophic shallow estuaries and lagoons* (McComb, A.J., editor). CRC Press, Boca Raton. Chapter 3 19-29.

Longmore, A.R. (1990). In *Nutrient budget for northern Lake King, Gippsland Lakes, 1987-88* (Longmore, A. R., Environment Protection Authority, [Melbourne], p59.

Longmore, A. R. (1994). Nutrient release rates for sediment cores from the Gippsland Lakes (1988). *Victoria, Environment Protection Authority, Melbourne VIC, p.37*.

Pailles, C., McConchie, D. M., Arakel, A. V., and Saenger, P. (1993). The distribution of phosphate in sediments of the Johnstone Rivers catchment-estuary system, North Queensland, Australia. *Sedimentary Geology* **85**, 253-269.

Pailles, C. and Moody, P. W. (1996). Assessment of the downstream impact of sediment-bound phosphorous from southern canelands. SIRP Project 3 Resource Sciences Centre, Department of Natural Resources, Queensland, p49.

Ullman, W. J. and Sandstrom, M. W. (1987). Dissolved nutrient fluxes from the nearshore sediments of Bowling Green Bay, central Great Barrier Reef Lagoon, Australia. *Estuarine, Coastal and Shelf Science* **24**, 289-303.

Ward, T. J. and Young, P. C. (1981). Trace metal contamination of shallow marine sediments near a lead smelter, Spencer Gulf, south Australia. *Australian Journal of Marine and Freshwater Research* **32**, 45-56.

Webb, McKeown & Associates Pty. Ltd. (1999). Wallis Lake Estuary Processes Study. Great Lakes Council pp129.

Worth, G. D. (1992). Some aspects of the sedimentology of the Broadwater, Myall Lakes, NSW. Grad. Dip Thesis, Dept. of Geography, University of Newcastle, NSW, pp78.

8.4. References Used to Derive the Three-Dimensional Conceptual Models and Supporting Tables

Abal, E. G. and Dennison, W. C. (1996). Seagrass depth range and water quality in southern Moreton bay, Queensland, Australia. *Marine and Freshwater Research*, **47**:763-71.

Alongi, D. (1996). The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests. *Journal of Marine Research*, **54**:123-148.

Alongi, D. M. (1988). Bacterial productivity and microbial biomass in tropical mangrove sediments. *Microbial Ecology*, **15**:59-80.

Alongi, D. M. (1988). Microbial-meiofaunal interrelationships in some tropical intertidal sediments. *Journal of Marine Research*, **46**:349-365.

Alongi, D. M. (1990). Effect of mangrove detrital outwelling on nutrient regeneration and oxygen fluxes in coastal sediments of the central Great Barrier Reef lagoon. *Estuarine, Coastal and Shelf Sciences*, **31**:581-598.

Alongi, D. M., Boto, K. G., and Robertson, A. I. (1992). Nitrogen and Phosphorous Cycles. In Robertson, A. I. and Alongi, D. M. Tropical Mangrove Ecosystems, American Geophysical Union, 251-292.

Alongi, D. M., Sasekumar, F., Tirendi, F., and Dixon, P. (1998). The influence of stand age on benthic decomposition and recycling of organic matter in managed mangrove forests of Malaysia. *Journal of Experimental Marine Biology and Ecology*, **225**:197-218.

Alongi D. M., Tirendi F., Dixon P., Trott L. A. & Brunskill G. J. (1999). Mineralization of organic matter in intertidal sediments of a tropical semi-enclosed delta. *Estuarine, Coastal and Shelf Science*, **48**:451-467.

Ayukai T. & Wolanski E. (1997). Importance of biologically mediated removal of fine sediments from the Fly River plume, Papua New Guinea. *Estuarine, Coastal and Shelf Science,* **44**:629-639.

Ayukai, T., Miller, D., Wolanski, E., and Spagnol, S. (1998). Fluxes of nutrients and dissolved and particulate organic carbon in two mangrove creeks in northeastern Australia. *Mangroves and Salt Marshes*, **2**:223-230.

Bertness, M. D. (1985). Fiddler crab regulation of Spartina alterniflora production on a New England saltmarsh. *Ecology*, **66**:1042-1055.

Black R. E., Lukatelich R. J., McComb A. J. & Rosher J. E. (1981). Exchange of water, salt, nutrients and phytoplankton between Peel Inlet, Western Australia, and the Indian Ocean. Australian Journal of Marine and Freshwater Research, **32**:709-720.

Blackburn, T. H., Christensen, D., Fenger, A. M., Henriksen, K., Iizumi, H., and Iverson, N. (1987). Mineralization processes in mangrove and seagrass sediments. In Hylleberg, J. & Yon A. A mangrove in the Andaman Sea. Institute of Ecological Genetics, Aarhus University, Aarhus p.22-32.

Boon, P. I. and Cain, S. (1988). Nitrogen cycling in salt-marsh and mangrove sediments at Western Port, Victoria. *Australian Journal of Marine and Freshwater Research,* **39**:607-623.

Boorman L. A., Garbutt A. & Barratt D. (1998). The role of vegetation in determining patterns of the accretion of saltmarsh sediment. In Black K. S., Paterson D. M. & Cramp A. (Eds) Sedimentary Processes in the Intertidal Zone. Geological Society, London, Special Publications, 139, pp 389-399.

Boto K. & Bunt J.S. (1981). Tidal export of particulate organic matter from a northern Australian mangrove system. *Estuarine, Coastal and Shelf Science*, **13**:247-255.

Boto, K. G. and Wellington, J. T. (1988). Seasonal variations in concentrations and fluxes of dissolved organic and inorganic materials in a tropical, tidally-dominated, mangrove waterway. *Marine Ecology Progress Series Inter-Research*, Federal Republic of Germany, **50:**151-160.

Bowers D. G & Al-Barakati A. (1997). Tidal rectification on drying estuarine sandbanks. *Estuaries*, **20(3):**559-568.

Brown S. L. (1998). Sedimentation on a Humber saltmarsh. In Black K. S., Paterson D. M. & Cramp A. (Eds) Sedimentary Processes in the Intertidal Zone. Geological Society, London, Special Publications, 139, pp 69-83.

Bulthuis, D. A., Axelrad, D. M., and Mickelson, M. J. (1992). Growth of the seagrass *Heterozostera tasmanica* limited by nitrogen in Port Phillip Bay, Australia. *Marine Ecology Progress Series* Inter-Research, Federal Republic of Germany, **89**:269-275.

Bulthuis, D. A., Brand, G. W., and Mobeley, M. C. (1984). Suspended sediments and nutrients in water ebbing from seagrass-covered and denuded tidal mudflats in a southern Australian embayment. *Aquatic Botany* 3-4, **20**:257-266.

Cahoon L. B., Nearhoof J. E. & Tilton C. L. (1999). Sediment grain size effect on benthic microalgal biomass in shallow aquatic ecosystems. *Estuaries,* **22**(3B):735-741.

Chapman M. G. & Underwood A. J. (1995). Mangrove forests. *In* Underwood A. J. & Chapman M. G. (Eds) *Coastal Marine Ecology of Temperate Australia*. UNSW Press Ltd., pp.187-204.

Clarke P. J. (1985). Nitrogen pools and soil characteristics of a temperate estuarine wetland in eastern Australia. *Aquatic Botany*, **23**:275-290.

Connell D. W., Bycroft B. M. Miller G. J. & Lather P. (1981). Effects of a barrage on flushing and water quality in the Fitzroy River estuary, Queensland. *Australian Journal of Marine and Freshwater Research*, **32**:57-63.

Cooper J. A. G. (1993). Sedimentation in a river dominated estuary. *Sedimentology*, **40**:979-1017.

Dalrymple R. W., Zaitlin B. A. & Boyd R. (1992). Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology*, **62**(6):1130-1146.

Dyer K. R. (1998). The typology of intertidal mudflats. *In* Black K. S., Paterson D. M. & Cramp A. (Eds) *Sedimentary Processes in the Intertidal Zone*. Geological Society, London, Special Publications, **139**, pp 11-24.

Eyre B. (1995). A first-order nutrient budget for the tropical Moresby estuary and catchment, North Queensland, Australia. *Journal of Coastal Research*, **11**(3):717-732.

Eyre B. (1998). Transport, Retention and Transformation of Material in Australian Estuaries. *Estuaries*, **21**(4A):540-551.

Eyre B. & Balls P. (1999). A comparative study of nutrient behaviour along the salinity gradient of tropical and temperate estuaries. *Estuaries*, **22**(2A):313-326

Frey R. W. & Basan P. B. (1978). Coastal saltmarshes. *In* Davis R. A. (Ed) *Coastal Sedimentary Environments*. Springer-Verlag, New York, pp. 101-169.

Gabric A. J. & Bell P. R. F. (1993). Review of the effects of non-point nutrient loading on coastal ecosystems. *Australian Journal of Marine and Freshwater Research*, **44**:261-283.

Harris G. (1999). The response of Australian estuaries and coastal embayments to increased nutrient loadings and changes in hydrology. *In* Smith S. V. & Crossland C. J. (Eds) *Land-Ocean Interactions in the Coastal Zone (LOICZ): Australian Estuarine Systems: Carbon, Nitrogen and Phosphorus Fluxes*. LOICZ Reports and Studies, No. 12.

Heggie D. T. & Skyring G. W. (1999). Flushing of Australian estuaries, coastal lakes and embayments: an overview with biogeochemical commentary. *AGSO Journal of Australian Geology and Geophysics*, **17**(5/6):211-225.

Heggie D. T., Skyring G. W., Berelson W. E., Longmore A. R., Nicholson G. J. (1999). Sediment-water interaction in Australian coastal environments: implications for water and sediment quality. *AGSO Journal of Australian Geology and Geophysics*, **17**(5/6):159-173.

House W. A., Jickells T. D., Edwards A. C., Praska K. E. & Dennison F. H. (1998). Reactions of phosphorus with sediments in fresh and marine waters. *Soil Use and Management*, **14**:139-146.

Howes, B. L. and Goehringer, D. D. (1994). Porewater drainage and dissolved organic carbon and nutrient losses through the intertidal creekbanks of a New England saltmarsh. *Marine Ecology Progress Series*, **114**:289-301.

Iizumi, H.,Hattori, A., and McRoy, C.P. Nitrate and nitrite in interstitial waters of eelgrass beds in relation to the rhizosphere. *J. exp. Mar. Biol. Ecol*. **47**: 191-201.

Iizumi, H. (1986). Soil Nutrient Dynamics. In Cragg, S. Polunin N., Workshop on Mangrove Ecosystem Dynamics UNDP/UNESCO Regional Project (RAS/79/002), New Dehli. 171-180.

Inglis G. J. (1995). Intertidal muddy shores. In Underwood A. J. & Chapman M. G. (Eds) Coastal Marine Ecology of Temperate Australia. UNSW Press Ltd., pp. 171-186.

Jones B. G., Martin G. R. & Senapati N. (1993). Riverine-tidal interactions in the monsoonal Gilbert River fan delta, northern Australia. *Sedimentary Geology*, **83**:319-337.

Kemp W. M., Sampou P., Caffrey J. Mayer M., Henriksen K. & Boynton W. R. (1990). Ammonium recycling versus denitrification in Chesapeake Bay sediments. Limnology *and Oceanography*, **35**(7):1545-1563.

King, G. M. (1983). Sulfate reduction in Georgia saltmarsh soils: an evaluation of pyrite formation by use of "SUP 35"S and "SUP 55"Fe tracers. *Limnology and Oceanography*, **28**: 987-995.

King, G. M., Klug, M. J., Wiegert, R. G., Chalmers, and A.G. (1982). Relation of soil water movement and sulphide concentration to Spartina alterniflora production in a Georgia saltmarsh. *Science*, **218**:61-63.

Knighton A. D., Woodroffe C. D. & Mills K. (1992). The evolution of tidal creek networks, Mary River, northern Australia. *Earth Surface Processes and Landforms*, **17**:167-190.

Kristensen, E., Jensen, M. H., Banta, G. T., Hansen, K., Holmer, M., and King, G. M. (1998). Transformation and transport of inorganic nitrogen in sediments of a southeast Asian mangrove forest. *Aquatic Microbial Ecology*, **15**:165-175.

Lukatelich R. J., Schofield N. J. & McComb A. J. (1987). Nutrient loading and macrophyte growth in Wilson Inlet, a bar-built southwestern Australian estuary. *Estuarine, Coastal and Shelf Science*, **24**:141-165.

Maguer, J.-F., ’Helguen, S., and Le Corre, P. (2000). Nitrogen uptake by phytoplankton in a shallow water tidal front. *Estuarine, Coastal and Shelf Science*, **51**:349-357.

McNae W. (1968). A general account of the flora and fauna of mangrove swamps and forests in the Indo-West Pacific region. *Advances in Marine Biology*, 6:73-270.

Morrisey D. (1995). Saltmarshes. In Underwood A. J. & Chapman M. G. (Eds) Coastal Marine Ecology of Temperate Australia. UNSW Press Ltd., pp. 205-220.

Nichol S. L. (1991). Zonation and sedimentology of estuarine facies in an incised valley, wave dominated, microtidal setting, New South Wales, Australia. In Smith D. G., Reinson G. E., Zaitlin B. A. & Rahmani R. A. (Eds) Clastic Tidal Sedimentology. *Canadian Society of Petroleum Geologists, Memoir* **16**, pp. 41-58.

Nixon S. W., Furnas B. N., Lee V., Marshall N., Jun-Eong O., Chee-Hoong W., Wooi-Knoon G. & Sasekumar A. (1984). The role of mangroves in the carbon and nutrient dynamics of Malaysia estuaries. In Soepardmo E., Rao A. N. & Macintosh D. J. (Eds) Proceedings of the Asian Symposium on Mangrove Environment: Research and Management. University of Malaya, Kuala Lumpur, Malaysia, pp. 534-544.

Nedwell, D. B. (1973). Inorganic nitrogen metabolism in a eutrophicated tropical mangrove estuary. *Water Research*, **9**:221-231.

Nedwell, D. B., Blackburn, T. H., and Wiebe, W. J. (1994). Dynamic nature of the turnover of organic carbon, nitrogen and sulphur in the sediments of a Jamaican forest. *Marine Ecology Progress Series*, **110**:223-231.

Nuttall P. M., Richardson B. J. & Condina P. (1989). Effects of saline flushing to a polluted estuary to enhance water quality standards. *Water Science & Technology*, **21**(2):167-176.

O'Donohue, M. J., Glibert, P. M., and Dennison, W. C. (2000). Utilization of nitrogen and carbon by phytoplankton in Moreton Bay, Australia. *Marine and Freshwater Research*, **51**:703-712.

Opdyke B. N., Smith S. V., Eyre B., Heggie D. T., Skyring G. G., Crossland C. J. & Zeldis J. (1999). Australian coastal systems overview. In Smith S. V. & Crossland C. J. (Eds) Land-Ocean Interactions in the Coastal Zone (LOICZ): Australian Estuarine Systems: Carbon, Nitrogen and Phosphorus Fluxes. LOICZ Reports and Studies, No. 12.

Paterson, A. W. and Whitfield, A. K. (2000). Do shallow-water habitats function as refugia for juvenile fishes? *Estuarine, Coastal and Shelf Science*, **51**:359-364.

Paterson D. M. (1989). Short-term changes to the erodibility of intertidal sediments related to the migratory behaviour of epipelic diatoms. *Limnology and Oceanography*, **34**:223-234.

Reide Corbett, D., Dillon, K., and Burnett, W. (2000). Tracing groundwater flow on a barrier island in the north-east Gulf of Mexico. *Estuarine, Coastal and Shelf Science*, **51**:227-242.

Ridd P. (1996). Flow through animal burrows in mangrove creeks. *Estuarine, Coastal and Shelf Science*, **43**:617-625.

Ridd, P. V. and Sam, R. (1996). Profiling groundwater salt concentrations in mangrove swamps and tropical saltflats. *Estuarine, Coastal and Shelf Science*, **43**:627-635.

Ridd P., Sam R., Hollins S. & Brunskill G. (1997). Water, salt and nutrient fluxes of tropical saltflats. *Mangroves and Salt Marshes*, **1**:229-238.

Ridd P., Sandstrom M. W. & Wolanski E. (1988). Outwelling from tropical tidal saltflats. *Estuarine, Coastal and Shelf Science*, **26**:243-253.

Ridd P. V., Wolanski E. & Mazda Y. (1990). Longitudinal diffusion in mangrove fringed tidal creeks. *Estuarine, Coastal and Shelf Science*, **31**:541-554.

Rivera-Monroy, V. H. and Twilley, R. R. (1996). The relative role of denitrification and immobilization in the fate of inorganic nitrogen in mangrove sediments (Terminos Lagoon, Mexico). *Limnology and Oceanography*, **41**:284-296.

Rivera-Monroy, V. H., Twilley, R. R., Boustany, R. G., Day, J. W., Vera-Herrera, F., and del Carmen Ramirez, M. (1995). Direct denitrification in mangrove sediments in Terminos Lagoon, Mexico. *Marine Ecology Progress Series*, **126**:97-109.

Robertson A. I. (1991). Plant-animal interactions and the structure and function of mangrove forest ecosystems. *Australian Journal of Ecology*, **16**:433-443.

Roy P. S. (1984). New South Wales estuaries: their origin and evolution. In Thom B. G. (Ed) Developments in Coastal Geomorphology in Australia, Academic Press, New York, pp. 99-121.

Rysgaard S., Risgaard-Peterson N., Sloth N. P., Jensen K. & Nielsen L. P. (1994). Oxygen regulation of nitrification and denitrification in sediments. *Limnology and Oceanography*, **39**(7):1643-1652.

Semeniuk V. (1982). Geomorphology and Holocene history of the tidal flats, King Sound, north-western Australia. *Journal of the Royal Society of Western Australia*, **65**(2):47-68.

Smith, T. J. III, Boto, K. G., Frusher, S. D., and Giddins, R. L. (1991). Keystone species and mangrove forest dynamics: the influence of burrowing by crabs on soli nutrient status and forest productivity. *Estuarine, Coastal Shelf Science*, **33**:419-432.

Ward, T., Butler, E., Hill, B. (1998). Environmental indicators for National State of the Environment Reporting, CSIRO Division of Marine Research, Commonwealth of Australia, pp. 84.

Wells J. T. (1995). Tide dominated estuaries and tidal rivers. In Perillo G. M. E. (Ed.) Geomorphology and Sedimentology of Estuaries. Elsevier Science, *Developments in Sedimentology* **53**, pp. 179-205.

West R. J. (1983). The seagrasses of NSW estuaries and embayments. *Wetlands*, **3**(1):34-44.

West, J. and Zedler, J.B. (2000). Marsh-creek connectivity: Fish use of a tidal saltmarsh in Southern California. *Estuaries* **23**(5): 699-710.

Wolanski E. (1992a). Hydrodynamics of tropical coastal marine systems. In Connell D. W. & Hawker D. W. (Eds) Pollution in Tropical Aquatic Systems. CRC Press, Inc., London, pp 4-24.

Wolanski E. (1992b). Hydrodynamics of mangrove swamps and their coastal waters. *Hydrobiologia*, **247**:141-161.

Wolanski E., Spagnol S., Thomas S., Moore K., Alongi D. M., Trott L. & Davidson A. (2000). Modelling and visualising the fate of shrimp pond effluent in a mangrove-fringed tidal creek. *Estuarine, Coastal and Shelf Science*, **50**:85-97.

Wulff A., Sundback K., Nilsson C., Carlson L. & Jonsson B. (1997). Effect of sediment load on the microbenthic community of a shallow-water sandy sediment. *Estuaries*, **20**(3):547-558.

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Appendix A Estuarine Condition Map and Criteria

A.1 Estuarine Condition Map

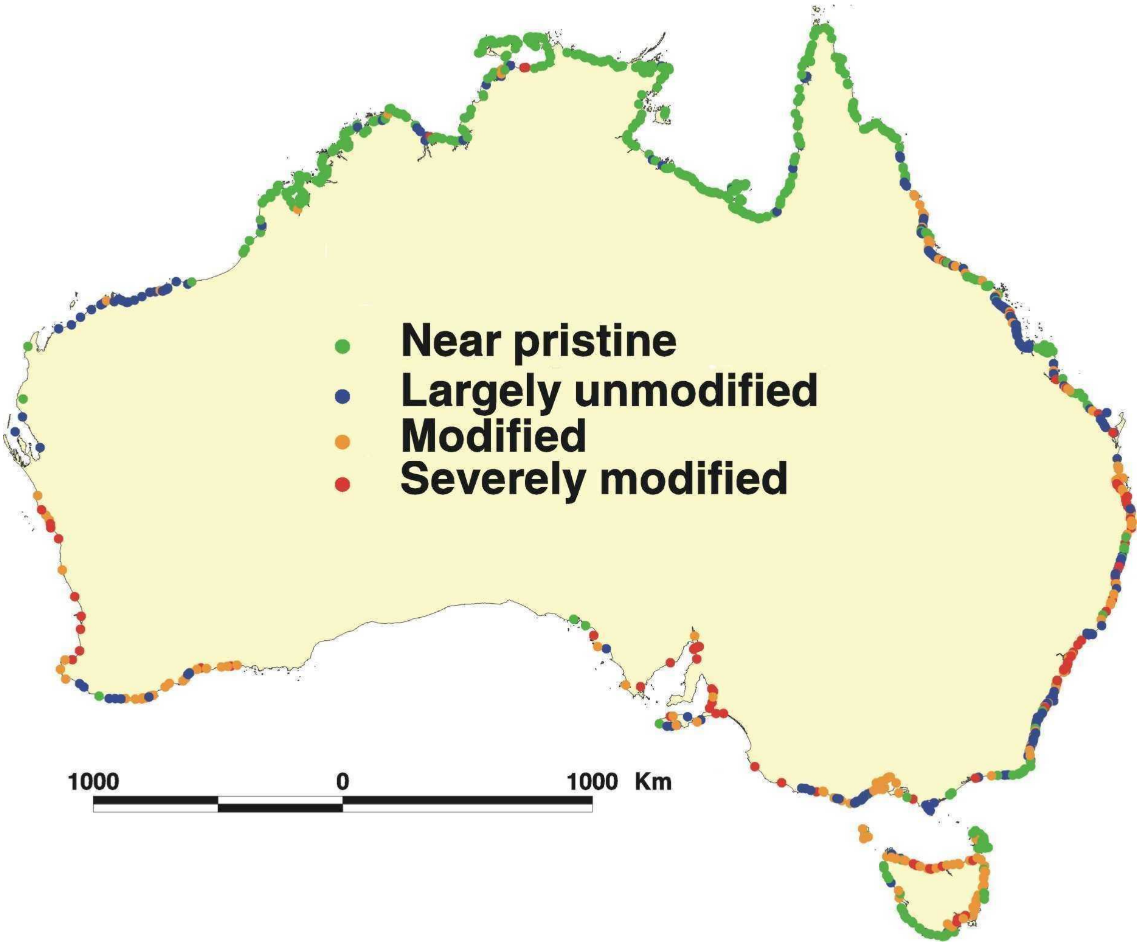

Figure 36. Estuarine Condition Map.

A.2 Condition Criteria

Table 18. Draft Criteria for Initial Classification of estuaries.

	Physical Characteristics	Condition
Near Pristine These estuaries are generally recognised as being in excellent condition, with management activities focused particularly on the protection of natural values. These estuaries are likely to provide baselines to judge the condition of other estuaries.	Catchment natural cover	>90%
	Land use	Limited roads & disturbance to natural conditions and processes
	Catchment hydrology	No dams or impoundments, virtually nil abstraction
	Tidal regime	No impediments to tidal flow, changes from natural morphology (e.g. training walls, barrages, bridges and causeways)
	Floodplain	Wetlands intact in vegetation and hydrology, no alterations to flood pattern
	Estuary Use	Extractive activities limited to indigenous or limited and sustainable commercial and recreational fishing, no aquaculture
	Pests & weeds	Minimal impact on estuary from catchment weeds and limited pests and weeds within estuary
	Estuarine Ecology	Ecological systems and processes intact (e.g. benthic flora and fauna)
Largely unmodified These estuaries are generally recognised and documented as being in good condition, but with some catchment and estuary use	Catchment natural cover	~65 -90%
	Land use	No known gross impacts from land use (e.g. sediment to waterways and estuary)
	Catchment hydrology	No dams or significant impoundments, some abstraction
	Tidal regime	No significant impediments to tidal flow or changes from natural morphology
	Floodplain	Wetlands mostly intact in vegetation and hydrology, no alterations to flood pattern
	Estuary Use	Extractive activities limited to sustainable commercial and recreational fishing, minor aquaculture
	Pests & weeds	Minimal impact on estuary from catchment weeds and limited pests and weeds within estuary
	Estuarine Ecology	Ecological systems and processes mostly intact (eg some changes to benthic flora and fauna)

Modified These estuaries are generally recognised and documented as having some problems due to a complexity of impacts from within the catchment, waterway and estuary. Remedial works and activities for recovery may range from minor to substantial	Catchment natural cover	<65%
	Land use	Documented impacts from land use eg sediment and nutrients to waterways
	Catchment hydrology	Dams and impoundments, significant abstraction modifying natural flows
	Tidal regime	Impediments to tidal flow and/or changes from natural morphology e.g. training walls, causeways, artificial opening of entrance
	Floodplain	Wetlands mostly cleared in vegetation an/or changes in hydrology, e.g. drains, tidal barrages, levees
	Estuary Use	Extractive activities include dredging, extensive aquaculture, habitat modifying fishing methods, e.g. prawn trawling
	Pests & weeds	Significant impact on estuary from catchment weeds and impact on estuary ecology from pests and weeds within estuary
	Estuarine Ecology	Ecological systems and processes modified (e.g. loss of benthic flora and fauna)
Severely Impacted These estuaries are generally recognised and documented as having multiple problems due to a complexity of impacts from within the catchment, waterway and estuary. Remedial works and activities for recovery are likely to be substantial and may be cost prohibitive.	Catchment natural cover	<35%
	Land use	Documented impacts from land use throughout waterways and into estuary
	Catchment hydrology	Dams and impoundments, significant abstraction modifying natural flows
	Tidal regime	Major changes to tidal flow and/or major changes from natural morphology
	Floodplain	Wetlands mostly cleared in vegetation an/or changes in hydrology, e.g. major losses in fresh to brackish wetlands
	Estuary Use	Extractive activities include dredging, extensive aquaculture, habitat modifying fishing methods, e.g. prawn trawling
	Pests & weeds	Significant impact on estuary from catchment weeds and impact on estuary ecology from pests and weeds within estuary
	Estuarine Ecology	Ecological systems and processes degraded (e.g. major changes to habitats or species assemblages)

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Appendix B Estuarine Classification Methodology

The ratio of wave and tidal power is used to classify estuaries along the base of the ternary diagram (Figure 1). The energy of a wave (E; J m^{-2}) is given as:

$$E = 1/8(\rho g H^2) \quad (1)$$

where ρ is the water density (kg m^{-3}), g is acceleration due to gravity (m s^{-2}) and H is the wave height (m). The wave and tidal power P_w and P_t (J m^{-2} s^{-1}), respectively, is the energy per wave period[1] (T), which is the ratio of E and T. Because waves and tides are both wave phenomena, the relative (dimensionless) wave/tide power ratio (P_r) can be calculated from P_w and P_t as follows:

$$Pr = Pw/Pt = K\ [H2/T]wave\ /\ [H2/T]tide \quad (2)$$

where K is a dimensionless coefficient, that is derived from a line of best fit that delineates wave- and tide-dominated systems as defined by their geomorphology (see Section 2.3).

Surface wind speed estimates generated by the Australian Bureau of Meteorology's regional atmospheric model provided input to the Wave Model, WAM (Hasselman *et al.* 1988; Komen *et al.* 1994) to yield estimates of mean wave height and period. The data are 6-hourly predictions of Significant Wave Height (SWH) and mean wave period (T) that were grided at 0.1° (~11 km) spatial resolution for the period March 1997 to February 1998 inclusive. Using a cubic spline, the annual mean SWH and T were extrapolated from the model grid points to estuaries and coastal waterways around Australia.

The maximum spring tide range was calculated at 423 tide gauges located around Australia and then extrapolated to the 780 estuaries and coastal waterways contained in the AED using a cubic spline. Tidal period (T) was determined on the basis of the ratio of major tidal constituents K_1 (lunar-solar diurnal), O_1 (principal lunar diurnal), M_2 (principal lunar semi-diurnal) and S_2 (principal solar semi-diurnal) as follows:

$$T = (K1 + O1)/(M2 + S2) \quad (3)$$

The derived wave and tidal power are considered to represent the regional conditions at the coast and will not necessarily reflect local effects such as sheltering by headlands.

Annual mean fluvial discharge, presented in Digby *et al.* (1998), then was incorporated into the energy classification to obtain a measure of river energy. Although the use of annual mean fluvial discharge is consistent with annual mean wave and tide values, we acknowledge that the discharge of many Australian river systems is event-driven (e.g. Erksine and Warner, 1978) and will not necessarily reflect the extreme river energy associated with flood events.

An independent check of the geomorphology of the 780 estuaries and coastal waterways contained in the AED and subject to the energy classification was undertaken by a visual inspection of Landsat TM images and aerial photographs (where available). In order to classify all 974 estuaries and coastal waterways defined by the NLWRA into the coastal system types, the additional 194 estuaries and coastal waterways were also classified into their respective types using Landsat TM images and aerial photographs. Initially systems were classified as wave, tide or mixed based on the overall geomorphology. This geomorphic classification was then divided into six subclasses (Figure 1) to account for the variation in fluvial energy (c.f. Boyd *et al.* 1992).

[1] The wave period is the time it takes for successive wave crests to pass a stationary point.

The results of the geomorphic classification of AED estuaries for which runoff data were available indicate that there are 515 tide-dominated systems (tide-dominated estuaries, tide-dominated deltas, tidal flat/creeks) compared to 170 wave-dominated systems (wave-dominated estuaries, wave-dominated deltas, strandplains) and 95 “mixed” systems (i.e. systems with geomorphology showing major wave- and tide-dominated features). Because of the uneven number of wave- and tide-dominated systems, a line of best fit, separating the two groups was drawn with a slope of 3.2. This slope was used as the coefficient (K) in equation 2, to centre the distribution, so that the transition between wave- and tide-dominated systems occurred at a $P_w/P_t = 1$ (i.e. Log $(P_w/P_t) = 0$) when included with river energy (Figure 3).

B.1 References

Erskine, W.D. & Warner, R.F. (1978). Geomorphic effects of alternating flood- and drought-dominated regimes on NSW coastal rivers. *In*: Warner, R.F. (Ed.) *Fluvial geomorphology of Australia*. Academic Press, Sydney.

Boyd, R., Dalrymple, R.W. & Zaitlin, B.A. (1992). Classification of clastic coastal depositional environments. *Sedimentary Geology* **80**, 139-150.

Hasselman, K. & WAMDI Group, (1998). The WAM model – A third generation ocean wave prediction model. *Journal of Physical Oceanography* **18**, 1775-1810.

Komen, G., Cavaleri, L., Donelan, M., Hasselman, K., Hasselman, S. & Janssen, P.A.E.M. (1994). *Dynamics and modelling of ocean waves*. Cambridge, Cambridge University Press. 532pp.

Appendix C General Sedimentary Characteristics Of Facies Types

Table 19. General characteristics of each facies type.
BBB = barrier and back barrier; BED = bedrock (BED); CB = central basin; COR = coral reef; FBD = fluvial bayhead delta; FED = flood and ebb tide delta; IF = intertidal flats; MAN = mangrove; RR = rocky reef (RR); SM = saltflat/saltmarsh; and TSB = tidal sand banks

	TSB	CB	FBD	BBB	IF	MAN.	SM	SF	COR	BED/RR	FED
Grain size	Sand	Mud/Sandy-Mud	Muddy-Sand	Sand	Sandy-Mud/ Sand	Silt/Clay	Silt/Clay	Silt/Clay	Sand/Gravel	Clay/Gravel	Sand
Sorting	Mod.-Well	Poor	Poor-Mod.	Well	Poor-Mod.	Poor	Poor	Poor	Poor	Poor-Mod.	Well
% Carbonate	High	High	High	High	High	Low	Low	High	High	High	High
% Organic	Low	High	High	Low	High	High	High	Low	Low	Low	Low
Elevation	<MHWS	<MHWS	<Supra-tidal	>MLWS	MLWS-MHWS	MLWS-MHWS	>MHWS	>MHWS	<MLWS	<Supra-tidal	<Supra-tidal
Bedforms	Straight/Sinuous crested dunes	Nil	Poorly developed	Cusps, Dunes, Ripples	Nil	Nil	Nil	Nil	Nil	Nil	Straight/Sinuous crested dunes
Vegetation	Seagrass, Mangroves	Nil	Mangroves, Terrestrial	Seagrass, Mangroves, Terrestrial	Nil	Mangroves	Grasses, Reeds, Sedges	Algal Mats, Grasses	Nil	Algal Mats	Seagrass
Biol. Activity	High	High	High	Mod.	High	High	High	High	High	Mod.	Mod.
Turbid	Mod.-High	Low	Mod.-High	Low	Mod.	Mod.	Low	Low	Low	Low	Mod.
Energy	High	Low	Mod.-High	High	Low/Mod.	Low	Low	Low	Mod.-High	Mod.-High	High
Other		Anoxic Sed.			Low gradient surface	Strongly reduced sed.	Anoxic Sed., Low gradient surface	Anoxic Sed., Low gradient surface	Oxygenated, Oligotrophic conditions		

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Appendix D Estuarine Geometry

D.1 Image Preparation

AGSO holds a database of Landsat TM satellite imagery (acquired from ACRES), comprising over 90% of the Australian coastline. These data were the primary source of information for measurement of geometric data for estuaries and coastal waterways.

These scenes were georectified (located within geographical space) using Image Processing Software (*ER Mapper*™), and the AGD66 geodetic datum. Ground control points (10-15 per scene) were correlated with the appropriate AUSLIG 1:250 000 series map sheet, producing a spatially located scene with a pixel resolution of 25-30 m.

These scenes were then “masked” to define the boundary between ocean and terrestrial environments. A formula involving Band 1 (Blue) and Band 5 (Infrared) was used to highlight the boundary between water (which characteristically has very low reflectance values for Band 5) and land (which has very high Band 5 values). The images were then printed at an appropriate scale to show the relevant extents of the estuaries. The hard copies were passed to the interpreter for identification of areas, lengths, and locations.

D.2 Defining the Estuarine Geometry Indices

Interpretation and definition of the geometric measurements was made on hardcopies of AGSO’s Landsat TM images, with the aid of reference material such as 1:100 000 topographic maps, and literature sources where available. Interpretative boundaries were set in order to define the estuarine zone and derive quantitative data for further analysis. These boundaries include the seaward (downstream), landward (upstream), and boundaries between adjacent and interlinking estuaries. Over 90% of the 974 Audit-defined estuaries were covered, however, gaps within the Landsat TM coverage were the primary cause for omitting the remaining 66 estuaries.

The seaward limit of each estuary and coastal waterway (boundary between estuarine and oceanic conditions) was defined using some or all of the following criteria:

- the point at which one or more constricting heads narrows (AGSO 1:100 000 (WGS84) Coastline coverage);
- the point equidistant between headlands, where the estuarine entrance channel is perpendicular to the coastline; and
- in less clear circumstances, an arbitrarily set boundary was used. This boundary was defined as the point at which the distance between the two opposing banks first narrows to a distance of less than 2 km when approached from seaward (after Digby *et al.* 1998).

The landward limit of the estuary or coastal waterway was defined using some or all of the following criteria:

- the point at which the fluvial channel first shows signs of symmetrical sinuosity (indicating a loss of tidal influence) (Dalrymple *et al.* 1992);
- the point at which estuarine facies first become absent, and fluvial facies predominate (this was only obvious with high quality images);
- the point at which the Landsat TM coverage reaches a width of less than 1 pixel (25-30 m); and
- the point at which the estuary is wide enough to be represented as double lines on a 1:100 000 topographic map (after Digby *et al.* 1998).

Boundaries between adjacent estuaries and coastal waterways (where estuaries are interlinked) were made using information from 1:100 000 topographic map sheets. Boundaries defining the area of connected waterways or passages were set at an arbitrary point, equidistant from the entrance points of each waterway.

D.3 Spatial Capture of Geometric Indices

The spatial capture of these geometrical properties was compiled using image processing software (*ERMapper*™). The "heads up" digitising method was used to transfer the interpretation to an *ERMapper*™ vector (.erv) file. Each geometric index was saved in a single file for each Landsat TM scene. Scales available for the digitising of geometry ranged from 1:1000 to 1:50 000, although most occurred at 1:5000 or 1:10 000. The image window size remained constant at 500x500 pixels for all estuaries.

A GIS-based polygon or vector data coverage was produced for each estuary and coastal waterway. The value of the relevant geometrical properties were established for each estuary, collated and stored in spreadsheet form.

D.4 Explanation of Database fields

Descriptions of each data type obtained from the Landsat TM images is given below, including metadata associated with each field.

An example (Lake Illawarra, NSW) of each of the geometric measurements is also given for each of the geometric indices.

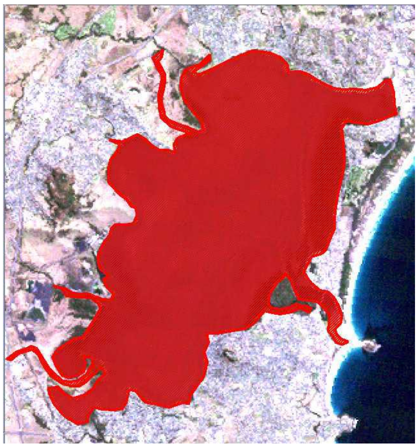
Estuarine Water Area - Polygon

Area of water comprising the estuary between the upstream and downstream estuarine limits. This does not include areas of subaerial deposits (ie saltmarshes, fluvial deltas, but does include the area of intertidal facies (e.g. intertidal flat, sandbars). Thus, all high-tide subaqueous environments are considered.

The water area, as determined by Landsat TM, was delineated using a formula involving the infrared Band 5, which has characteristically low values for areas of water. With experiments in known areas, a boundary Band 5 value of 15-20 was chosen, with all Band 5 values lower than this being considered water.

The water area of macrotidal estuaries (regions with a tidal range of >4 m), is thus a measurement of the water area apparent on the scene, as well as any intertidal facies, as defined by the limit of vegetation on the flanks of the estuary.

Islands within estuaries have been taken into account; these are stored as separate polygons (with the same estuary number), and their area has been subtracted from the total water area.



Estuarine Water Area & Perimeter

Perimeter of the Estuary - Polygon

Derived from the polygon obtained in measuring the estuarine water area. This reflects the amount of shoreline environment, so 'island' polygons are added to the total perimeter. For a measurement of shoreline habitat within the estuary, the entrance width(s) should be subtracted from the perimeter value.

Total Length of the Estuary - Vector

Total Estuarine Length

Maximum channel distance a particle of water would have to travel in moving from the upstream boundary, to the downstream boundary (marine conditions). Only 1 measurement per estuary, considering the main fluvial source, and ignoring minor tributaries.

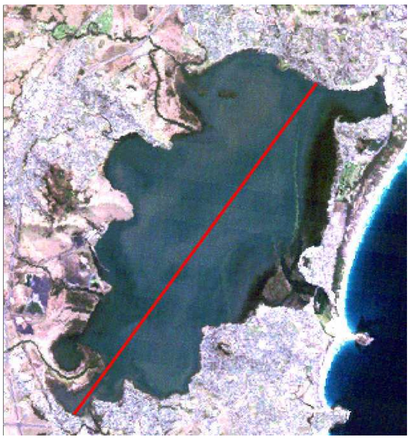
In the case of bays and bay-like features, a fluvial source is not always apparent. In this case the length is simply defined as the largest straight-line distance perpendicular to the entrance that a particle of water might travel.

In the case of marine passages [such as Hinchinbrook Channel (385)], the length will refer to the maximum distance between the largest entrance (entwidth) and the subordinate entrance (entwidth2 or 3), which will reflect distance required for tidal flushing.

Maximum Width of the Estuary - Vector

Maximum width of the estuarine 'basin', if present. The measurement is approximately perpendicular to the estuarine length measurement, and does not include 'cut-off embayments' - features that are significantly isolated from the main channel and water flow within the estuary.

In estuaries with multiple basins, the smaller basins removed from the fluvial/tidal channel were considered cut-off embayments.



Maximum Width

Entrance Width - Vector

Width of the estuary at the point of constriction, or otherwise identified entrance (see above). In the event of multiple entrances, the main entrance is digitised as "entwidth", followed by progressively smaller entrances as "entwidth2" and "entwidth3". The entrance widths can then be totalled or analysed separately.

On wave dominated coastlines, entrances are often obscured by the presence of a 'surf zone' of shoaling water, which masks the correct water signature and appears white. Entrance widths were thus estimated from the width of the channel immediately landward of the surf zone.

Entrance Width

Entrance widths less than 0.1 km were lumped together as “less than 100m” as the resolution of Landsat TM does not allow accurate length calculations of features this small.

Entrance Length

Entrance Length - Vector

Defined as the length of the constricted section of the entrance channel, from the seaward limit to the ‘basin’. Only applicable to some estuaries.

Location Point

The location of the mid point of the main (largest) entrance to the estuary or coastal waterway. Location units are GDA94 decimal degrees.

Appendix E Technical Report for Estuarine Facies Mapping/Digitising

The digitising and archiving of estuarine facies maps has occurred in several stages. These are:

1. image preparation
2. facies interpretation;
3. Creating Coverages and associated Statistical Files; and
4. Archiving of Interpretation Maps and Data.

E.1 Image Preparation:

Coastline Landsat TM imagery was acquired from ACRES and added to the AGSO image library. These scenes were then geo-rectified using Image Processing Software (ER Mapper™) using 10 - 15 ground control points per image. Correlation of these points was to the appropriate AUSLIG 1:250 000 series map sheet. Individual estuaries were then identified within a scene, saved as specific algorithms. The resultant algorithms were printed at appropriate scales ranging from 1:15 000 to 1:40 000. These images then became the “base image” for the recording of estuarine facies units. In cases where TM imagery was unavailable, digital images of 1:100 000 topographic maps were used as a replacement.

E.2 Facies Interpretation:

Identification of Estuarine facies was undertaken by interpreting the Landsat TM image with the assistance of relevant aerial photographs and compiled onto overlays / transparencies attached to the image. Creating Coverages and associated Statistical Files.

Digitising interpretation

The resultant interpretation overlays were then digitised using the 'heads up' digitising approach within ERMapper using either the algorithm or topographic image as a base. The scale at which each estuary was digitised was no greater than 1:5000 with a window size of 650x650 pixels. All boundaries were spatially captured using the Transverse Mercator Projection and the AGD66 datum. The digitised facies boundaries were saved as a ER Mapper vector layer (.erv), this was then converted to a AutoCAD/dxf file format (.dxf).

Converting vectors to coverages

The AutoCAD (.dxf) files were then converted to ArcInfo™ coverages using an Arc Macro Language (AML) script. The AML spatially referenced and named the coverage by entering relevant information when prompted such as cover name, projection/zone and datum. The AML also cleaned, built and added standard Data Dictionary items to both the polygon (.pat) and arc (.aat) attribute tables associated with the coverages.

The items added to the arc attribute tables (.aat) were:

ITEM	WIDTH	OUTPUT	TYPE
FEATURE	12	12	C
UFI	6	6	I
AGSO_CODE	8	8	I
CLASS	2	2	I
DESC	100	100	C
PLOTRANK	2	5	B

While the items added to the polygon attribute tables (.pat) were:

ITEM	WIDTH	OUTPUT	TYPE
UFI	6	6	I
FEATURE	12	12	C
POLYLABEL	5	5	C
DESC	60	60	C
SYMBOL	4	4	I
DEFINITION	254	254	C

Editing and Labelling

Editing of the coverage involved the removal of dangling arcs and pseudo nodes, corrections of undershoots, snapping of nodes/arcs, and the labelling of polygon units. Also annotated here are the channel-bedrock facies interface/boundary. The label of facies units were recorded in the .pat file under the polylabel item while the channel-bedrock facies interface/boundary was recorded in the .aat file under the description item.

After completion of editing and labelling, the coverage was then 'built' to create topology and a checkplot printed. This checkplot was used to correlate the coverage with initial interpretations. Corrections were noted on the checkplot and corrected on the coverage within the arc environment. In the situation where polygons had been overlooked ERDAS Imagine may be used to display and edit an ARC coverage over the Landsat TM image in order to accurately make additions. This process of correction and editing was continued until the Quality Control procedure was passed and a final checkplot was produced.

Creation of Frequency Tables and Quantification of Facies Relationships

Frequency tables were then created for complete coverages and associated .aat and .pat files through the use of several AML scripts that quantified several aspects of each cover. These were as follows:

- channel boundary/contacts relationships
- length of bedrock-channel/interface boundaries
- frequency and area of each facies type present within the coverage
- frequency of specific polygon relationships to assist in determining estuarine classification (i.e. wave, tide or river).

This data was then collated and stored in spreadsheet form in preparation for further analysis and entry into the OZESTUARIES database.

Archiving of Interpretation Maps and Data

Interpretation maps/images and associated checkplots have been catalogued and stored in the AGSO map library. These also have attached a hardcopy of the associated individual frequency outputs. Digital coverages and frequency files were archived in appropriately labelled directories.

Appendix F Facies Descriptions

F.1 Tidal Sand Banks (TSB)

Generally comprises elongate bodies of moderate- to well-sorted, inter-tidal to sub-tidal sand, dissected by shallow channels. The banks and channels are often aligned approximately with the main tidal currents. Gravel is often also present in low concentrations, particularly in the channels. Carbonate concentrations are generally high. Organic concentrations are generally low. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Tidal Sand Banks generally do not occur above mean high water spring elevations, but may have considerable relief, and straight and sinuous crested, full-bedded small to medium dunes often occur. Surface sand may fine towards the head of the estuary. Tidal Sand Banks may also be vegetated. Biological activity is generally abundant, particularly where tidal currents are weak. High turbidity caused by strong tidal currents often limits primary productivity.

F.2 Central Basin (CB)

Generally comprises poorly-sorted, organic-rich sub-tidal mud and sandy mud. Gravel is usually present in low concentrations. Locally, shell bioherms made up of gravel-sized estuarine bivalve shells may develop. Carbonate concentrations are generally low. Concentrations of organic material are generally high. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Surfaces are generally planar and not vegetated, however autochthonous organic carbon may be present. Sediment may be anoxic, but is generally heavily bioturbated. Biological activity is high with an abundance of infauna and epifauna.

F.3 Fluvial (bay-head) Delta (FBD)

Generally comprises poorly- to moderately-sorted, organic-rich supra-tidal to sub-tidal muddy-sand and sandy-mud. Gravel is usually present in low concentrations. Carbonate concentrations are generally low. Concentrations of organic material are generally high. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Bedforms in the channel and inter-distributary bays are poorly developed due to large fluctuations in river energy and generally low tidal energy. Biological activity in the sediment is generally high throughout. Supra-tidal regions are usually well vegetated with saltmarsh to terrestrial woodland ecosystems. Due to large salinity ranges, the diversity of fish and crustacean species is generally limited. Supra-tidal areas of the floodplain may contain human development.

F.4 Barrier/back-barrier (BBB)

Generally comprises well-sorted fine to coarse, quartz-rich supra-tidal to sub-tidal sand. Heavy minerals may occur in low concentrations. Carbonate concentrations are generally high, except in the supra-tidal dunes. Concentrations of organic material are generally low. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. The beach-face often displays a distinctive reduction in slope close to low tide and may contain cusps, a berm, and/or shallow channels and low amplitude bars. Dunes are often interspersed by blow-outs and may be separated by deflation zones, with gentle morphology. Back-barrier regions may contain wash-overs. Biological activity is most abundant in sub- and inter-tidal areas were tide and wave-generated currents are weak (e.g. back-barrier regions). Except for the beach-face, surfaces are generally vegetated. Infauna and epifauna (e.g. interstitial microfauna, crustaceans, worms and molluscs) occur at supra-tidal to sub-tidal elevations. The stability of biological communities is variable, and is generally associated with dune-stabilising vegetation above supra-tidal elevations. These habitats may also intermittently support birds, turtles and seals. Supra-tidal areas may contain human development.

F.5 Intertidal Flats (IF)

Generally comprises low-gradient, poorly- to moderately-sorted inter-tidal shelly sandy mud to well-sorted sand. Gravel may be present in moderate concentrations at the base of shallow drainage channels. Carbonate concentrations are generally high. Concentrations of organic material is generally high. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Surfaces tend to occur from mean low water spring to mean high water spring elevations and are usually flat and not vegetated, but may be dissected by shallow drainage channels. Biological activity is generally abundant throughout, and consists of both high and low tide visitors, as well as permanent inhabitants. Burrowing infauna, crustaceans, molluscs, fish and birds are generally abundant.

F.6 Mangrove (MAN)

Generally comprises forests of salt-tolerant mangrove vegetation. Mangrove forests are generally more common and extensive in tropical regions. Sediment that accumulates beneath the mangrove forests generally comprises strongly-reduced, poorly- to moderately-sorted stiff silts and clays. Carbonate concentrations are generally low. Concentrations of organic material are generally high. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Surfaces beneath the mangrove forests generally occur from mean sea level to mean high water spring elevations and are flat, but are usually pock-marked by burrowing infauna. Biological activity is generally abundant throughout. Burrowing infauna, sessile organisms, crustaceans, molluscs, fish and birds are generally abundant.

F.7 Saltmarsh (SM)

Generally comprises poorly-sorted, high-intertidal to supra-tidal, anoxic sandy silts and clays. Carbonate concentrations are generally low. Concentrations of organic material are generally high. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Saltmarshes are generally more common in temperate regions. Saltmarshes have low gradients and may be dissected by shallow brackish pools. Saltmarshes generally occur above mean high water spring and are usually vegetated with salt tolerant grasses, reeds, sedges and small shrubs. Biological activity is generally abundant throughout. Saltmarshes and associated vegetation are habitats for a wide range of infaunal and epifaunal invertebrates, as well as water birds.

F.8 Saltflat (SM)

Generally comprises poorly-sorted, high-intertidal to supra-tidal, hyper-saline sandy silts and clays. Carbonate concentrations are generally high. Concentrations of organic material are generally low. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Saltflats are generally more common in tropical regions. Saltflats generally occur above mean high water spring, and infrequent inundation by king tides creates a highly evaporative environment in which algal mats and salt tolerant grasses may be present. Biological activity is generally abundant throughout. Saltflats and associated wetland vegetation are habitats for birds, particularly during the wet season.

F.9 Coral (COR)

Generally comprise a low inter-tidal to sub-tidal community of corals and associated organisms. Sediment associated with coral communities are generally poorly-sorted, mixed siliciclastic silts and clays and/or carbonate sand and gravels. Carbonate concentrations are generally high. Concentrations of organic material are generally low. Coral communities mostly occur in tropical regions and may co-exist with rocky reef communities. Biological activity is generally abundant throughout. Coral communities tend to thrive in oligotrophic, oxygenated conditions and are a habitat for a wide range of infaunal, epifaunal, hard substrate and pelagic communities. They are typically depauperate in estuarine or nearshore environments.

F.10 Rocky Reef (RR)

Generally comprise a hard substrate that may occur at supra-tidal to sub-tidal elevations. Surfaces are generally non-depositional and sometimes erosional, and usually dominated by epifaunal and algal communities. Bedrock is often the major control on waterway geometry (width, length and depth). Below the waterline, common habitats include inter-tidal rocky shorelines to sub-tidal reefs. Bedrock/Rocky Reefs limit the available habitat for burrowing organisms, but are vital habitats for sessile organisms, organisms requiring sheltered conditions, and their associated fish communities.

F.11 Flood- and Ebb-tide Delta (FED)

Generally comprise moderately- to well-sorted, quartz-rich supra-tidal to sub-tidal sand. Gravels often occur as a lag in the main tidal channels, where tidal currents are strong. Heavy minerals may occur in low concentrations. Carbonate concentrations are generally high. Concentrations of organic material are generally low. Concentrations of carbonate and organic material are generally higher in tropical estuaries than in temperate and sub-polar estuaries. Flood oriented bedforms can occur on the shoals (e.g. straight crested, full-bedded small dunes) and ebb-oriented bedforms (e.g. sinuous crested, full-bedded small to medium dunes) can occur in the channels. Biological activity is most abundant where tidal currents are weak (e.g. headward regions of the flood tide delta shoal). Seagrasses and associated communities often occur where tidal currents are weak. Infauna and epifauna (e.g. interstitial microfauna, crustaceans, worms and molluscs) occur at supra-tidal to sub-tidal elevations. Surfaces may be vegetated. Human development on supra-tidal areas is rare.

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Appendix G Facies Mapping Boundary Definitions

The nature, distribution and geometry of each facies can be used to define its boundaries from air photos and Landsat TM imagery. Below is listed the definitions by which each of the facies was mapped. The definitions are purposefully generic in nature so that they could be identified in a wide range of estuary types.

G.1 Tidal Sand Banks (TSB)

TSB were mapped as the distinct visible area of generally elongate sediment shoals and channels near the mouths of tide-dominated estuaries. The sediment shoals are generally aligned parallel to the dominant tidal currents.

G.2 Central Basin (CB)

CB was mapped as the visible area of open water, in a wave-dominated estuary, that had not been allocated to another substrate/facies type, and that did not occur within the fluvial bay-head or tidal deltas. The central basin usually occurred landward of marine derived sediment bodies and seaward of river-derived sediment bodies.

G.3 Fluvial (bay-head) Delta (FBD)

FBD was mapped as the distinct visible area of the river floodplain, encompassing the main channel, smaller distributary channels, inter-distributary areas, and associated shoreline. In wave-dominated estuaries, the delta is called a Bay-head delta and is generally located at the head of the estuary. The headward limit is given by a line drawn across the palaeo-valley at the headward limit of salt tolerant vegetation. In cases where salt tolerant vegetation is not present or can not be reliably determined, the headward limit is the same as that used to calculate estuary length.

G.4 Barrier/back-barrier (BBB)

Barrier/back-barrier is mapped as the distinct visible area of a generally elongate sediment body, located near the mouth of wave-dominated estuaries, that separates the estuary from the ocean. The area mapped includes the distinct visible beach-face, dunes and back-barrier regions. The length of the barrier is defined as the length of the distinct visible area located between the inlet mouth and/or bedrock.

G.5 Intertidal Flats (IF)

Intertidal Flats is mapped as the distinct visible laterally continuous, that contains no vegetated and extends from the seaward limit of halophytic vegetation to the waterline.

G.6 Mangrove (MAN)

Mangrove is mapped as the distinct visible area of mangrove vegetation.

G.7 Saltflat (SM)

Saltflat is mapped as the distinct visible area encompassed by terrestrial vegetation/estuary perimeter at its landward boundary and salt-tolerant vegetation at the seaward boundary.

G.8 Saltmarsh (SM)

Saltmarsh is mapped as the saltmarsh is defined as the distinct visible area of saltmarsh vegetation.

G.9 Coral (COR)

Coral is mapped as the visible area of a coral community within the estuary. A coral community is defined as a community based upon living corals.

G.10 Rocky Reef (RR)

Rocky Reef is mapped as the distinct visible area of sub-tidal rock within the estuary.

G.11 Bedrock (BED)

Bedrock is mapped as the visible perimeter of regional pre-Holocene rock that comes into direct contact with the estuary. The headward limit of the bedrock boundary is the same as that defined for estuary length.

G.12 Flood- and Ebb-tide Delta (FED

Flood- and Ebb-tide Delta is mapped as the distinct visible perimeter of shoals proximal to, and extending immediately landward and seaward of, the inlet mouth.

Appendix H Deviation Index Methodology

Diagnostic facies (Diag.) for each of the wave- and tide-dominated subclasses (Figure 1) were defined on the basis of the groupings revealed in the cluster analysis (Figure 10), from the degree of association (as defined by the probabilities in Table 9), and also on the basis of the facies observed during the classification of estuaries and coastal waterways based on geomorphology (Table 10). Along with the diagnostic facies, each subclass may contain other facies that are present due to regional factors, such as: climate, tidal range, fluvial discharge and estuarine maturity. These facies are termed qualifiers (Qual.) and were defined on the basis of moderate associations with each subclass (Table 9) Also, a system may contain facies that are diagnostic to another subclass (Non.). Their presence may represent severe modification to that system either by human or natural processes.

Table 20. Rules for deviation for subclasses.
BBB = barrier and back barrier; CB = central basin; FBD = fluvial bayhead delta; FED = flood and ebb tide delta; IF = intertidal flats; MAN = mangrove; SM = saltflat/saltmarsh; TSB = tidal sand banks. WDD = wave-dominated delta' WDE = wave-dominated estuary; SP = strandplain; TDE = tide-dominated estuary; TDD = tide-dominated delta; and TF/TC = tidal flats/tidal creeks.

WDE			**WDD**			**SP**		
Diag.	Qual.	Non.	Diag.	Qual.	Non.	Diag.	Qual.	Non.
BBB	FED	TSB	BBB	IF	TSB	BBB	FED	FBD
CB	IF		FBD	SM	CB		IF	CB
FBD	SM		FED	MAN			SM	TSB
	MAN						MAN	

TDE			**TDD**			**TF/TC**		
Diag.	Qual.	Non.	Diag.	Qual.	Non.	Diag.	Qual.	Non.
MAN	FED	BBB	MAN	FED	BBB	MAN	FED	BBB
SM		CB	SM		CB	SM		CB
IF		FBD	IF		FBD	IF		FBD
TSB			TSB			TSB		

No weighting was applied between diagnostic, qualifier or non-diagnostic facies types. The deviation score for individual systems can thus represent either the absence of facies that should be associated with that subclass and/or the presence of facies that are not generally associated with that subclass.

H.1 Deviation Index Results

Table 21. Deviation Index Results.

NSW

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Lake Ainsworth	790	8	no estuarine facies	-8
Arrawarra/Yarrawarra Creek	793	1	no sm	-1
Avoca Lake	807	1	contains fbd	+1
Back Lagoon	835	3	contains fbd/no man/no sm	-2 / +1
Baragoot Lake	833	3	contains fbd/no man/no sm	-2 / +1
Bega River	73	1	contains tsb's	+1
Bellinger River	18	2	no fbd/contains tsb's	-1 / +1

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Bellambi Lake	815	2	no feds/no sm	-2
Bellambi Creek	814	3	no fed/no man/no sm	-3
Belongil Creek	6	3	no bbb/no fed/contains tsb's	-2 / +1
Bermagui River	67	0		0
Berrara Creek	819	2	no man/no sm	-2
Boambee Creek	16	3	no bbb/no fbd/contains tsb's	-2 / +1
Bonville Creek	17	2	no fbd/contains tsb's	-1 / +1
Botany Bay	38	1	no fed	-1
Brisbane Water	33	1	no bbb	-1
Brunswick River	5	4	no bbb/no fbd/no fed/contains tsb's	-3 / +1
Bunga Lagoon	834	2	no man/no sm	-2
Burrill Lake	51	2	no man/contains tsb's	-1 / +1
Camden Haven River	24	2	no bbb/contains tsb's	-1 / +1
Candlagan Creek And Lagoon	826	1	no fbd	-1
Lake Cathie/Innes	23	2	no fbd/no man	-2
Clarence River	9	3	no bbb/contains cb/contains tsb's	-1 / +2
Clyde River/Batemans Bay	56	0		0
Cockrone Lake	808	1	contains tsb's	+1
Coffs Harbour Creek	795	1	no man	-1
Coila Lake	59	1	no man	-1
Congo Creek And Lagoon	827	3	no fed/no man/no tsb's	-3
Corunna Lake	64	3	no if/no man/no sm	-3
Corindi River/Red Rock River	13	2	no fbd/contains tsb's	-1 / +1
Cooks River	812	3	contains fbd/no fed/no man	-2 / +1
Crooked River And Lagoon	818	2	no man/no sm	-2
Cudgen Lake	2	0		0
Cudgera Creek	3	2	no fed/contains tsb's	-1 / +1
Cullendulla Creek	825	1	no tsb's	-1
Curalo Lagoon	77	0		0
Curl Curl/Harbord Lagoon	810	3	no fed/no man/contains tsb's	-2 / +1
Currambeen Creek	46	3	no fbd/no fed/contains tsb's	-2 / +1
Cuttagee Lake	68	3	no if/no man/no sm	-3
Dalhousie Creek And Lagoon	796	2	no man/no sm	-2
Deep Creek	19	1	contains tsb's	+1
Dee Why Lagoon	809	3	contains fbd/no fed/no man	-2 / +1
Evans River	8	3	no fbd/no sm/contains tsb's	-2 / +1
Fairy Creek	816	1	no sm	-1
Georges River	813	1	no fed	-1
Hastings River	22	2	no fbd/contains tsb's	-1 / +1
Hawkesbury River	34	3	no fed/no tsb's	-2 / +1
Hearns Lake	794	1	no man	-1
Hunter River	30	2	no fbd/no fed	-2
Jervis Bay	45	1	contains bbb	+1
Karuah River	1029	1	no tsb's	-1
Kianga Lake	831	2	no man/no sm	-2
Killick Creek	801	3	no if/no man/contains tsb's	-2 / +1
Kioloa Lagoon	824	2	no if/no man	-2
Korogoro Creek	800	3	no fed/no sm/contains tsb's	-2 / +1
Wollumboola Lake	44	1	no sm	-1
Lake Brou	61	1	no man	-1

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Lake Conjola	49	0		0
Lake Illawarra	41	2	no man/contains tsb's	-1 / +1
Macleay River	21	3	contains cb/no fbd/contains tsb's	-1 / +2
Lake Macquarie	31	2	no bbb/contains tsb's	-1 / +1
Manning River	25	1	contains tsb's	+1
Manly Lagoon And Creek	811	4	no fed/no if/no man/no sm	-4
Merimbula Lake	75	2	no man/no sm	-2
Meringo Creek And Lagoon	828	1	no man	-1
Middle Lagoon	71	1	no sm	-1
Minnamurra River	42	1	no fbd	-1
Mollymook Creek	821	3	no fed/no man/no tsb's	-3
Mooball Creek	4	3	no bbb/no sm/contains tsb's	-2 / +1
Moonee Creek And Lagoon	15	0		0
Moruya River	58	2	no bbb/contains tsb's	-1 / +1
Lake Mummuga	62	1	no if	-1
Murrah Lagoon	69	1	no man	-1
Myall Lake And Myall River	802	0		0
Nambucca River	20	2	no fbd/contains tsb's	-1 / +1
Nangudga Lake	832	2	no man/no sm	-2
Narrawallee Inlet	50	2	no cb/no fbd	-2
Narrabeen Lagoon	36	2	no man/no sm	-2
Nelson Lagoon	72	0		0
Nerrindillah Creek	820	1	no sm	-1
Nullica River	78	2	no man/no sm	-2
Oyster Creek	797	3	no if/no man/no sm	-3
Pambula Lake	76	2	no bbb/no sm	-2
Pittwater	35	4	no fbd/no fed/no man/no tsb's	-4
Port Kembla Harbour	40	4	no fbd/no fed/no if/no man	-4
Port Hacking	39	1	contains bbb	+1
Port Stephens	29	3	no fed/no sm/no tsb's	-3
Port Jackson	37	2	no fed/contains tsb's	-1 / +1
Richmond River	7	3	no fbd/no sm/contains tsb's	-2 / +1
Saltwater Lagoon	799	2	no if/no man	-2
Shoalhaven/Crookhaven River	43	0		0
Smiths Lake	28	2	no man/no sm	-2
Saint Georges Basin	47	1	contains tsb's	+1
Swan Lake	48	2	no fbd/no man	-2
South West Rocks Creek	798	1	no tsb's	-1
Tabourie Lake	52	1	no man	-1
Tallow Creek	789	2	no bbb/no fed	-2
Terrigal Lagoon	806	2	no man/no sm	-2
Tilba Tilba Lake	65	1	no man	-1
Tilligery Creek	803	3	no bbb/no fbd/no fed	-3
Tomaga River	57	0		0
Towamba River	79	3	no cb/no man/contains tsb's	-2 / +1
Towradgi Creek	1030	5	no bbb/no fed/no if/no man/no sm	-5
Tuggerah Lakes	32	0		0
Tuross Lake	60	1	contains tsb's	+1
Tweed River	1	1	contains tsb's	+1
Twofold Bay / Eden	836	2	contains bbb/contains cb	+2

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Ulladulla Harbour/Millards Creek	822	4	no fed/no man/no sm/no tsb's	-4
Wagonga Inlet	63	0		0
Wallagoot Lake	74	2	no man/no sm	-2
Wallaga Lake	66	2	no man/no sm	-2
Wallis Lake	27	3	no bbb/no man/contains tsb's	-2 / +1
Wamberal Lagoon	805	2	no fed/no man	-2
Wapengo Lagoon	70	1	no bbb	-1
Werri Lagoon	817	4	no fbd/no if/no man/no sm	-4
Wonboyn River	80	1	no man	-1
Woolgoolga Lake	14	2	no man/no sm	-2
Wooli Wooli River	11	4	no cb/no fbd/no fed/contains tsb's	-3 / +1

NT

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Adelaide River	107	2	no fed/no tsb's	-2
Bing Bong Creek	182	0		0
Buffalo Creek	838	2	no fed/no tsb's	-2
Darwin Harbour	98	2	no fbd/no fed	-2
East Arm	102	2	no fbd/no fed	-2
Finnis River	94	3	no bbb/no fbd/no fed	-3
Hope Inlet	105	1	no fed	-1
Mcarthur River	184	1	no fed	-1
Melville Bay	157	0		0
Micket Creek	104	1	no fed	-1
Middle Arm	101	2	no fbd/no fed	-2
Reichardt Creek	103	1	no fed	-1
Sampan Creek	109	1	no tsb's	-1
Tommycut Creek	108	2	no fed/no tsb's	-2
Victoria River	85	1	no fed	-1

QLD

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Alligator Creek	408	1	no tsb's	-1
Althaus Creek	403	1	no fbd	-1
Annan River	360	2	no fbd/contains tsb's	-1 / +1
Andoom Creek	298	1	no tsb's	-1
Auckland Inlet	487	3	no fed/no if/no tsb's	-3
Bakers Creek	442	1	contains bbb	+1
Barratta Creek	413	1	no if	-1
Barron River	372	1	no fbd	-1
Barramundi Creek	411	1	no tsb's	-1
Basin Creek	453	1	no fed	-1
Beelbi Creek	503	2	no fbd/contains tsb's	-1 / +1
Black River	404	3	no fbd/contains tsb's	-2 / +1
Blackrock Creek	433	1	no fed	-1
Bluewater Creek	402	3	no fbd/contains tsb's	-2 / +1
Bohle River	405	0		0

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Boyne River	488	0		0
Brisbane Airport Floodway/Kedron Brook	515	2	no fed/no tsb's	-2
Brisbane River	516	1	no tsb's	-1
Burdekin River	416	2	no fbd/contains tsb's	-1 / +1
Burnett River	498	1	no fed	-1
Burpengary Creek	512	0		0
Burrum River	502	0		0
Caboolture River	511	0		0
Calliope River	486	1	no fed	-1
Cape Creek	449	0		0
Carmila Creek	455	0		0
Castrades Inlet	445	4	no cb/no fbd/no fed/contains tsb's	-3 / +1
Cattle Creek	395	0		0
Causeway Lake	480	2	no bbb/no fbd	-2
Cawarral Creek	481	1	no fbd	-1
Clairview Creek	457	3	no fed/no if/no tsb's	-3
Cobaki Broadwater	788	3	no bbb/no fed/no sm	-3
Coconut Creek	448	0		0
Constant Creek	437	2	no fbd/contains tsb's	-1 / +1
Coomera River	785	2	no fed/no tsb's	-2
Coombabah Lake	787	3	no bbb/no fbd/contains tsb's	-2 / +1
Coonar Creek	500	1	contains tsb's	+1
Corio Bay	479	1	contains bbb	+1
Crystal Creek	397	1	no fbd	-1
Currumbin Creek	523	3	contains bbb/contains cb/no tsb's	+2 / -1
Currimundi Creek	508	2	no man/no sm	-2
Dicksons Inlet	369	2	no fed/no tsb's	-2
Don River	422	3	no fbd/no if/contains tsb's	-2 / +1
Elliot River	499	0		0
Embley River	296	1	no fed	-1
Endeavour River	359	2	no fbd/contains tsb's	-1 / +1
Eprapah Creek	519	1	no tsb's	-1
Feather Creek	456	1	no tsb's	-1
Fig Tree Creek	396	2	no fbd/contains tsb's	-1 / +1
Fitzroy River	483	1	no fed	-1
Gentle Annie Creek	391	4	no fbd/no fed/no sm/contains tsb's	-3 / +1
Half Moon Creek	371	2	no fbd/no if	-2
Haughton River	410	0		0
Herbert Creek	461	1	no fed	-1
Herbert River	781	0		0
Hervey Creek	432	1	contains bbb	+1
Hervey Bay	783	2	contains bbb/no fed	-1 / +1
Hilliards Creek	518	1	no tsb's	-1
Hinchinbrook Channel	385	4	no fbd/no fed/no if/no tsb's	-4
Hull River	379	2	no fbd/contains tsb's	-1 / +1
Johnstone River	375	0		0
Knobler Creek	450	0		0
Kolan River	497	2	no fbd/contains tsb's	-1 / +1
Leichhardt Creek	400	1	no fbd	-2

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Littabella Creek	496	3	no fbd/no if/contains tsb's	-2 / +1
Liverpool Creek	377	3	no fbd/no sm/contains tsb's	-2 / +1
Logan Albert River	520	1	no fed	-1
Louisa Creek	444	3	no fbd/no fed/contains tsb's	-2 / +1
Maria Creek	378	2	no fbd/contains tsb's	-1 / +1
Marion Creek	452	1	no fed	-1
Maroochy River	506	3	no cb/no fbd/contains tsb's	-2 / +1
Mary River	782	1	no fed	-1
Meunga Creek	384	1	no if	-1
Mitchell River	285	1	no tsb's	-1
Mooloolah River	507	3	no fbd/no fed/no if	-3
Moresby River	376	2	no fed/no if	-2
Mossman River	368	1	contains bbb	+1
Mowbray River	370	2	no fed/no tsb's	-2
Mud Creek	414	1	contains tsb's	+1
Murray Creek	434	1	no bbb/no fbd	-2
Murray River	381	1	no fed	-1
Mutchero Inlet/Russell Mulgrave	374	2	no fbd/contains tsb's	-1 / +1
The Narrows	485	2	no fbd/no fed	-2
Nassau River	282	3	no bbb/no fbd/no fed	-3
Nerang River	784	6	no bbb/no fbd/no fed/no man/no sm/contains tsb's	-5 / +1
Moreton Bay - Northern	509	1	contains tsb's	+1
Noosa River	505	1	contains tsb's	+1
Norman River	271	1	no tsb's	-1
Nundah/Cabbage Tree Creek	514	1	no tsb's	-1
O'Connell River	430	1	no fed	-1
Ollera Creek	398	2	no fbd/no if	-2
Orient Creek	394	3	no fbd/no if/contains tsb's	-2 / +1
Palm Creek	393	3	no bbb/no fbd/contains tsb's	-2 / +1
Pimpama River	786	1	no fed	-1
Pine River	513	0		0
Pioneer River	441	2	no fbd/contains tsb's	-1 / +1
Plantation Creek	436	1	no fed	-1
Plantation Creek	415	1	no fed	-1
Proserpine River	428	1	no fed	-1
Pumicestone Passage	510	2	contains bbb/no fbd	-1 / +1
Pumpkin Creek	482	1	no tsb's	-1
Q195	412	1	no fbd	-1
Q221	438	2	no tsb's	-1
Q223	440	0		0
Q017	235	2	no fbd/contains tsb's	-1 / +1
Q245	462	1	no fed	-1
Q246	463	1	no fed	-1
Reliance/Leila Creek	439	0		0
Rocky Dam Creek	447	1	no fed	-1
Rollingstone Creek	399	4	no bbb/no fbd/no fed/no sm	-4
Ross River	406	1	no tsb's	-1
Saltwater Creek	367	2	no sm/no tsb's	-2
Sandfly Creek	407	2	no fed/no tsb's	-2

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Sandy Creek	443	0		0
Great Sandy Strait	504	0		0
Sarina Inlet	446	1	no fed	-1
Sleeper Log Creek	401	2	no bbb/no fbd	-2
St Lawrence Creek	458	3	contains bbb/contains cb/no fbd	-1 / +2
Southern Moreton Bay	521	1	no fed	-1
Styx River	460	1	no fed	-1
Tallebudgera Creek	522	1	no sm	-1
Theodolite/Lagoon Creek	501	0		0
Thirsty Sound	464	3	no fbd/no fed/no tsb's	-3
Thompson Creek	429	1	no fed	-1
Tingalpa Creek	517	1	no tsb's	-1
Trinity Inlet	373	1	no tsb's	-1
Tully River	380	2	no fbd/contains tsb's	-1 / +1
Victoria Creek	392	4	no fbd/no if/no sm/contains tsb's	-3 / +1
Victor Creek	435	2	no fed/no tsb's	-2
Walter Hall Creek	451	0		0
Waverly Creek	459	1	no fed	-1
West Hill Creek	454	1	no fed	-1

SA

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
American River	840	3	no bbb/no man/contains tsb's	-2 / +1
Baird Bay	535	3	contains cb/no fbd/no fed	-2 / +1
Port River Barker Inlet System	525	1	no fed	-1
Blanche Port	536	2	no fbd/no fed	-2
Breakneck River	847	3	no fed/no man/no sm	-3
Port Broughton Estuary	858	1	no fed	-1
Chapman River	843	3	no fed/no man/contains tsb's	-2 / +1
The Coorong And Lower Lakes	524	2	no fbd/contains tsb's	-1 / +1
Cygnet River	841	4	no bbb/n fed/no sm/contains tsb's	-3 / +1
Port Davis Creek/Broughton River Estuary	526	2	no fed/no tsb's	-2
Eleanor River	842	5	no bbb/no fed/no if/no man/no sm	-5
First Creek	859	0		0
Fisherman Creek	527	1	no tsb's	-1
Franklin Harbour	532	2	no bbb/no fbd	-2
Gawler River	856	2	no fed/no tsb's	-2
Harriet River	850	5	no bbb/no fed/no man/no sm/contains tsb's	-3 / +1
Hindmarsh River	853	5	no fbd/no fed/no if/no man/no sm	-5
Inman River	852	4	no bbb/no fed/no if/no man/no sm	-4
Lake George	839	2	no man/no sm	-2
Light River Delta	857	2	contains fed/no tsb's	-1 / +1
Middle River	849	2	no fed/no man	-2
Myponga River	854	3	no fed/no man/no sm	-3
Onkaparinga River	855	3	no fbd/no fed/no man	-3
Patawalonga Creek	1047	2	no man/no sm	-2
Port Pirie	530	2	no fed/no tsb's	-2

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Port Douglas/Coffin Bay	533	2	no fbd/contains tsb's	-1 / +1
Second Creek	529	0		0
Northern Spencer Gulf	531	2	contains fbd/no fed	-1 / +1
Stunsail Boom	844	3	no fed/no man/contains tsb's	-2 / +1
South West River	1038	2	no fed/no man	-2
Third Creek	528	1	no tsb's	-1
Venus Bay	534	3	no bbb/no fbd/contains tsb's	-2 / +1
Wakefield River	1039	1	no tsb's	-1
Western River	846	3	no fed/no man/no sm	-3
Willson River	851	4	no fed/ no if/no man/no sm	-4

TAS

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Ansons Bay	563	1	no man	-1
Port Arthur	577	2	no man/no tsb's	-2
Blackman Bay	574	1	no man	-1
Blyth River	549	4	no bbb/no fbd/no man/no sm	-4
Brid River	558	3	no fbd/no man/contains tsb's	-2 / +1
Browns River	1018	4	no bbb/no cb/no fbd/no man	-4
Buxton River	1022	3	no bbb/no fbd/no man	-3
Cam River	547	2	no bbb	-2
Carlton River	575	2	no fbd/no man	-2
Crayfish Creek	1006	3	no fed/no man/no sm	-3
Crookes Rivulet	1014	3	no fed/no man/no tsb's	-3
Curries River	1028	3	no bbb/no man/no sm	-3
Port Cygnet	1015	3	no fed/no man/no tsb's	-3
D'Entrecasteaux Channel	580	3	contains bbb/contains cb/ no man	-1 / +2
Derwent River	579	4	no fed/no man/no sm/no tsb's	-4
Detention River	545	2	no man/contains tsb's	-1 / +1
Don River	552	2	no man/no sm	-2
Douglas River	567	2	no bbb/no man	-2
Duck Bay	1004	3	no cb/no fbd/no man	-3
Earlham Lagoon	572	2	no man/no tsb's	-2
East Inlet	543	2	no cb/no man	-2
Emu River	548	5	no bbb/no fbd/no fed/no man/no sm	-5
Esperance River	582	2	no fed/no man	-2
Ettick River	865	4	no bbb/no fed/no man/no sm	-4
Little Forester River	557	2	no man/no sm	-2
Forth River	551	5	contains fbd/no fed/no man/no sm/no tsb's	-4 / +1
Frederick Henry Bay	573	4	contains bbb/contains cb/no man/no tsb's	-2 / +2
Garden Island	1016	4	no bbb/no fed/no man/no sm	-4
Georges Bay	564	1	no man	-1
Great Musselroe River	562	2	no man/no sm	-2
Grants Lagoon	1003	2	no man/no sm	-2
Grindstone	1020	3	contains fbd/no fed/no man/no sm	-2 / +1
Henderson Lagoon	566	1	no fbd/no man	-2

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Huon River	581	4	no fbd/no fed/no man/no tsb's	-3
Inglis River	546	5	no bbb/no fbd/no fed/no man/no sm	-5
Levan River	550	5	no bbb/no fed/no man/no sm/contains tsb's	-4 / +1
Little Henty River	597	3	no fbd/no man/no sm	-3
Lisdillon Lagoon	1021	3	contains cb/contains fbd/no man	-1 / +2
Little Musselroe River	561	2	no if/no man/no sm	-2
Macquarie Harbour	595	2	no man/no sm	-2
Meredith River	1024	3	no fed/no man/no sm	-3
Mersey River	553	2	no bbb/no man	-2
Montagu	1005	3	no fed/no man/no tsb's	-3
Mosquito Inlet	541	3	contans bbb/no fbd/no man	-2 / +1
North West Bay	1017	3	no fed/no man/no tsb's	-3
Pats River	874	2	no bbb/no man	-2
Pieman River	598	4	no fbd/no man/no sm/no tsb's	-4
Pipeclay Lagoon	1019	2	no fbd/no man	-2
Pipers River	556	2	no cb/no man	-2
Pitt Water	576	1	no man	-1
Prosser River	571	4	no cb/no fbd/no man/no sm	-4
Ralphs Bay	578	6	contains bbb/contains cb/no fbd/no fed/no man/no tsb's	-4 / +2
Recherche Bay	586	3	no man/no sm/no tsb's	-3
Ringarooma River	560	4	no fbd/no if/contains tsb's	-3 / +1
Robbins Passage	540	3	contans bbb/no fbd/no man	-2 / +1
Scamander River	565	2	no cb/no man	-2
Seal River	866	3	no fbd/no fed/no man	-3
Port Sorell	554	4	no cb/no fbd/no man/contains tsb's	-3 / +1
Southport	584	3	no bbb/no man/no sm	-3
Spring Bay	570	4	no fed/no man/no sm/no tsb's	-4
Stoney Lagoon	1023	4	no bbb/contains fbd/no man/no sm	-3 / +1
Little Swanport	569	2	no bbb/no man	-2
Tamar River	555	3	no fed/no man/no tsb's	-3
Tomahawk River	559	3	no cb/no fbd/no man	-3
Welcome Inlet	539	3	no fed/no man/no tsb's	-3
West Inlet	542	3	contains bbb/no man/no tsb's	-2 / +1
Yarra Creek	864	4	no fed/no if/no man/no sm	-4
Yellow Rock River	1046	1	no man	-1

VIC

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Western Port Bay	616	0		0

WA

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Barker Inlet	883	3	no fed/no man/no sm	-3
Beaufort Inlet	640	2	no fed/no man	-2

Coastal System	ID Number	Deviation	Reason(s) for deviation	Facies deviations
Broke Inlet	647	2	no man/no sm	-2
Cheyne Inlet	892	2	no fbd/no man	-2
Culham Inlet	638	2	no man/no sm	-2
Dempster Inlet	889	2	no man/no sm	-2
Donnelly Inlet	898	3	no man/no sm/contains tsb's	-2 / +1
Fitzgerald Inlet	890	1	no man	-1
Gardner Lake	897	3	no bbb/no fbd/no man	-3
Gordon Inlet	891	2	no fbd/no man	-2
Hamersley Inlet	888	2	no man/no sm	-2
Hardy Inlet	649	2	no man/contains tsb's	-1 / +1
Irwin Inlet	645	1	no man	-1
Jerdacuttup Lakes	887	8	no estuarine facies	-8
Leschenault Inlet	652	1	no man	-1
Margaret River	650	3	no fed/no man/no sm	-3
Moore River Estuary	900	1	no fbd	-1
Normans Inlet	894	4	no fed/no if/no man/no sm	-4
Oldfield Estuary	885	3	no fbd/no man/no sm	-3
Oyster Harbour	641	2	no bbb/no man	-2
Parry Inlet	644	2	no bbb/no man	-2
Peel-Harvey Estuary	653	2	no man/contains tsb's	-1 / +1
Princess Royal Harbour	642	3	no fed/no man/no tsb's	-3
Saint Marys River	1037	2	no cb/no man	-2
Stokes Inlet	637	2	no man/no sm	-2
Swan River	654	2	no fed/contains tsb's	-1 / +1
Taylor Inlet	895	3	no fbd/no man/no sm	-3
Tobys Inlet	899	0		0
Torbay Inlet	896	2	no fbd/no man	-2
Torradup River	884	3	no fed/no man/no sm	-3
Vasse-Wonnerup Estuary	651	2	no man/contains tsb's	-1 / +1
Walpole/Nornalup Inlet	646	2	no man	-1
Warren River	648	2	no man/contains tsb's	-1 / +1
Waychinicup Inlet	893	6	no fbd/no fed/no if/no man/no sm/no tsb's	-6
Wellstead Estuary	639	2	no fbd/no man	-2
Wilson Inlet	643	1	no man	-1