A Compendium of Ecological Information on Australia's Northern Tropical Rivers

REPORT 2

Estuaries

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1. INTRODUCTION

By definition, estuaries are semi-enclosed coastal water bodies in which there is mixing of terrestrial, marine and ambient basin waters (Dyer 1973, 1986; Dalrymple *et al.* 1992). In northern Australia, as in other parts of the world, this definition encompasses a very wide range of physical, climatic, oceanographic and ecological settings at the coast. Their coastal location implies that estuaries are tied to sea level dynamics as much as to fluvial and internal processes. Modern estuaries are a response to the Holocene rise in sea level from inundation of existing basins (Semeniuk 1982, 1985; Roy 1994) and through development of bay-mouth barriers (Roy 1984; Thom 1984) or deltaic floodplains (Woodroffe 2003). They are highly dynamic, and may be geologically short-lived due to sediment infilling.

Following Perillo (1995), Dyer (1997) points out there are over 40 different definitions of estuaries, placing various levels of emphasis upon salinity, tides, sediments, topography, hydrology and morphology. The diversity of definitions and estuarine forms is also reflected in formulation of estuary classifications, with a similarly broad range of emphases on the type of information gathered to derive them. Scalar factors are an important component of classification schemes. These may be grouped for convenience into global, regional and local scales.

1. At a global scale, classification schemes are focused upon scientific description of estuarine issues and their management. Primary descriptions are based upon salinity structure, driving mechanisms and geological inheritance (Pritchard 1952 & 1955; Dalrymple *et al.* 1992; Prandle 1985; van Rijn 1996).
2. For regional scale descriptions, driving mechanisms and geological inheritance are often similar in character across the range of estuaries being considered. Therefore global-type classification schemes provide limited distinction between estuary types. Secondary descriptions are based upon water quality, geomorphology, catchment scale and biota (CSIRO 2003; Ryan *et al.* 2003; Finlayson & von Oertzen 1996a).
3. At a local scale, application of classification schemes is most directly focused upon estuarine management, with normally a narrow field of interest. Examples include flood management, entrance dynamics and habitat areas (Escoffier 1940, 1977; CSIRO, 2003; Brearley 2005)

The different scales provide a context in which estuaries are described. The scales approximately parallel hierarchies used in planning and management that range from broad scale strategic levels, through regional to local plans and site designs. For example, the WAPC (2003) and Kay and Alder (2005) describe hierarchies used in coastal planning and management. Two scales are significant in the current discussion, regional description of estuaries in the wet-dry tropics of northern Australia and description of individual estuarine systems from Cape York to King Sound. Both have been used in the literature.

North Australian estuaries have a strong inherited geological character. The sequence of Holocene estuarine evolution is dependent on factors such as the dimensions and geometry of the containing basin, sediment supplies from fluvial and marine sources, sediment redistribution in the basin and active hydrodynamics. Estuaries with a relatively low degree of sediment accumulation include the Prince Regent River and Mitchell River in Western Australia, which are strongly controlled by faulted rock geology. More fully infilled basins include the Alligator Rivers Region in the Northern Territory and the outwash plains of rivers in the southern Gulf of Carpentaria.

The upper limits of estuaries in northern Australia have been defined for practical purposes in this project as the upstream limit of tidal activity, although this is a very arbitrary definition. On the low, flat coastal plains of northern Australia the tidal limit varies with fluctuation in sea level at seasonal and longer periods. Over the past 30 years, at least, saltwater incursion of freshwater wetlands has been driven by landward extension of tidal creek networks into the coastal plains (Knighton *et al*. 1991, 1992: Woodroffe & Mulrennan 1993; Ahmad & Hill 1995). Additionally, mangrove communities have migrated upstream, colonising river banks formerly occupied by fresh to brackish water species (Woodroffe & Mulrennan 1993; Cobb 1997; Cobb *et al.* 2000; Heerdegen & Hill 2000). This implies identification of estuarine environments on the coastal plains of northern Australia must be a snapshot, a baseline from which change may be assessed.

Wright *et al*. (1973, 1975) and Thom *et al.* (1975) originally described the stratigraphy and morphology of the estuarine reaches of the Ord River, Western Australia as part of a global examination of river delta and floodplain formation. Since then, the geomorphology of other northern Australian estuaries has been examined by a number of people including Woodroffe *et al.* (1989 & 1993); Wasson (1992); Chappell (1993); and Jones *et al.* (1993). In particular, Chappell & Woodroffe (1985) provide a conceptual model detailing the geomorphologic components of north Australian estuaries. Their model includes an estuarine funnel at the river mouth where bi-directional tidal flows are dominant; a sinuous reach experiencing tidal asymmetry; a cuspate reach in which ebb and flood tides balance and an upstream estuarine reach dominated by river flow, which is still affected by tides. The upstream reach grades into the river proper. These forms are considered to be characteristic of macrotidal environments, for which the tidal range exceeds four metres. However, not all four components are present in all north Australian estuaries. Differences arise because of the geological inheritance and regional disparities in driving processes at specific sites.

This document presents a review of regional classifications applied to north Australian estuaries, focusing on estuarine morphology and dynamics, in accordance with the project Terms of Reference.

2. COMPONENTS OF ESTUARIES AND ESTUARINE ENVIRONMENTS

Estuaries occur in a wide variety of geologic basins, some of which have been described as physiographic types by Pritchard (1952) and Fairbridge (1980). Several basin forms are found in Northern Australia, including rias, coastal plain basins, bar built estuaries, blind estuaries and delta front estuaries following the terminology of Dyer (1986: 10). The diversity of landforms described primarily indicates the importance of geological structure and the relative relief of bedrock topography as major determinants of estuary type although the classification of basin shapes, originally by Fairbridge (1980), is arguably based on a mixture of geologic, sedimentologic and hydrodynamic attributes.

From their time of formation, when marine waters first transgress an estuary basin, estuaries undergo a developmental sequence lasting until the basin is filled with sediment of fluvial, marine and biogenic origin or until sea level again changes substantially. The rates of infill are a function of the dimensions and stability of the containing basin as well as the availability of sediment and the intensity of processes transporting it. At the outset, basin dimensions are related to their geologic setting and elevation on the coastal profile (hypsometric curve). In turn, the structure and composition of the bedrock geology determines the relative relief of the coast and, in part, the availability of sediment that might be transported into the estuary basin.

Fluvio-deltaic and estuarine processes transport the sediment and shape the morphology within the basins, including the water bodies and sedimentary landforms associated with them. A composite of estuary features observed in Northern Australian estuaries is listed in Table 1. The particular assemblage of landforms varies from estuary to estuary, although there may be a similarity of estuarine form in a particular region, as has been indicated in temperate Australia by Jennings & Bird (1967), Roy (1984) and Brearley (2005), and in northern Australia by Bucher and Saenger (1991, 1994) and Digby *et al.* (1998). For example, ria topography is a major feature of the Kimberley Region in Western Australia, whereas bar built estuaries are more common on the eastern shores of the Gulf of Carpentaria. Several landform assemblages are common although not all members of an assemblage are present in each estuary. The assemblages include landforms of deltaic floodplains and lowlands; the bars, shoals and characteristic geometry of the estuary basins, tidal creeks and landforms of the estuary mouths. They are briefly described below to illustrate the diversity of forms to be considered in a geomorphologic classification of estuaries.

Table 1 Landform Features in Estuarine Environments

Major Feature	Component Landforms	Surficial Landforms
Estuarine waters & Containing Basins	Fluvial channel	Meander point bars, river banks, slumps and mudflows,
	Cuspate channel	Meander point bars, river banks, slumps and mudflows
	Sinuous channel	Meander point bars, river banks, slumps and mudflows, mid-channel shoals and bars
	Estuary basin	Intertidal and subtidal shoals, low bluffs and rock outcrops, islands
	Marginal shoals	Shallow shoals much of which may be sub-tidal & ending in a noticeable drop to deep water; bars and tidal channels may be apparent on the surface
	Estuary Mouth	Entrance constriction, number of entrances and channels, presence of off-channel embayments; Tide dominated and wave dominated bar forms are apparent, both of which may be modified by littoral drift
Tidal Creeks	Tributary / distributary fans	Upwardly convex deposition fans, gullies - upwardly concave tributary networks in fan shape
	Tributaries	Meandering or straight channels with a shallow U cross section; banks lined with mangroves
	Trunk stream	Funnel shaped plan form with mangroves on low levee banks
	Mouth	U or V shaped cross-sections at junction with main estuary waters
Floodplains & Wetlands	Upper floodplain	Freshwater meadows in basins adjacent to upland, tidal creeks
	Middle floodplain	Palaeochannels, oxbow lakes, tidal creeks, saltwater basins, mud flats
	Lower floodplain	Cheniers, mudflats, mangals, levee banks

2.1. ESTUARINE WATERS AND CONTAINING BASINS

In a downstream sequence and following Woodroffe *et al.* (1985), the basin components of a tropical estuary may include an upstream segment that is more fluvial than estuarine in character, although it is affected by tides. This segment passes to a reach of cuspate meanders where the tidal river has numerous sandbanks and shoals. It flows through a floodplain crossed by cut-off meanders and tidal creeks. Further downstream the channel widens and becomes more sinuous. The tidal creeks, cut-off meanders and salt flats are most common here and in the vicinity of the river mouth. Near its mouth the river is likely to be funnel shaped if it flows through mud or silty mud; constitute a small, bell-shaped basin in sandy sediments; or be constrained by the rock in a ria.

2.2. TIDAL CREEKS

Tidal creeks occur in estuaries under meso- to macro-tidal conditions, as well as along the ocean coast, and are common features of the estuaries of Northern Australia. In an estuary the creeks become more common features of the landscape with proximity to the coast and are best developed in the funnel and meandering segments of riverine estuaries on low-gradient shores. Typically, the creeks develop in low-gradient, coastal flats with a seaward-slope (Dalrymple *et al.* 1992; Semeniuk 1982, 1985) although this is not always the case and some slope landward to a wetland. They have funnel-shaped channels that narrow exponentially upstream and shoal to landward (Wolanski 1992) through interconnected dendritic arms in some places. The creeks have a very low or negligible freshwater input and discharge freshwater from the adjacent floodplains only during very high rainfall events. This implies that there may be some fluctuation between extreme dry and wet season conditions, with the modally prevalent tidal processes dominant during the dry and infrequent surficial discharge of freshwater from terrestrial run-off during the wet.

Large areas of intertidal mudflat, supporting mangroves, bare salt flats and salt marsh (Wells 1995) flank the tidal channels. The mangroves line their banks and form low levees. Landward of the fringing mangroves coastal salt flats and mudflats tend to be at or above the limit of high tide, and seawater is mainly confined to the tidal channel, except during spring tides. Under dry season conditions the tributaries of tidal creeks function as distributaries. Marine and estuarine sediment is moved into tidal creeks by shoreward-directed bedload transport. Channel infilling occurs as the channel shoals, and the intertidal merges with the terrestrial environment (Harris 1988, Knighton *et al.*1991, 1992). Distributary fans with convex upward surfaces are apparent at the landward limit of the tidal channels under these conditions.

During wet season floods, a combination of ebbing spring tide and freshwater runoff combine to form small tributaries draining into the tidal creek. Surface runoff and stream flow from the surfaces of bare mudflats and salt flats may combine to strip sediment, transporting it into the tidal creek and main estuary channel. Under these conditions the headwaters of the creek are characterised by concave upward surfaces that form a gully system of low relief, although the gullies may be pronounced in places where salt water intrusion and the extension of tidal creeks is rapid. The interplay of extreme conditions contributes to change in the elevation of the lower reaches of floodplain with the combination of mild rainfall and high water levels contributing to heightening of the floodplain, whereas high rainfall and low water levels contribute to channel entrenchment. In the first instance, this involves a loss of sediment from the estuary or coast. In the second, the tidal creeks contribute sediment to the estuarine basin.

2.3. FLOODPLAINS AND COASTAL WETLANDS

Coastal floodplains are areas of low-lying land along the coast and adjacent to estuaries. Delta building processes form the floodplains, principally through sediment discharge from the land (Coleman & Wright 1971; Chappell & Woodroffe 1985; Woodroffe *et al.* 1989; Roy 1994). Secondary reworking of sediment along the coast by ocean processes (Woodroffe *et al.* 1989 & 1993; Roy 1994) and by tidal creeks contributes to the formation of surficial landforms (Woodroffe *et al.* 1993; Heerdegen & Hill 2000; Winn *et al.* 2006), as do biotic factors (Finlayson & von Oertzen 1996a; Storrs & Finlayson 1997; Finlayson & Lukacs 2004)

The coastal floodplains buffer the coastal hinterland from tidal flooding, but can be flooded by extreme events. Floodplains adjacent to estuaries can be flooded from raised sea levels, floodwater from rivers, or a combination of both. In the Northern Territory, which contain Australia's largest areas of relatively unmodified wetlands (Turner 2001), the floodplains formed following the sedimentation of river estuaries drowned during the last post-glacial sea level rise and many are only 2-3000 years old (Woodroffe *et al.* 1985; Chappell & Woodroffe 1994; Jones *et al.* 1993). Their soils are predominantly heavy black cracking clays overlaying estuarine mud.

Downstream variation in estuary morphology is closely linked to the structure of the river delta and floodplain. Several components are apparent:

(1) An upper plain is transitional from the high ground of the coastal hinterland. It marks the area where the river channel becomes tidal and elsewhere may be apparent as a transition from floodplain soils to older, lateritic soils of the higher ground. Much of the coarse sediment, transported as bedload in the stream channel, is deposited along this reach of the estuary when the river in flood and spreads as it loses grade. The floodplain is likely to include freshwater swamps and billabongs. Rainforest and freshwater meadow alternate with mangals along the channel, although mangroves are the common species where tidal effects are present.

(2) In the middle to upper part of the floodplain the estuary channel is characterised by cuspate forms. Silty sediment accumulates in sand bars and shoals in the estuary channel. Mangals are common features along the channel banks and low levees form in them. The adjoining floodplain includes cut off meanders (billabongs) as well as freshwater basins along the margin of the floodplain where it abuts higher ground. Tidal creeks connect the estuary to some of these basins, making them saline.

(3) The lower to middle plain adjoins the sinuous section of the estuary. Fine sediments, predominantly suspended and fine siltation load, are common in the channel, and transported along this reach. Here, the floodplain is likely to include salt and brackish water swamps and billabongs, most of which are likely to have been encroached by tidal creeks. Mangals commonly front mudflats and saline meadows.

(4) Near the mouth of the estuary the adjoining floodplain includes cheniers, extensive mudflats and saline meadows between mangals and higher ground to landward. Landforms within the mangal zone are related to the state of the shore or estuary bank. Cheniers and levees are present where the coast is accreting or stable, and where pulsatory sediment transport along the coast produces elongate spits at the mouths of rivers. Small scarps are present where the shore is eroding. Debris lines, commonly comprised of timber, shell and other flotsam and jetsam are deposited on the lower floodplain during flooding events.

3. ESTUARY FORMING PROCESSES & GEOGRAPHIC SETTINGS

Several processes contribute to the formation of estuaries and the landforms within them. They include climatic factors, sea level change, tides, and wave action at the coast as well as river discharge. The processes operate within a geologic framework. The aspect of the coast, its geographic setting with respect to prevailing and dominant climatic and oceanographic conditions determines the effect of these processes. A broad description of the processes and the environmental conditions in which they function are outlined below.

3.1. CLIMATE

Many of the processes driving estuarine formation are due to climatic factors, including those related to rainfall and coastal hydrodynamics (Jimenez & Sanchez-Arcilla 1997). A primary factor has been the affect of climate as a driver of sea level change (Warwick *et al.* 1993; Warrick & Oerlemans 1990; Chappell *et al.* 1996; Lambeck & Chappell 2001). As a secondary influence the climate determines the types and abundance of vegetation and biota, which affect surface landform development and pedologic composition (Jennings & Bird 1967; East 1996).

Gross changes in climate over hundreds to thousands of years drive oscillations in sea level and are directly responsible for the inundation of coastal basins (Dalrymple *et al.* 1994). The most recent (Holocene) rise in sea level occurred over the past 20,000 years, with the major transgression of the coast completed by approximately 6,000 years ago (Thom & Chappell 1975; Semeniuk 1982; Pirazzoli 1996). This highstand of sea level caused inundation of old estuary basins, as well as the development of new ones. It brings into question the role of antecedent conditions in estuary formation and development. For example, the ria topography of Arnhem Land and the Kimberley is substantially older than the Holocene (Semeniuk 1982), whereas river estuaries of the Alligator Rivers Region were formed recently (Woodroffe *et al.* 1985; Wasson 1992).

Climate variability influences the estuarine dynamics at a number of different time scales. At long time scales, sea level fluctuations and variations in sediment availability determine the gross formation and evolution of estuary basins (Galloway, 1975). Climate fluctuations over centuries and decades, or shorter periods, may cause cycles of marine transgression or regression with associated patterns of salinisation, erosion or deposition (Woodroffe, 2003; Winn *et al.* 2006).

Estuarine response may also occur at smaller time scales, including seasonal shift and even individual weather events. In most instances, these time scales produce fluctuations around a longer-term trend of evolution. However, in the wet-dry tropics, the relative significant of singular intense weather events, including floods and tropical cyclones may cause much greater impact than an extended period of prevailing processes (Sanchez-Arcilla & Jimenez, 1997; Nott, 2006).

3.2. SEA LEVEL CHANGE

Less apparent, but perhaps no less important, are the effects of shorter period climate change on sea level at a wide range of temporal scales (Table 2). Since the Holocene post-glacial rise in sea level reached its peak approximately 6,000 years ago, many drowned valleys, especially those of the Alligator Rivers Region in the Northern Territory, have been substantially infilled with sediment and extensive coastal plains have formed (Chappell 1988; Chappell & Woodroffe 1994). In an historical context, processes such as ENSO phenomena (Aubrey & Emery 1986; Lambeck & Chappell 2001) and the 19-year lunar nodical cycle (Wood 2001) produce inter-annual and longer fluctuations in sea level and tide upon which short-term tides, surges and flood levels are superimposed. Similarly, variations in weather at seasonal and higher frequency scales determine estuarine water level conditions, commonly at a local scale.

Table 2 Changes in Sea Level Occurring at Inter-annual and Shorter Periods

Process	Time Scale	Reference
Basin Resonance	0.5-3 hours	USACE (1991)
Pressure Surge	1-3 hours	Bode & Hardy (1997)
Wind Set-up	3-6 hours	Bode & Hardy (1997)
Tidal Conditions	12 / 24 hours	Cartwright (1971)
Land-sea Breezes	24 hours	
Shelf Waves	1-5 days	Fandry & Steedman (1994)
Weather Systems	2-15 days	
Steric Changes	1-3 months	
Seasonal Dynamics	12 months	Pariwono *et al.* (1986)
ENSO Effects	4-8 years	Meyers (1996); Aubrey & Emery (1986)
Rotation of Lunar Ellipse	4.4 / 8.8 years	Wood (2001)
Lunar Nodical Cycle	19 years	Wood (2001)

Dalrymple *et al.* (1992) outlined an evolutionary classification of coastal environments in which marine transgression associated with a relative rise in sea level results in a temporary reduction of sediments and the formation of estuaries. Conversely, shore progradation associated with a relative fall in sea level, or where the amount of sediment delivered to the coast by rivers exceeds the rate of drowning by the rising sea level, facilitates the formation of river deltas at the expense of estuary formation. The former is particularly so where the transgression occurs on high relief and irregular coast such as those of the Kimberley and east Arnhem Land, where ria formation is common.

3.3. TIDES & SURGES

Tides and surges play a range of roles in the development of estuarine structures. The most well recognised tidal mechanism is the flood and ebb cycle of water exchange. The effect of tidal asymmetry has been designated as one of the causes of estuarine infilling, with velocity greater on flood than ebb, enabling a net inward movement of sediment (Dyer 1997).

Second, tidal exchange also influences the rate of mixing within the estuarine water body, making it one of the most significant factors for estuarine salinity structure. As noted previously, the salinity structure affects the deposition area for cohesive sediments subject to flocculation (Eyre & Balls 1999).

The water level range provides strong influence on the coastal structure and lower estuarine morphology. Under high tide conditions, beaches are more commonly long and flat, reducing the available littoral transport (Wright & Short 1991). Within the lower estuary tides, surges and waves may cause the formation of chenier ridges (Rhodes 1982; Chappell & Grindrod 1984; Lees 1987), which create a fragile barrier to estuarine flows. Breaching of these ridges facilitates the formation of tidal creek systems (Winn *et al.* 2006).

3.4. WAVES

Waves affect estuarine development indirectly through their capacity to transport marine sediments along the coast. Tidal asymmetry, increased depth at the estuary mouth and change in shoreline aspect disrupt the capacity for transport. This provides a tendency for littoral material to accumulate within the estuary or near its entrance (Cowell & Thom 1994). Under active littoral transport, there is a tendency to form a smoothly shaped coastline, commonly expressed in the form of a coastal barrier or spit. The formation of this feature is countered by tidal and riverine flows, which has been confirmed for Australian estuaries (Heap *et al.* 2001; Ryan *et al.* 2003).

It may be important to recognise that the wave conditions only represent a potential for sediment transport. Sediment supply through wave action may be disrupted by a number of mechanisms, including:

- Low supply from upstream due to low mobility of material;
- Capture of sediment upstream due to shoreline features during alongshore sediment transport events;
- Enhanced bypassing of the estuary entrance due to shoreline features causing relative offshore movement; and
- Restriction of sediment supply due to closure or partial closure of estuary entrances during alongshore sediment transport events.

These features are common reasons for the presence of estuary mouths to be located adjacent to headlands or other zones of low sediment mobility. This behaviour is enhanced where sediment transport is predominantly unidirectional.

3.5. STREAM HYDROLOGY

Heavy rains associated with the seasonally wet monsoonal climate of northern Australia fall on the low, flat topography of the coastal plains to produce widespread and prolonged flooding (Finlayson & Woodroffe 1996; McQuade *et al.* 1996). The duration, depth and extent of the flooding is highly variable, although a generalised pattern with five distinct phases has been discerned:

i) intermittent heavy rain storms (Nov-Dec);
ii) consistent rain and creek flow inundates the floodplain (Dec-Apr);
iii) rain ceases and water draw down occurs (May-Oct);
iv) flow ceases and the floodplain dries out (May-Oct);
v) floodplain is dry (Oct-Nov).

The floodwaters on the coastal plains are derived from three sources: direct inputs from rainfall, tides, and overbank flow from streamflow (Kingston 1991).

The flooding on sections of coastal floodplains markedly affected by rainfall is a function of topography, antecedent soil moisture, rainfall intensity and duration (Kingston 1991). Runoff occurs after the initial saturation of the soil and evaporative losses are surpassed. This usually happens two to three months after the rains begin. Areas on the coastal floodplains subject to inundation from direct rainfall may pond water well ahead of peak flow in the rivers draining onto the fringes of the plains. The general pattern for these plains is for coastal reaches to be inundated by direct rainfall and the upper floodplain reaches to be inundated by local runoff and periodic overflow from principal rivers (Kingston 1991). The upper reaches often contain perennial freshwater lagoons sustained by groundwater inflow.

Coastal processes have a major influence on flooding in coastal wetlands (Kingston 1991; Winn *et al.* 2006). A combination of coastal and fluvial processes created the coastal floodplains and ground levels may be lower than high tide levels. The interplay of coastal and fluvial processes continues to contribute to floodplain development with apparent switching between interannual phases of river flooding and surge inundation of the coastal lowlands (Winn *et al.* 2006). The flow balance is complicated as surface slopes, storage changes and infiltration components affect flooding patterns on the coastal floodplains.

3.6. GEOLOGIC CONTROLS

Geology plays a large role in type of estuaries found in any region, yet it is rarely discussed in recent estuary classification schemes other than to distinguish areas in which the bedrock configuration is a primary determinant of estuarine morphology from those where estuaries have formed in unconsolidated sediments. While this is a useful distinction, the structure and composition of the catchment geology determines the relative relief of the coast and, in part, the availability of sediment to the estuarine basin. High relative relief is commonly associated with rias, estuaries formed by drowned bedrock embayments with little infilling whereas barrier or lagoonal estuaries are more common on low-lying coastal plains and deltaic environments in geologic basins. Sediment availability is a function of the mineralogy of the bedrock and its susceptibility to weathering and transport by terrestrial geomorphic processes.

Coleman & Wright (1971, 1975) note the high significance of tectonics and receiving basin geometry in controlling the development of modern river deltas. Their discussion points to the difficulty in quantifying such factors for landform classification and is equally applicable to estuary formation in Northern Australia.

Pedologic influences upon estuary structure are caused by the availability and mobility of both marine and fluvial sediments. For cohesive sediments, the relative influence of salinity upon flocculation is a crucial factor affecting deposition zones of sediment and consequent patterns of infill or dispersal (van Rijn 1996). Hence the estuarine salinity structure plays an important part in the estuarine development.

3.7. COASTAL ASPECT: ENVIRONMENTAL SETTINGS IN NORTHERN AUSTRALIA

Coastal aspect refers to the orientation of the shore in the vicinity of the estuary mouth. This is an important factor in the tropics, where the orientation of the coast affects the impact of tropical cyclones and that of onshore winds during the monsoon season (Winn *et al.* 2006). Orientation of the coast with respect to the path of tropical cyclones is a significant determinant of the extent and duration of storm surge and its potential effect on the estuarine system (Figure 1). Due to the strength of offshore winds and proximity to the coast, cyclone paths parallel to and landward of the coast may produce a set down (negative surge) of ocean water levels despite low barometric pressure. Conversely those travelling parallel to and offshore from the coast are likely to produce raised water levels (positive surge) due to wind, wave and barometric pressure. The level of surge is variable between these extremes.

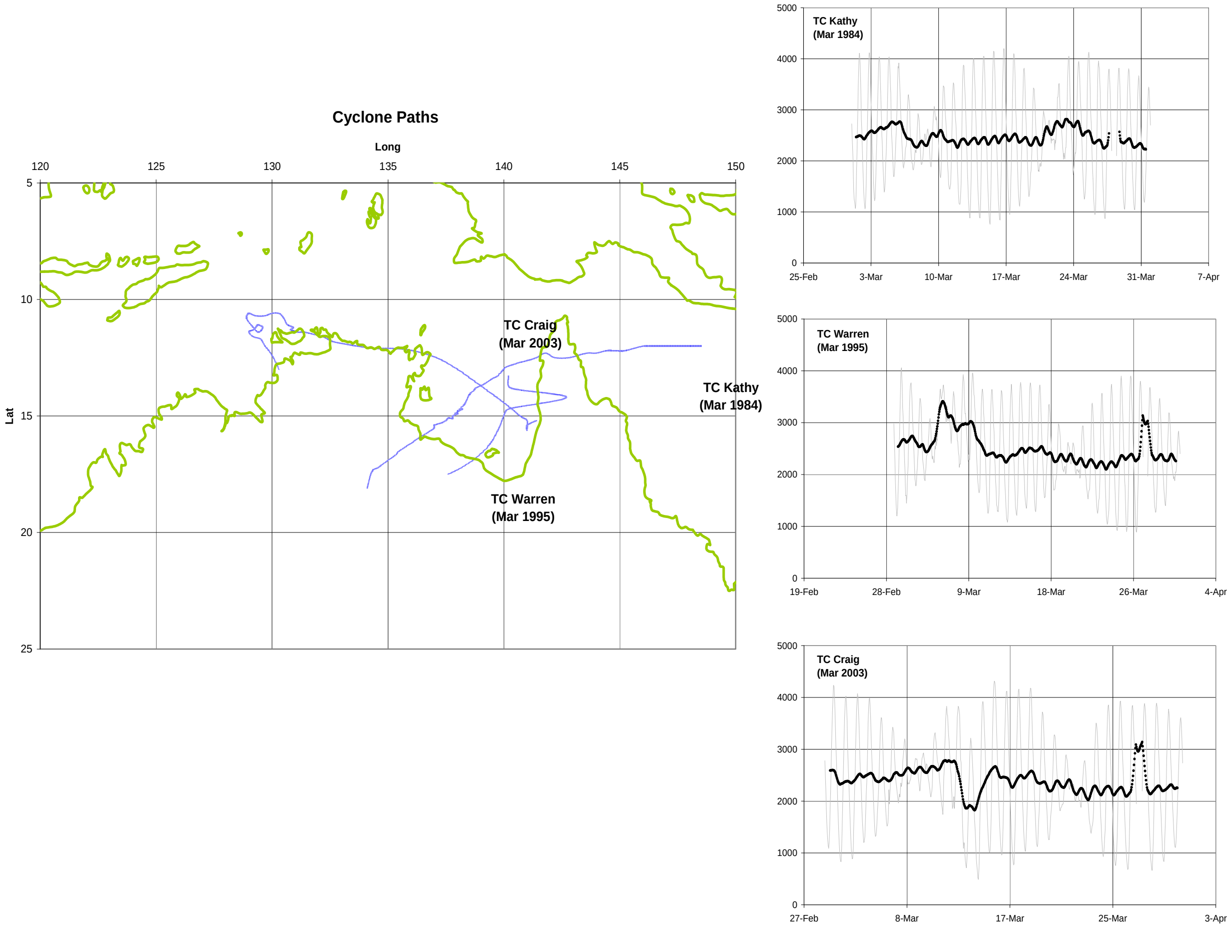

Figure 1 **Surges Associated with Tropical Cyclones**

(After Winn *et al.* 2006)

4. STRUCTURES, DRIVING PROCESSES AND DYNAMICS

Estuaries, like all coastal geomorphic features, are subject to a change as a result of fluvial, marine, aeolian, tectonic, geotechnical and biophysical processes (van Rijn 1996). The role of estuaries as a transition between riverine and marine conditions determines that their dynamics may be an expression of a range of these processes (Dyer 1986). The structures, driving process and dynamics are all primary variables to be considered in a detailed geomorphic classification of estuaries. Widely examined and often inter-related dynamics include circulation, salinity structure, water quality, sediment transport and biophysical processes. System models aim to apply a selection of driving processes to represent the principal dynamics.

For salinity structure and water quality, simple estuarine models are widely applied, which combine river inflow, tidal exchange at the estuary entrance and evaporation (Fischer *et al.* 1979; Sanford *et al.* 1992; CSIRO 2003). The effects of wind-driven circulation or groundwater flows are rarely considered, although for certain conditions they may be significant (Hunter & Hearn 1987; Erskine *et al.* 2003).

Geomorphic dynamics are normally considered within a ternary classification framework indicating the relative dominance of wave, tide and river flow processes (Galloway 1975; Dalrymple *et al.* 1992; Heap *et al.* 2001; Ryan *et al.* 2003). However, it is recognised that this relatively simple classification scheme may acquire greater complexity when these processes are considered over different time scales (Jimenez & Sanchez-Arcilla 1997). An example of this is barrier estuaries of the eastern Gulf of Carpentaria (Jones *et al.* 1993), for which episodes of high sediment transport along the coast result in barrier closure, rather than sediment input to the estuary. Under extreme conditions, barrier collapse occurs, producing massive deposition of marine sediments.

In order to evaluate the validity of a system model for incorporation into a classification scheme it is necessary to consider how well the potential driving processes describe the natural system dynamics.

4.1. NATURAL SYSTEM DYNAMICS

Approaches for modelling natural systems vary along a continuum from fixed systems through to highly mobile systems. In reality, natural systems are comprised of a large number of different elements, each with their own dynamics. To model natural systems, it is necessary to understand the relative importance of these elements and their contribution to overall dynamics. The effect of each element may vary significantly when the system is considered for different time scales or processes. For example, in an estuary, tidal flows are critical for interpreting daily water quality observations; their relative influence is less for seasonal water quality interpretation; and when considering decadal water quality change, they are commonly neglected, considered to be a constant phenomenon.

Modelling of natural systems conventionally uses a pressure-state approach, where the system's condition (state) is a function of the forces it experiences, including hydrodynamics and hydrology. In practice, the behaviour may be classified as indicated in Figure 2, as:

- Fixed systems, where natural dynamics are very low, either through a lack of sensitivity, or lack of variation from modal conditions;
- Equilibrium systems, where the natural system varies around modal behaviour;
- Episodic systems, which experience change as the result of occasional extreme events, and have little or no subsequent change until the next extreme event;
- Dynamic systems, for which change occurs on an almost constant basis, due to the mobility of the system elements and variability of forcing conditions.

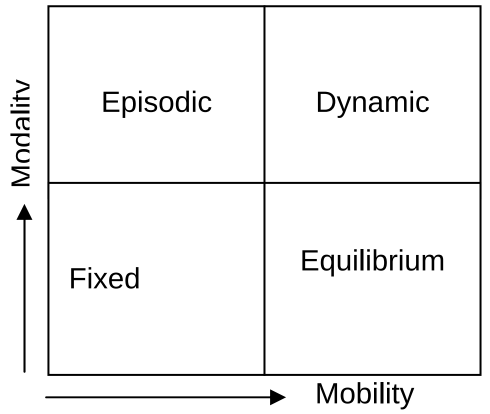

Figure 2 Schematic Classification of Natural Systems

Identification of the system class may not be readily undertaken using snapshot evaluations or by consideration of median pressures upon the system. Instead, it is necessary to examine the sequence of driving event and response for a natural system. Two aspects that are most relevant for tropical Australia include the strongly seasonal climate and the episodic character of extreme tropical weather, particularly tropical cyclones.

The importance of system classification is critical for the evaluation of natural system vulnerability to climate change. There may a strong disjunction between the driving processes and the observed state. For low modality systems, climate change is likely to represent a permanent shift of the modal condition. However, a mobile system is more likely to respond in a manner that reduces the influence of the climate shift. For multi-modal systems, climate change is only significant where the structural response represents a significant deviation from the existing range of conditions.

4.2. ESTUARINE SYSTEM DYNAMICS

The estuarine system represents a transition from fluvial (freshwater runoff) to marine (typically saline) conditions (Figure 3). This transition may produce quite significant spatial gradient in terms of hydrodynamic stresses, salinity, water quality, sediment characteristics, morphology and biota. Boyd *et al.* (1992) described the transition in terms of relative energy, salinity and sediment transport.

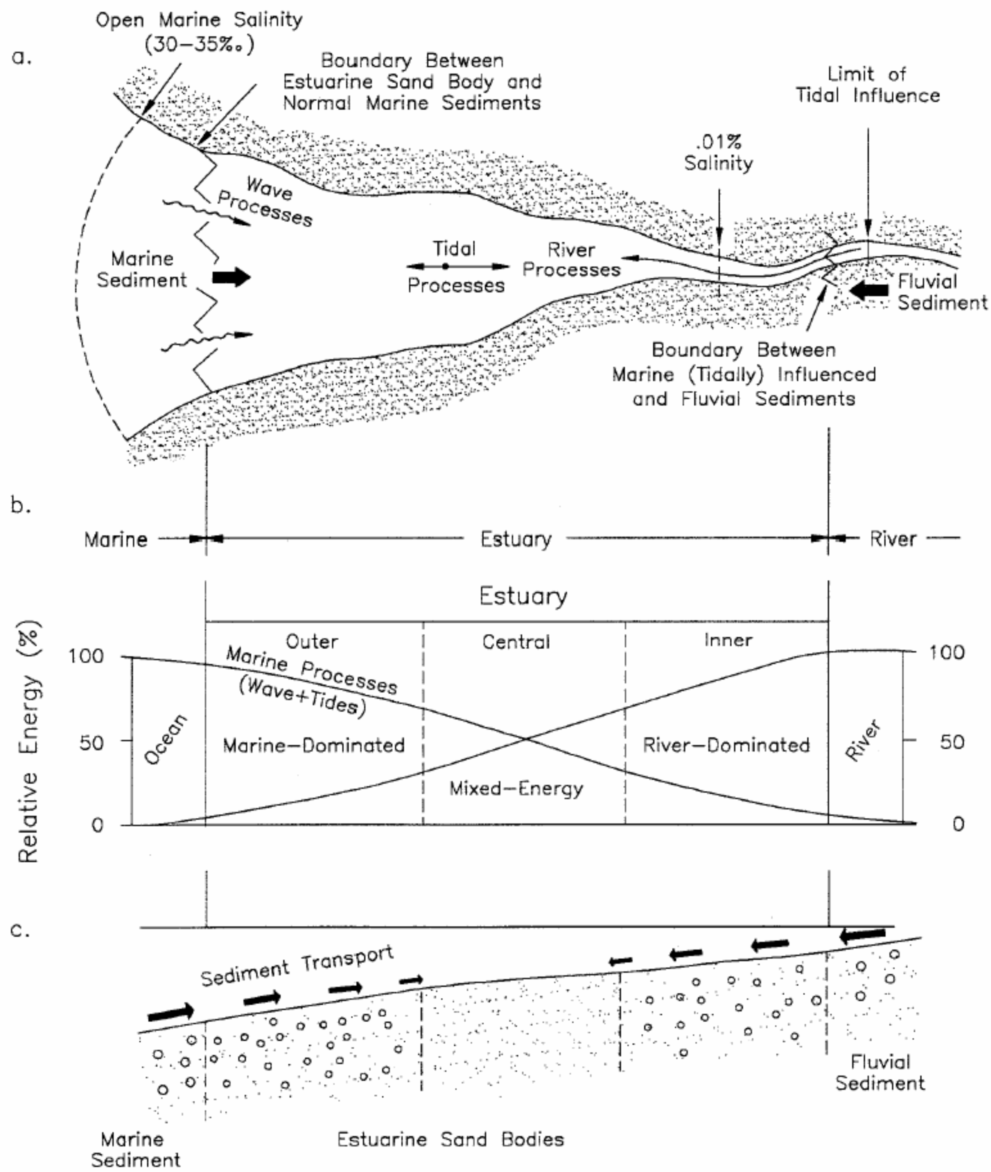

Figure 3 Schematic Description of Estuarine Processes

(after Dalrymple, Zaitlin & Boyd 1992)

At the upstream end, the estuary is influenced by streamflow, which is normally seasonal and uni-directional. At the downstream end, marine forcing, particularly through tidal exchange, provides a bi-directional flow, which may be relatively constant on a seasonal basis. Depending upon the structure of the estuary itself the dynamics of the entrance may be complicated by marine sediment transport, which is normally seasonal in response to changing weather.

Salinity Structure

The salinity structure of estuaries is principally determined by the density difference between marine and freshwater, with more dense saline water underlying the fresh water. Descriptions of estuarine mixing dynamics vary according to the balance of driving processes. At the simplest, a balance between tidal exchange and river flow is used (Fischer *et al.* 1979; Sanford *et al.* 1992). More complex dynamics incorporate boundary shear (Figure 4) and thermodynamics into the estuary characterisation (Wolanksi 1992; CSIRO 2003).

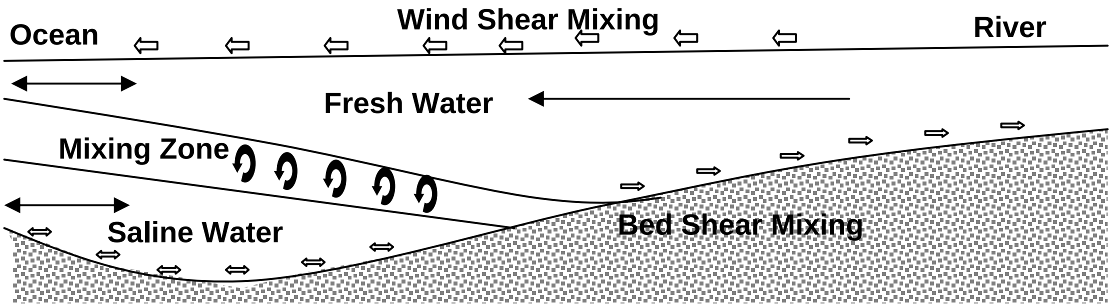

Figure 4 Schematic Illustration of Estuarine Mixing

The salinity structure interacts with the river flow and oceanic tidal forcing to determine the estuary hydrodynamics.

Hydrodynamics

The simplest model of riverine hydrodynamics is described by longitudinal pressure gradients from the river towards the ocean, following the principles of open channel flow (Chow 1959; Bras, 1990). However, this model holds less relevance within the estuarine zone, due to tide-induced motions and the salinity structure. At smaller scales, even unsteady flow models have limited application, as basin and channel structures become more distinct (USACE, 1993).

Sediment Dynamics

A primary distinction within estuarine systems is their effect upon coastal sediment budgets. Most simply, deltas are those systems that contribute sediment to the coast, whereas estuaries are those that remove sediment from the littoral budget (Coleman & Wright 1971; Ryan *et al.* 2003). This distinction is somewhat blurred by a range of estuarine systems which may be alternately externally contributory or internally accretionary as environmental conditions vary.

The tendency for estuaries to accumulate sediment suggests a geomorphic evolutionary sequence from estuaries towards floodplains and deltas (Roy 1984; Dalrymple *et al.* 1992). This process has been observed in the stratigraphic record for a number of estuarine systems across northern Australia (Chappell & Woodroffe 1985). However, it has been suggested that the sequence is driven by relative sea level change, with most estuarine systems responding to relatively stable sea levels over recent millennia.

Sediments within an estuarine system may come from a combination of marine, fluvial and biogenic sources. In general, wave action and nearshore currents transport marine sediments. Consequently, marine sediment supply is limited by the same factors affecting alongshore transport, including sediment mobility and availability, littoral barriers, reef or island sheltering and other bathymetric features.

Terrigenous sediments are transported principally by bed stresses caused by river flow, as a combination of bed load and suspended load. The capacity to carry sediment is reduced if the river grade declines, its depth or its cross-sectional area increases (Biedenharn *et al.* 1997). Floodplains are largely created as a result of the deposition as the river grade drops over the transition from highlands to coastal plains. Closer to the coast and at a more detailed scale, phases when either storm surge or tidal creek incursion is dominant may alternate with phases of floodwater runoff and enhance deposition of marine and estuarine sediments on the lower coastal plain (Winn *et al.* 2006). The role of such processes and their significance to estuary management is not thoroughly understood.

5. DATA SOURCES

Investigations of estuarine environments commonly fall within either a broad-scale "top-down" (divisive) or a detailed "bottom-up" (agglomerative) approach (Kingsford *et al.* 2005). The first involves regional differentiation that is purpose driven. For example, to establish the ecological health or well-being of estuary waters (Deeley & Paling, 1999) or to derive an indicator of relative habitat areas (Digby *et al*. 1998). This divisive approach (Kingsford *et al.* 2005) may involve application of a single criterion, or through the combined use of a suite of environmental parameters. The second, agglomerative approach requires detailed information from a range of estuarine systems and their subsequent grouping by similarity. Limitations to available information commonly restrict agglomerative assessment to a few estuaries as case studies within one region (Vertessy 1990; Sanderson & Taylor 2003) or inter-regionally (Coleman & Wright 1971; Chappell 1993). The Australia-wide classification by Heap *et al.* (2001) is an example of a large-scale agglomerative approach, using morphologic similarity as a basis for classification.

Assessment of the available information is based on sets of parameters contributing to the formation of estuaries, their internal processes, structures and dynamics. At a strategic, broad regional scale, there is a good coverage of data suited to a divisive approach. This is not so for an agglomerative approach to estuary classification since the processes and morphology of very few northern Australian estuaries have been surveyed in any detail or monitored over extended periods. Exceptions are provided by intermittent surveys of estuaries in the Alligator Rivers Region over the past thirty years.

5.1. AUSTRALIAN ESTUARINE DATABASE

The Australian Estuarine Database (AED) is a collation of information regarding estuaries, maintained by Geoscience Australia as part of the OzEstuaries website (http://www.ozestuaries.org/). The database has progressively evolved through a series of analyses and now covers a wide range of physical and chemical parameters. An original source of information was the collation of information by Bucher & Saenger (1989), which was further added to by Digby *et al.* (1998).

Subsequent expansion of the database was undertaken as part of the National Land and Water Resources Audit (Turner 2001), including detailed assessment of morphological facies, derived from photographic and remotely sensed imagery. This database has been used to develop a systematic morphology-based estuarine classification scheme (Heap *et al.* 2001), which has seen subsequent wide-ranging application (Harris *et al.* 2002; Heap & Harris 2002; Harris & Heap 2003; Ryan *et al.* 2003; Heap *et al.* 2004). The AED and OzEstuaries are subject to ongoing enhancement as part of the National Estuaries project (http://www.coastal.crc.org.au/index.asp).

5.2. GEOLOGY

Although parts of the Australian continent are pre-Cambrian in heritage, the configuration of the north Australian coast and contemporary location of its estuaries are significantly younger. Sea level fluctuations have occurred between glacial and interglacial climate phases. In the geologically recent past, sea level dramatically increased over the early Holocene, with maximum elevation reached approximately 6000 years before present and a relative stillstand subsequently (Kidson 1986; Pirazzolli 1996). For the Australian region, sedimentary records suggest mean sea level has progressively declined about 1-2 m from this highstand, reaching a stable level (Thom & Chappell 1975; Roy 1994). The effect of tectonics and isostasy to drive this sequence has been examined and there may be differences around Australia (Kidson 1986; Lambeck & Chappell 2001).

As a result, the physical location of estuaries around Australia has been determined by global sea levels, the inherited geomorphology and the subsequent evolution of coastal plains (Harris 1988; Kench 1999). Consequently, amongst the most significant features affecting estuarine structure is the regional geology, which affects geomorphology, pedology and provides preferential paths for river development along major fault lines.

Relevant geological records are available from Geoscience Australia:

Geological Provinces	http://www.ga.gov.au/oracle/provinces/
Geological Maps	http://www.geoscience.gov.au/geoportal/250
Geoscience Databases	http://www.ga.gov.au/map/national

5.3. CLIMATE

The Bureau of Meteorology provides a systematic collection of meteorologic data across Australia and commonly provides interpretation of synoptic conditions. Prior to the 1960's much of the data was derived from manual observation of meteorological instruments, including anemometers and barometers. Information was typically limited to selected periods of the day, which for many regional locations was at 9 am and 3 pm. Since the late 1960's the data collection program has increasingly been via automatic weather stations (AWS), which are able to sample with a much higher frequency. Long-term summaries of weather data are used to describe climate, conventionally adopting a 30 year record.

Northern Australia experiences a wet-dry tropical climate throughout the study area (Gentilli 1972; Digby *et al.* 1998). Rainfall is heaviest with the onset of northwesterly monsoonal conditions between October and March, at a time when barometric pressures are low, thunderstorms frequent and tropical cyclones active. The dry season from March to September is subject to higher barometric pressure, south easterly trade winds and light sea breezes (Laughlin 1990, 1997; Gentilli 1972). The marked seasonality of climate has direct ramifications for estuarine water quality and flow, with river floodwaters prevailing in the wet and marine waters penetrating the upper reaches of estuaries during tidal conditions in the dry season.

Climate zone maps developed by the Bureau of Meteorology provide graphical descriptions of Australia-wide climate. These zones are suitable for the assessment of climate variation over a continental scale, but demonstrate little variation across the Tropical Rivers region.

Climate Zones based upon rainfall and temperature (Bureau of Meteorology 2005)

http://www.bom.gov.au/climate/environ/other/IDCJCM0001_aus_clim_zones.shtml

Climate Zones based upon temperature and humidity (Bureau of Meteorology 2005)

http://www.bom.gov.au/climate/environ/travel/IDCJCM0000_tmp_rh_climaticzones.shtml

5.4. SEA LEVELS, TIDES & SURGES

Relative sea levels are determined by a wide range of component processes, including eustasy, isostatsy, tectonics, astronomic tides, atmospheric surges, steric variation and the effects of coastal circulation (Pugh 1987; Gornitz 1993; Csanady 1997; Douglas *et al.* 2001; Church *et al.* 2004). Variation of these processes occurs at different rates, generally requiring careful consideration of sea-level processes according to the time scale examined. Efforts to determine morphological and environmental response to sea level fluctuations may require very clear identification and delineation of these processes (Komar & Enfield 1987; de Vriend *et al.* 1993a, 1993b; Wolanski & Chappell 1995; Jimenez & Sanchez-Arcilla 1997; van Goor *et al.* 2003).

Long-term (Holocene) Records

Sea level variations over the Holocene have been interpreted from sedimentary records (van der Plaasche 1986; Lambeck & Chappell 2001). These observations are conventionally inferred from a distributed range of sedimentary records due to the potential for local effects caused by tectonics or neo-tectonics, including basin compaction (Woodroffe *et al.* 1987 & 1989). Site-specific measurements exist for very few locations, preventing comparison at anything except regional scales.

Historic (20th Century) Records

Over historic time scales, sea level records are available from tide gauge observations, with approximately one decade of satellite altimetry. Tide gauge coverage around Australia increased progressively over the course of the 20th Century. Ongoing measurements of sea level are available through coastal tide gauges and satellite altimetry. The Bureau of Meteorology, through the National Tidal Centre, coordinates the collation and analysis of tide gauge data for the Australian region (Ronai 2001). However, data is collected and tide gauges are maintained by State and Territory agencies:

- National (National Tidal Centre)

  http://www.bom.gov.au/oceanography/

- Queensland (Queensland Environmental Protection Agency_

  http://www.epa.qld.gov.au/environmental_management/coast_and_oceans/waves_and_storm_tides/storm_tide_monitoring/

- Northern Territory (Department for Planning, Infrastructure & Environment)
- Western Australia (Department for Planning & Infrastructure)

  http://www.dpi.wa.gov.au/imarine/coastaldata/

Sea level records summarised as monthly means are available from the Permanent Service for Mean Sea Level (http://www.pol.ac.uk/psmsl/). These data sets are derived from the Australian tide gauge data, but provide a convenient format for the analysis of monthly to annual sea level variations. Interpretations of the relative sea level record are available for the Australian region (Aubrey & Emery 1986; Mitchell *et al.* 1999; Church *et al.* 2004). However, in general these records are insufficient to clear distinguish relative sea level rise from inter-annual sea level fluctuations (Douglas *et al.* 2001).

Tides

Tidal observations are conventionally converted to a sequence of tidal constituents, following harmonic analysis of the sea level record (Cartwright 1977; Ducarme 2003). These records are published, along with tidal predictions, on an annual basis in the Australian National Tide Tables (Department of Defence, 1965 to 2006). Regional patters of tide range, seasonal signal and tidal form number are shown on Figure 5.

A significant difficulty with directly applying tidal parameters to estuarine classification is brought about by local scale effects upon tidal propagation and damping within an estuary. This includes barrier (Tang & Grimshaw 2003) and plan-form effects (Nichols & Biggs 1985). Consequently, the relative spatial distribution of tides within an estuary may be quite different between estuaries with similar tide range.

Although estuary entrance morphology generally relates well to tidal magnitude, there are substantial variations due to local effects within any tidal region. For example, the mouth of the Adelaide River is geologically controlled and contrasts in form with that of the South Alligator River in the same region.

Surges

Surges are, by convention, often considered the rapidly varying non-tidal component of the water level signal. It is common practice to remove a linear trend, then apply harmonic analysis to derive tidal constituents (Foreman 1977; Ducarme 2003). In general, surge data is not explicitly stored, as it may be regenerated from the water level observations, minus tidal estimates derived from constituents.

A mild disadvantage of this approach is that the “surge” signal generated contains a multitude of processes, including error related to tidal fit. Consequently, this restricts the application of the surge estimate to the represent individual processes, such as tropical cyclone generated surge.

Short-term surges and tidal fluctuations, including inter-annual cycles (Wood, 2001) must be abstracted from high frequency data sets. Analysts face the difficulty of deriving long-term distributions from short-term data sets (Pugh & Vassie 1980; Middleton & Thompson 1986) particularly within the tropical region, due to the small spatial scale of tropical cyclones.

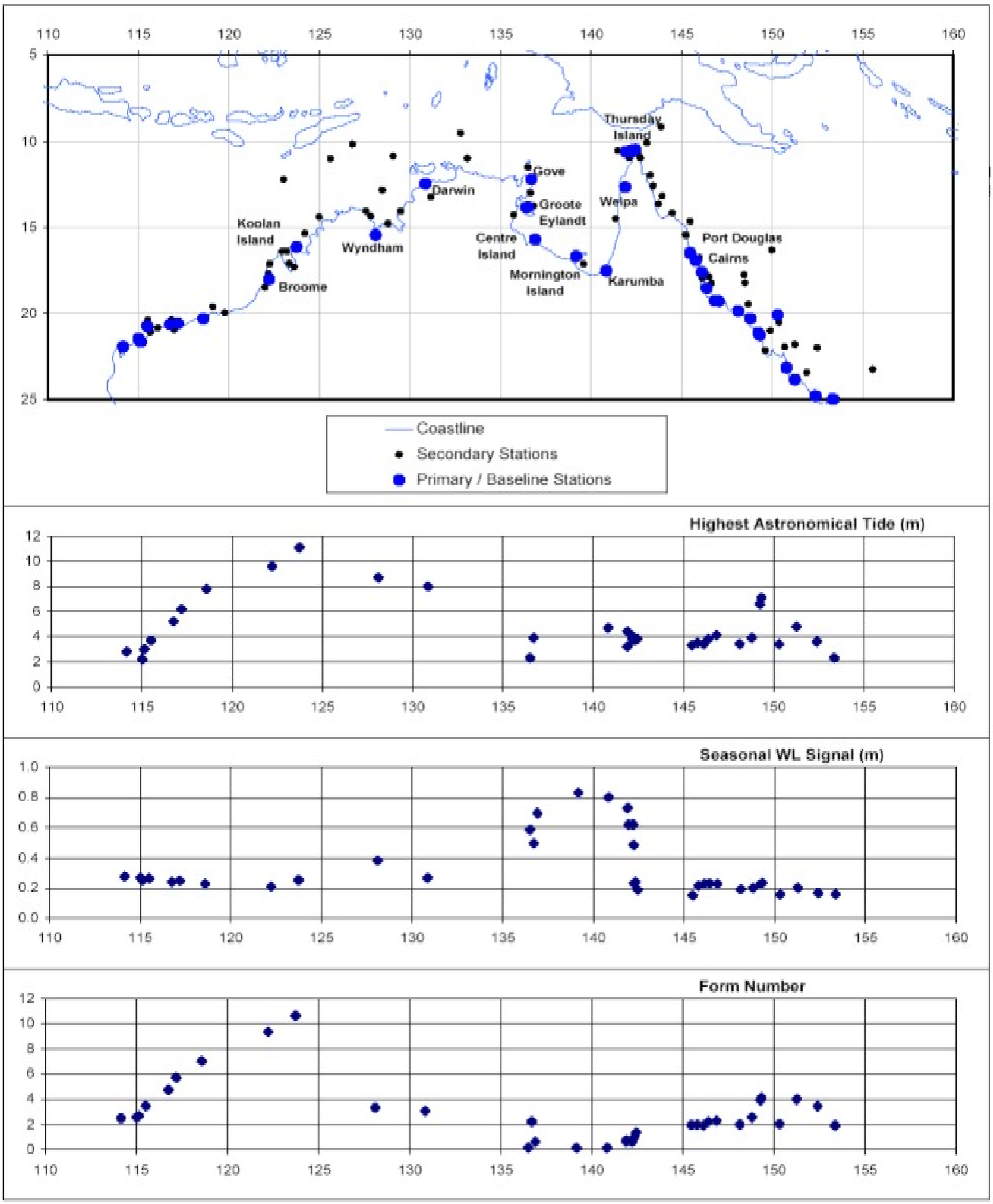

Figure 5 **Geographic Variation of Tidal Parameters**

The figure illustrates the influence of latitude, geology and aspect on tidal conditions across northern Australia.

Early studies to establish relationships between tropical cyclone characteristics and the resulting storm surge applied simple parametric models based upon continental shelf structure, cyclone speed and intensity and statistically compared them with tide gauge measurements (Hopley & Harvey 1976; Silvester & Mitchell 1977; Jelesnianski 1978).

Subsequent development of improved atmospheric (Gray 1979; Holland 1980 & 1983) and hydrodynamic models (Reid 1990; Fandry & Steedman 1994; Blain 1996; Tang *et al.* 1996; Bode & Hardy 1997) has facilitated the use of more advanced cyclone surge models. Applications in the Australian region have covered a range of site specific areas (Bureau of Meteorology Special Services Unit 1991, 1993, 1994 & 1995; McInnes *et al.* 2000 & 2002), with a broad regional study for Queensland (DNRM 2001; Hardy *et al.* 2004).

There is limited analysis of cyclonic surges across the Tropical Rivers Region. Individual analyses of tide gauge records have been undertaken by the relevant tide monitoring agencies, but these have not generally been put into context of the cyclonic record. Analysis of the Gulf of Carpentaria region is scheduled by the Queensland Government as part of its statewide assessment of coastal hazards (DNRM 2004), linking to historic observations (Callaghan 2004).

Satellite Altimetry

Satellite altimetry is available through international cooperative agreements, predominantly from US and European satellites. The TOPEX-Poseidon satellite provides 450-km swathe mapping which gives altimetry to an accuracy of approximately 0.1-m (Tokmakian & Challenor 1999). Due to the relatively slow sampling frequency, altimetry observations must be carefully corrected to account for tidal variations, and are therefore of limited value for the detection of short-term sea level oscillations. Church *et al.* (2004) provide an approach for the treatment of altimetry to identify sea level changes over a 10-year period.

Altimetry is available from http://www7320.nrlssc.navy.mil/altimetry/data.html.

Future Sea Level Trends

Global sea levels are expected to rise under projected Greenhouse-gas emission scenarios (IPCC 2001a, b, c & d; Pittock 2003; NCCOE 2004). The global effect may be modified by local patterns of uplift or subsidence and regional differences in sea level change (Church *et al.* 2004).

Projection of sea level trends based upon historic tide gauge observations is limited by the relatively short data observation periods (Mitchell *et al.* 1999) and the high degree of inter-annual sea level fluctuations (Aubrey & Emery 1986; Lambeck & Chappell 2001). Tide gauge observations within the Tropical Rivers Region are generally limited to 20-30 years length, with Darwin having a 47 year data set.

5.5. HYDROLOGY

The hydrology of northern Australia is well researched, due to its contribution to human activities within the region, for example see the review by Butterworth (1995). More detail on this aspect of the environment is provided in other sections of the Tropical Rivers Information Assessment Program.

The Bureau of Meteorology maintains widespread rainfall datasets. Although these cover the majority of northern Australia, there are wide sections with relatively poor historic coverage (Section 9.2 Appendix).

Application of the rainfall record to streamflow hydrology requires further understanding of catchment structure, including vegetation, morphology and pedology. Analysis of these characteristics on an Australia-wide basis has been undertaken (Pilgrim 1987; Peel *et al.* 2000).

A systematic assessment of rainfall records and the associated catchment runoff is available from Australian Rainfall & Runoff (Pilgrim 1987). This document was revised in 1999 and is presently subject to further review (http://www.arq.org.au/ncweARR/arrSummary.htm).

5.6. SEDIMENT TRANSPORT

Geomorphic evolution of estuaries and deltas is strongly linked to available sediment sources and their potential for transport, through both marine and fluvial processes (Eyre 1998; Kench 1999; Heap *et al.* 2004). Direct measurement of sediment through in-flow gauges is comparatively difficult and often undertaken as discrete measurements. Instead, sediment transport patterns are either determined by measurement of morphology (Camfield & Morang 1996; Galgano *et al.* 1998; Parsons *et al.* 2001; Saynor 2003) or inferred through one or more process models which have been developed linking sediment transport with continuously observed parameters such as rainfall, streamflow, wave conditions or circulation (Moss *et al.* 1992; Johnston & Prendergast 1999; Harris 2001; CSIRO 2003).

For estuarine systems, the two most commonly utilised proxies for sediment transport are the wave climate and the stream runoff. These parameters offer potentially high quality information due to their strong link with nearshore currents and channel flows respectively. However, it is important to note that both parameters provide a measure of potential transport. Sediment dynamics are further complicated by variations in shore structure, channel structure, lithology, riparian vegetation and estuarine biochemistry (Jennings & Bird 1967; Eyre 1998). Across Northern Australia, distinct changes in coastal aspect cause significant differences in the potential for alongshore transport, under similar wind and wave climates. The effect of sheltering by islands, headlands or shoals creates variations in sediment transport at even smaller scales.

5.7. WAVES

No regional long-term wave observations have been identified.

Regional descriptions of the wave climate are available through shipboard observation (US Navy Marine Atlas, 1976) or more recent global and regional hindcasts (Wavewatch III, Bureau of Meteorology).

Wavewatch III Global Hindcast

https://www.fnmoc.navy.mil/PUBLIC/WW3/index.html

Bureau of Meteorology WAM Hindcast

http://www.bom.gov.au/marine/waves.shtml

For the Tropical Rivers Region, ambient wave conditions are strongly linked to monsoon winds. This provides a high level of directional stability, although there may be variations in the intensity or persistence of monsoonal events (Raghavan 1973; Suppiah1992; Webster *et al.* 1998). For more extreme tropical cyclone events, short-term wave observations or hindcast waves offer limited value as they are normally beyond the calibrated model range.

Extensive wind records are available from the Bureau of Meteorology. The network of weather stations and their length of recording history are identified within Section 9.1 Appendix.

Regional descriptions of wind record are available as monthly averages from the US National Oceanic and Atmospheric Administration division (http://www.cdc.noaa.gov/cdc/reanalysis/). Regional observations are aggregated and converted to a spatial distribution. Because these wind estimates are derived from a subset of the Australian Bureau of Meteorology records, they will potentially have the same limitations of coverage.

5.8. CIRCULATION & SALINITY

Circulation of the north Australian tropical region is driven by a combination of tides, wind systems and exchange between the Pacific and Indian Oceans. Analyses of the corresponding steric character and currents vary considerably in scope and focus depending upon the study scale and the process under consideration.

At the largest scale, northern Australia is influenced by exchange between the Pacific and Indian Oceans (Meyers 1996; Schiller *et al.* 2000; Godfrey *et al.* 2001). Analysis of circulation is undertaken through a combination of remote sensing, research ship cruises and numerical modelling.

Smaller scale analysis of circulation patterns have been applied for subsets of the Tropical Rivers region, including the Gulf of Carpentaria (Wolanski 1993; Somers & Long 1994). Simplified representation of circulation within the estuaries themselves is provided by modelling, using boundary conditions and basic morphology (Heggie & Skyring 1999). This is applied as part of the SERM II modelling (http://www.per.marine.csiro.au/serm2/index.htm).

5.9. TROPICAL CYCLONES

Tropical cyclones represent the most severe synoptic events affecting northern Australia, with on average eight cyclones affecting the region each year (Laughlin 1990; Nott 2006). Conditions influencing the formation, development and transit of tropical cyclones have been examined for the Australian region (McBride 1981; McBride & Keenan 1981; Callaghan & Smith 1998; Holland 2004). Relationships between cyclones and global climate parameters have been explored (Solow & Nicholls 1990; Nicholls 1992; Broadbridge & Hanstrum 1998).

Following Coleman (1972) and Lourensz (1981) the Bureau of Meteorology maintains a database of observed tropical cyclone parameters in the Australian region (http://www.bom.gov.au/climate/how/). However, it is important to understand that analysis of the cyclone record requires careful interpretation as observations of tropical cyclones have been made with progressively improving technology (Dvorak 1973; Lourensz 1981).

Further databases of tropical cyclones and severe weather events are available from the Joint Typhoon Warning Centre:

http://www.npmoc.navy.mil/jtwc.html

and the Australian Severe Weather website

http://australiasevereweather.com/index.html

In general, these records represent a more processed version of the Bureau of Meteorology database and their products are less readily incorporated into GIS assessment tools.

6. PHYSICAL ATTRIBUTES OF ESTUARIES

Sustainable management of the estuarine reaches of Australia's tropical rivers and wetlands requires development of policy to facilitate holistic management of environmental change, including impacts due to human activities. Ideally, this should be based on a detailed understanding of their ecological character, including the physical attributes supporting and maintaining their diverse biota (Dostine 2002). The physical and biotic components are coupled, especially through biotic responses to change in the physical environment. Because estuaries are highly dynamic they may be subject to change in geomorphic form and biologic function over very short periods. A challenge for management at all scales is to develop an information base to assess environmental change and undertake risk assessments of major pressures, particularly those resulting from human interference with environmental flows and the use of water either in the marine environment or the river catchments linked to estuaries (Pierson *et al*. 2002).

Management is facilitated by classification schemes that are used as simplified diagnostic tools. In this context development of a classification scheme conventionally aims to use a small number of variables to provide a limited set of categories from which management options are delineated. There is a need to balance the complexity required for suitable management with the simplicity of a cogent classification, subject to limits of available information (Kingsford *et al.* 2005).

Information on the ecology, biology, geomorphology and hydrology is mainly available for estuaries fronting river catchments with mining, industrial or intensive agricultural development. Such circumstances are uncommon in northern Australia (Turner 2001), hence the primary objects in this section of the report are to review descriptions of estuaries in the region, examine the information used in those descriptions, and assess current classifications of northern Australian estuaries as tools for assessment of potential ecological risks likely due to physical change.

6.1. GEOMORPHIC CLASSIFICATIONS

According to the focus of an estuarine research project and its scale, classification schemes have used a wide range of parameters (Coleman & Wright 1971; Kench 1999). These generally fall into the following groups, and often demonstrate links between them:

Estuarine Origin – sea level, tectonics, antecedent structure and lithology;

Driving Conditions – hydrology, wave climate, tides and surges;

Internal Processes – salinity, circulation and sedimentation;

Condition – morphology, water quality, biochemistry & structural modification;

Ecology – habitats, flora and fauna.

Early classification of estuarine systems focused on providing effective comparison between different sites, with interpretation of estuary exchange, circulation and water quality characteristics. USACE (1991) refers to early process descriptions developed by Pritchard

(1955), Ippen (1966) and Lauff (1967). Prior to 1970 research primarily focused upon one or two processes and used a small set of examples to consider the performance of process-based models. For example, Dyer (1997) describes a range of simple estuarine classification schemes and illustrates how they are directly relevant to salinity structure and water quality issues within estuarine systems. Subsequent classifications examine tidal propagation (Nichols & Biggs 1985), structural origin (Fairbridge 1980), morphology (Dalrymple *et al.* 1992), salinity structure (Pritchard 1955) and salinity-circulation (Prandle 1981, 1985).

In a summary of previous process-based analyses of deltaic landforms and stratigraphy, Coleman & Wright (1971) identified a wide range of process and morphologic parameters that may contribute to estuarine structure and dynamics. These factors were considered with regards to stratigraphic sequences for 34 deltas around the world (Coleman & Wright 1975). Although the comparison suggested a simplified classification scheme may be developed, with six models derived from the data set, it also confirmed that more than one deltaic model was required to explain the observed patterns of deposition. The multivariate approach used by Coleman and Wright (1971) to classify deltaic sedimentation patterns provides a model for a holistic classification of estuarine geomorphology that is more complete than any attempted to date.

Galloway (1975) examined 21 major riverine deltas around the world and classified them on the basis of morphology. His classification was related to a ternary framework, with the relative strength of tide, wave and river flow determining the structure of medium to fine grained deltas. Dalrymple *et al.* (1992) and Boyd *et al.* (1992) expanded the scheme developed by Galloway (1975) to encompass a wider range of estuarine systems and demonstrated the evolutionary relationship between estuaries and deltas under transgressive or regressive relative sea levels. It is noted that the evolutionary maturity of estuarine systems may be constrained by limited sediment supply, due to coastal structure or lithology (Coleman & Wright, 1975; Kench, 1999).

A further difficulty applying a classification scheme based upon driving conditions is the inherent variability of those conditions and the capacity for estuarine systems to switch phase. This is particularly important in areas where there may be short periods of energetic conditions alternate with sustained periods of calm (Wright & Coleman 1973; Erskine & Warner 1988; Jimenenz & Sanchez-Arcilla 1997; Heap *et al.* 2002; Kingsford *et al.* 2005). Under such circumstances, it is possible that the estuarine condition is a relic of energetic conditions, with a disjunction between the estuary and ambient forcing. This will produce an estuary that is evolutionary in character over relatively short time scales, particularly between successive wet seasons (Erskine & Warner 1988) or subsequent to extreme events (Eyre 1998).

On the Northern Australian coast, one of the most significant features affecting the classification and development of the estuarine systems is the episodic character of meteorological conditions on a seasonal and interannual basis. This affects both oceanographic forcing and fluvial runoff, which have been identified as dominant driving processes for the region.

6.2. CLASSIFICATION OF ESTUARIES

Several approaches have been used to describe estuaries in northern Australia. All incorporate a description of their physical attributes, or part thereof, although the descriptions are derived in different ways and used for different purposes. The approaches may be grouped into two overlapping categories for convenience. As with other environmental systems, estuarine classification approaches may either be divisive or agglomerative (Kingsford *et al.* 2005). Divisive systems use limited information to provide distinction between estuaries, with progressive application of parameters until sufficiently diverse categories have been developed. Bucher & Saenger (1994) and Digby *et al.* (1998) provide examples of this classification approach. In contrast, agglomerative systems consider individual estuaries and group them together due to aspects of similarity. This approach may require a greater range and diversity of information.

There is a strong relationship between study scale and development of classification schemes. At global or continental scales, there is a diversity of very general environmental and climate conditions, which commonly provide a fundamental distinction for many environmental systems, including estuaries. It is the approach used by Thackway & Cresswell (1995), IMCRATG (1998) and Bucher & Saenger (1991) as well as Digby *et al.* (1998) and has significance at a strategic planning level. An alternative primary classification is to examine one or more physical processes, as was done in more detail by Pritchard (1955), and Galloway (1975).

Global classification schemes often lose relevance at regional scales, due to reduced spatial variability of climate, environmental, biotic, pedologic or tectonic conditions. The resultant classification does not serve to distinguish between geomorphic systems across the study region and provides no framework for management decision-making. In this situation, a divisive classification scheme may require refinement using an additional environmental parameter, whereas an agglomerative scheme may require reduction in the scheme order.

At local scales, classification appears to be more commonly driven by the estuarine management framework similar to those described for the Daly River (Erskine *et al.* 2003) or for temperate southwestern Australia (Hodgkin & Clark 1986 to 1990). In general, estuarine features such as the entrance channel dimensions or salt-wedge structure are essential descriptors for a locally based classification scheme (Dyer 1997, USACE 1995).

The development of estuarine classification schemes reflects the progressive development of estuarine science and increasing pressure upon natural resource management. Early studies reflected a data poor environment, and focused upon issues of direct relevance to human activities including sediment management (USACE 1991) and water quality (Ippen 1966). More recent studies place a greater emphasis on the role of estuaries for marine and estuarine ecology (Bucher & Saenger 1994; Digby *et al.* 1998). Increasing data capture and knowledge has facilitated the use of more comprehensive analyses of estuarine behaviour and examination of the links between climate, hydrology, water quality, estuarine morphology and ecology (Ryan *et al.* 2003; Kingsford *et al.* 2005).

As discussed by Digby *et al.* (1998) the extensive array of geophysical, environmental, morphologic, biochemical and ecological parameters provide the ability to create a vast array of potential classification schemes. Ultimately the scale of the database determines the order of the classification scheme, whilst the intended management outcomes of the scheme determine which restricted set of parameters is to be used for classification.

6.3. ESTUARINE GEOMORPHOLOGY IN NORTHERN AUSTRALIA

The most complete descriptions of estuarine geomorphology in northern Australia are provided from detailed field surveys reported by Wright et al (1973, 1975) and Semeniuk (1982, 1985) for the Kimberley; Chappell (1993) and Erskine *et al*. (2003) for the Daly River, Vertessy (1990), Wasson (1992), Woodroffe (1986), Woodroffe & Mulrennan (1993) & Woodroffe *et al.* (1985, 1989) from the Alligator Rivers Region; and Jones *et al*. (1993) from the Gulf of Carpentaria. Their observations were used in Section 2 to identify geomorphic components of the estuaries as well as identify process driving estuary development.

A broader picture of estuarine geomorphology in which the detailed surveys are given geographic context is presented in regional descriptions and inventories reported by Jennings & Bird (1967), Galloway (1975), Bucher & Saenger (1989, 1991, 1994), Digby *et al.* (1998) and Heap *et al.* (2001). The approach to inventory progressed from process identification, through quantification of climate, physical processes and morphology, to application of simplified classification schemes based on a select group of variables. The major purpose of the inventories has been to explain the distribution of habitats such as mangroves and mudflats rather than being an examination of the geomorphology. Most recently, relationships between classification schemes have been examined by Harris *et al.* (2002) and Ryan *et al.* (2003) through the use of conceptual models.

Bucher & Saenger (1989) provided an inventory of estuarine data, which led to the development of the Australian Estuarine Database (AED). They demonstrated that application of selected components of the database could be used to infer habitat distribution. In particular, tide and rainfall were used to describe the relative proportion of mangroves and saltmarsh (Bucher & Saenger 1994). Following refinement, the AED was used to classify estuaries according to a five morphological parameters: entrance constriction, width to length ratio, number of entrances and channels, and presence of off-channel embayments (Digby *et al.* 1998). The morphologic categories were combined with climate, tide and intertidal proportion then grouped according to statistical similarity to describe 23 classes of estuary. This grouping was then used to explain the distribution of salt marsh and mangrove habitats.

Several of the broader classifications use terminology related to the ternary classification scheme developed by Galloway (1975), who sorted the morphology of river deltas according to apparent relative wave, tide and river power. Heap *et al.* (2001) combined morphological facies with a relative wave – tide regime to define seven morphotypes. Harris *et al.* (2002) attempted to quantitatively compare estuary morphology according to the ternary scheme. Their analyses indicated a separation between wave and tidal regimes but did not demonstrate a close relationship with estuary morphology. The distribution of particular estuary classes demonstrates significant regional grouping.

7. OVERVIEW

A range of investigations of the geomorphology of specific estuaries together with available classification systems for estuaries has been examined. This has identified a link between the environmental management needs, available information and the scale of the study area to the classification scheme development. In general, there is a scalar effect, whereby small-scale estuarine features such as the entrance channel dimensions, or salt-wedge structure, are essential descriptors for a locally based classification scheme (Dyer 1997).

At a global or continental scale, the dynamics of individual estuaries are generally too complex for detailed development of a classification scheme, or there is a distinct lack of appropriate information. The potential information needs to develop a scheme suitable for environmental management is illustrated by the detailed multi-variate analysis conducted by Coleman & Wright (1971). As a simplified proxy, Galloway (1975) developed a ternary classification scheme, based upon tide, wave and river flow, which balanced available information with classification needs. This approach was adopted by Boyd *et al.* (1992), Dalrymple *et al.* (1992) and has more recently formed the fundamental basis for the comprehensive analysis of Australian estuarine geomorphology undertaken by Geoscience Australia (Heap *et al.* 2001; Ryan *et al.* 2003).

For estuaries for which there is a higher level of available information, the ternary classification scheme offers a very simple interpretation of active processes. However, it is important to be aware that the three factors used to describe the estuarine system are themselves proxy indicators of the active processes and may be modified by site specific characteristics. For example, alongshore sediment transport is heavily affected by wave power. However, this is significantly modified through coastal aspect and the sediment character and will produce very different patterns of estuarine evolution and morphology. These aspects and some the potential limitations are identified within the derivation of the estuarine classification system (Heap *et al.*2001).

Variation in the morphology of estuaries across northern Australia is apparent from satellite imagery at a wide range of scales (NCTWR 2005). This has contributed substantially to the broad-scale descriptions of estuarine morphology (Heap et al. 2001; Ryan et al. 2003) as well as to a similar understanding of the distribution of wetland vegetation (Finlayson & von Oertzen 1996a; Storrs & Finlayson 1997; Finlayson & Lukacs 2004). However, these sets of information are not matched by a similarly detailed description of the processes of estuary formation and continuing development. Such knowledge remains available for a few locations only and cannot be inferred from 'snapshots' of estuarine morphology and vegetation. Monitoring of geomorphic change, which combines observation of the interaction of process and landform is notably lacking (Eliot *et al.* 2000).

Despite these apparent shortcomings, considerable progress has been made in our understanding of estuarine geomorphology in northern Australia. Classification of estuaries according to whether they are located in river, tide or wave dominated environments, first mooted by Galloway (1975) and later expanded by Dalrymple *et al.* (1992) provide a general context for the detailed field surveys of individual estuarine systems. The field observations of Semeniuk (1982), Chappell (1993), Woodroffe *et al.* (1985 & 1986) and Jones *et al.* (1993) are examples of the more detailed surveys reported in the literature. These are being added to by projects such as the studies of Darwin Harbour, the Ord River and Fitzroy River (Margvelashvili *et al.* 2003). There is now considerable scope to develop a focussed classification of estuarine geomorphology and establish a range of sites to monitor ongoing change and the risks it presents to local communities.

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9. APPENDICES

9.1. LOCATION AND RECORD LENGTH – WIND RECORDING STATIONS

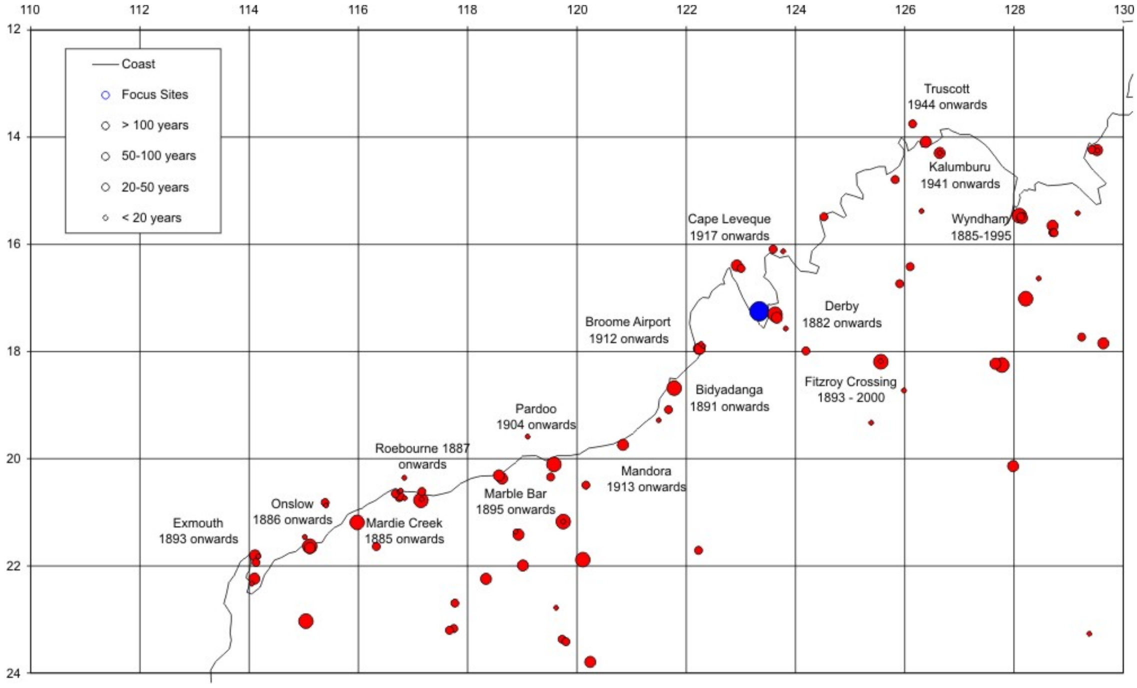

Figure 6 – Western Australian Wind Records

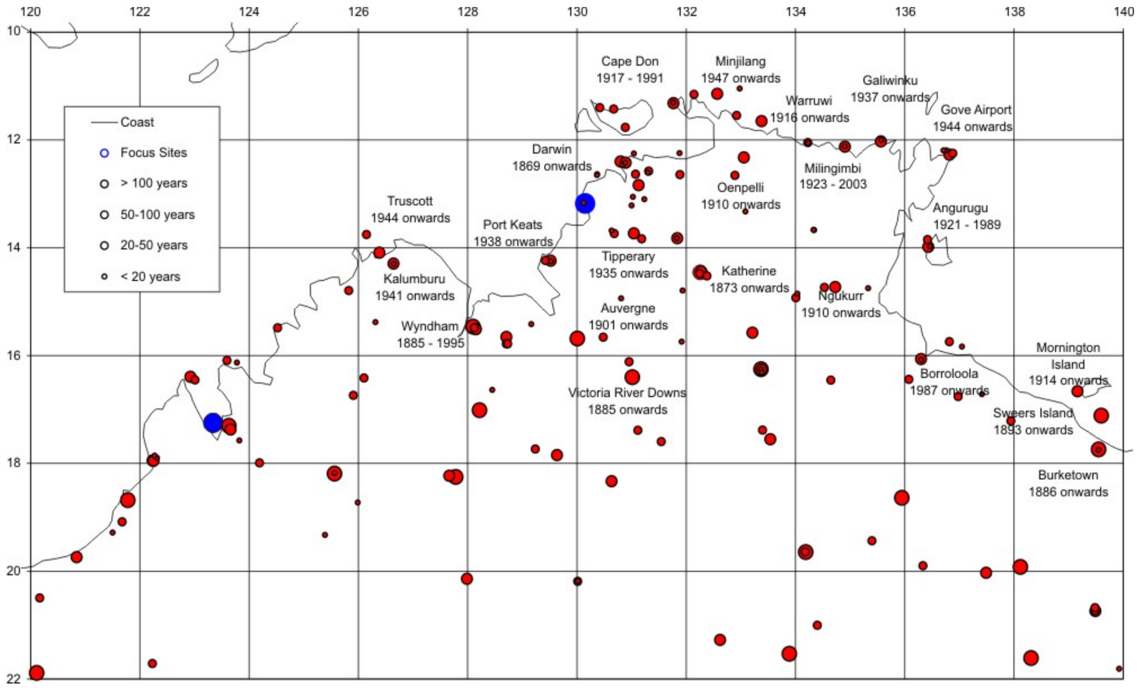

Figure 7 – Northern Territory Wind Records

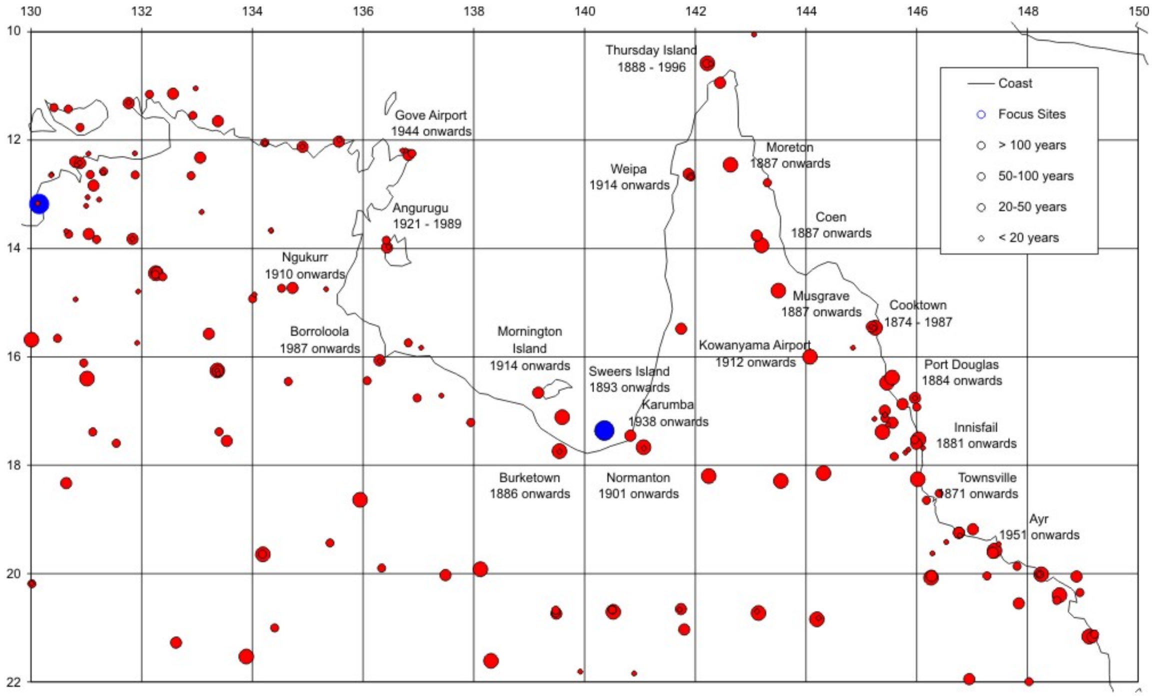

Figure 8 – Queensland Wind Records

9.2. LOCATION AND RECORD LENGTH – RAINFALL RECORDING STATIONS

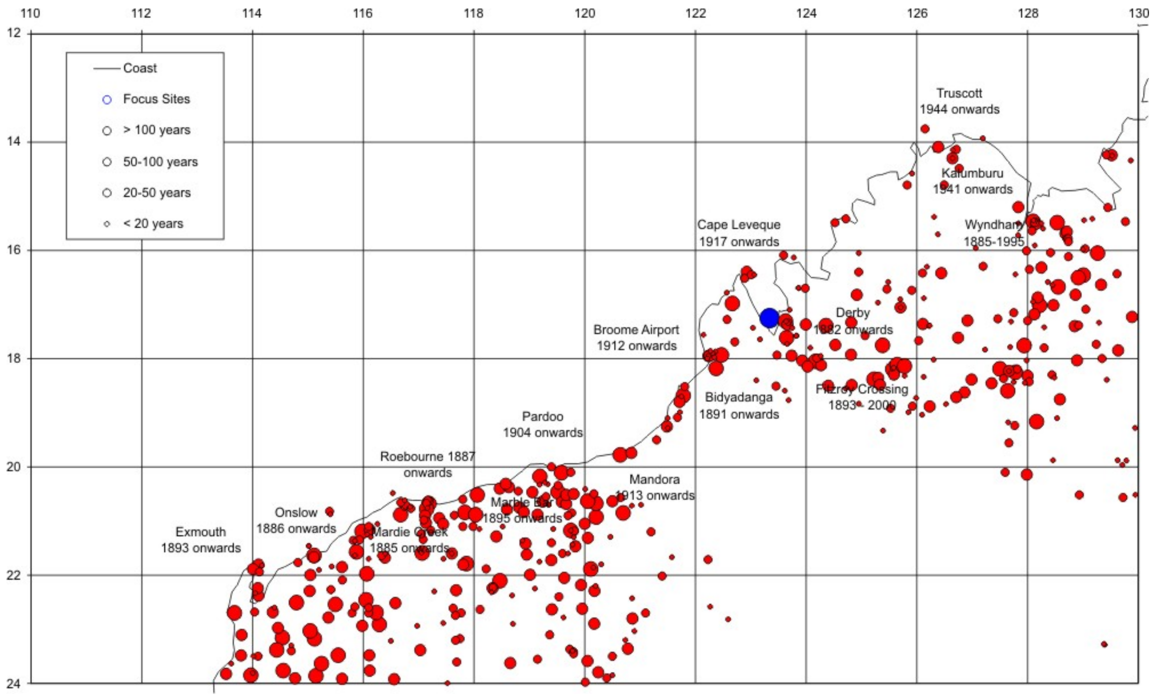

Figure 9 – Western Australian Rainfall Records

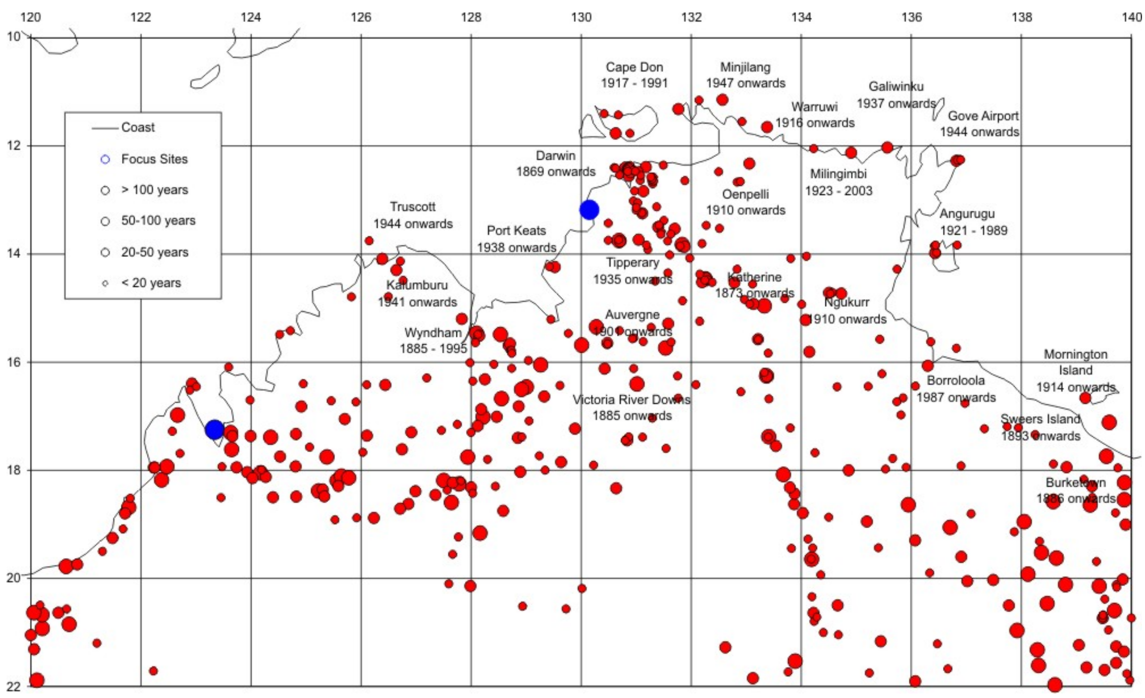

Figure 10 – Northern Territory Rainfall Records

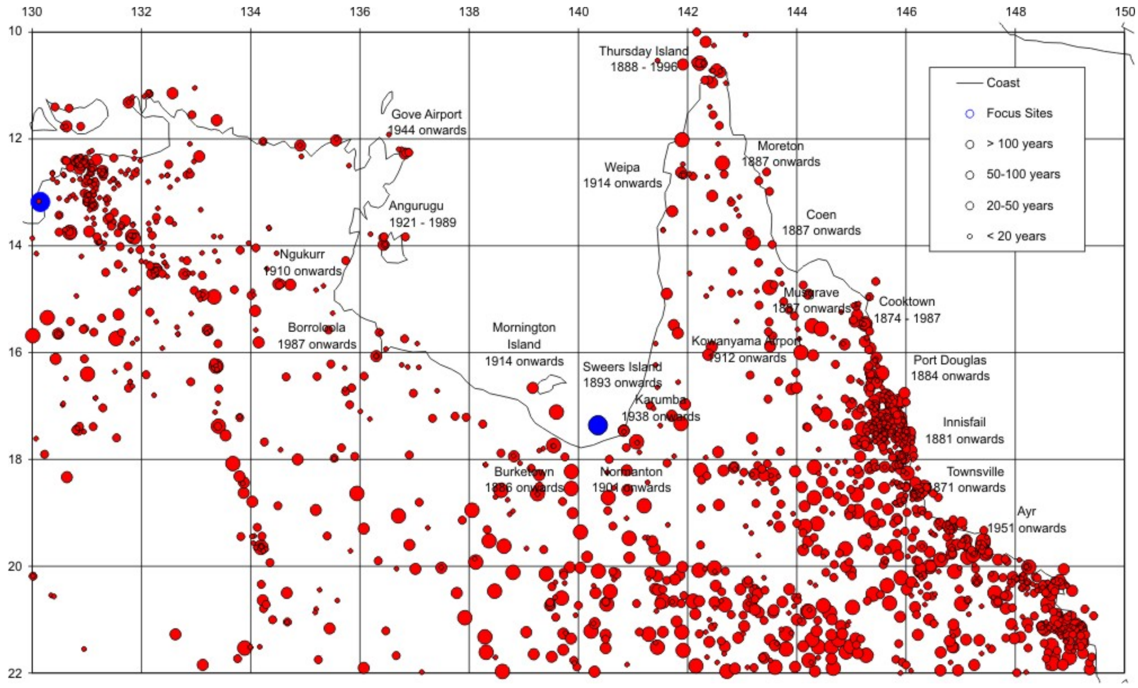

Figure 11 – Queensland Rainfall Records